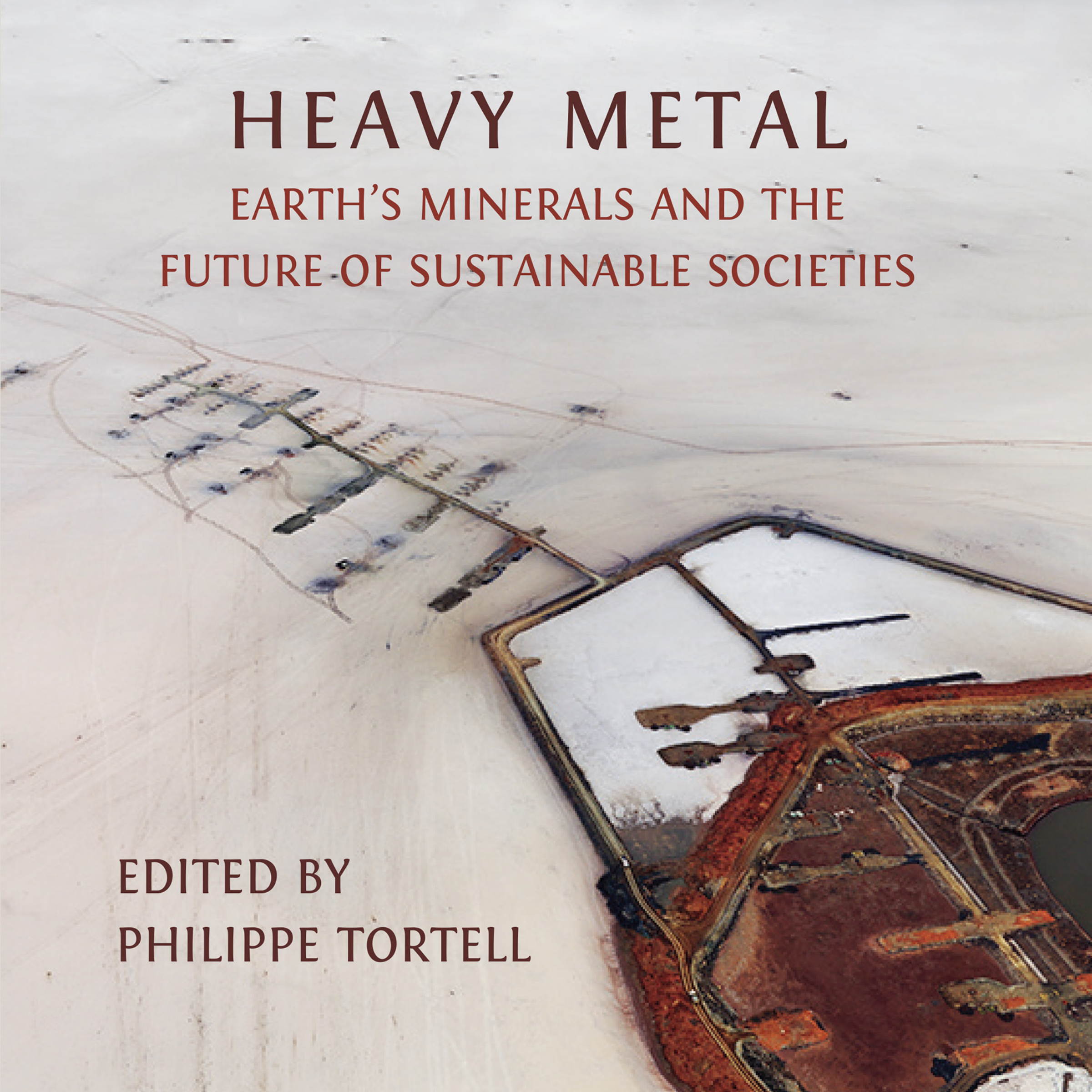
HEAVY METAL

EARTH'S MINERALS AND THE FUTURE OF SUSTAINABLE SOCIETIES



EDITED BY
PHILIPPE TORTELL

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Earth's Minerals and the Future of Sustainable Societies

Edited by Philippe D. Tortell

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Sammy Hagar, 'Heavy Metal',
Standing Hampton (Geffen, 1982).

Acknowledgements

I am grateful to all the contributors in this volume for sharing their insights, wisdom and creativity, and for their patience with all of my editorial suggestions. Through their words and ideas, I have come to better understand the challenges and opportunities ahead in humanity's search for future mineral resources. I also want to thank my wife, Maite Maldonado, for her support during the many hours this 'side-project' took away from shared evenings and weekends.

Contributor Biographies

Werner Antweiler is an Associate Professor in the Sauder School of Business at the University of British Columbia (UBC). He holds a Chair in International Trade Policy, and specializes in topics of international economics related to the environment, energy, natural resources and climate change. His recent work has focused on bilateral electricity trade, the integration of renewable energy into the electricity grid, grid-scale electricity storage and the electrification of transportation systems. Werner has authored the textbook *Elements of Environmental Management*, and co-authored the textbook *Government Policy, Business, and Society*, and is a frequent commentator on public policy topics in local and national news media.

Shaun Barker is an Associate Professor and Director of the Mineral Deposit Research Unit in the Department of Earth, Ocean and Atmospheric Science at UBC. He has a background in structural geology and geochemistry, and conducts research on hydrothermal systems, which form many types of ore deposits. Over the last few years, Shaun has focused on developing and applying new tools to improve exploration success for copper and base metal deposits that are needed to support the low-carbon energy transition. He is a Lindgren Fellow of the Society of Economic Geologists.

Roger Beckie is a Professor in the Department of Earth, Ocean and Atmospheric Science at UBC. He is a hydrogeologist and registered professional engineer, with expertise in drainage from mine waste rock. He serves on several Independent Technical Review Boards for tailings-management facilities, and is the liaison to the Tahltan Nation for the Red Chris Mine's tailings-management facility review board.

Edward Burtynsky is one of the world's most accomplished contemporary photographers, whose depictions of global industrial landscapes have documented the impact of humans on the planet for more than four decades. Burtynsky's photographs are included in the collections of over eighty major museums around the world. Major touring exhibitions include: *Anthropocene* (2018); *Water* (2013); *Oil* (2009); *China* (2005 five-year tour); and *Manufactured Landscapes* (2003). He was also a key production figure in the award-winning documentary trilogy *Manufactured Landscapes* (2006), *Watermark* (2013), and *Anthropocene: The Human Epoch* (2018). Burtynsky's distinctions include the inaugural TED Prize in 2005, which he shared with Bono and Robert Fischell; the 2016 Governor General's Awards in Visual and Media Arts; the 2018 Photo London Master of Photography Award, and the 2019 Lucie Award for Achievement in Documentary Photography. He was awarded a Royal Photographic Society Honorary Fellowship in 2020. In 2022, he was honored with the Outstanding Contribution to Photography Award by the World Photography Organization, and also inducted into the International Photography Hall of Fame. Burtynsky currently holds eight honorary doctorate degrees.

T. Patrick Carrabré is a Métis composer living in Vancouver. Construction of identity and community engagement are long-term themes in his compositions, artistic programming and administrative activities. His best-known works include *Inuit Games*, for katajjak (throat singers) and orchestra, which was a recommended work at the International Rostrum of Composers (2003), *Sonata No. 1, The Penitent*, for violin and piano, and *From the Dark Reaches*, which were nominated for JUNO awards. In 2021, he was recognized with a second Western Canadian Music Award (Classical Composer of the Year) for the album, *100,000 Lakes*. Other recent work includes *Métis Songs*, commissioned by Harbourfront for Rebecca Cuddy and the Wood and Wire String Quartet, and *Snewíyalh tl'a Stak̲w* (Teachings of the Water), written in collaboration with the Elektra Women's Choir. His composition *Orpheus (1)*, written in collaboration with pianist Megumi Masaki, was released on the Centredisc label in March 2023, and an EP of *Métis Songs* was released in September 2024 on Winter Wind Records.

Chris Chafe is a Professor, composer, improvisor and cellist, and the Director of Stanford University's Center for Computer Research in Music and Acoustics (CCRMA). He develops much of his music alongside computer-based research, and pursues methods for digital synthesis and network music performance. An active performer in both physical and virtual spaces, Chris' music reaches audiences in a range of venues, including gallery and museum installations, and even works performed by the horns of large ships in the port of St. Johns, Newfoundland. He has many active collaborative research projects, working with scientists and medical professionals in the 'sonification' of a wide range of data sets—from paleo ice core data to neurological electrical fields. He has been a Visiting Professor at UBC, Politecnico di Torino and the Technical University of Berlin, and an Artist in Residence at The Banff Centre for Arts and Creativity.

Yao Chen is a composer and a Professor of Composition at Central Conservatory of Music in Beijing. He received training in composition at Xinghai Conservatory of Music and Central Conservatory of Music, and obtained his PhD in Composition from the University of Chicago. Chen has received commissions and awards from many international organizations, including Radio France, Harvard University's Fromm Foundation, the Leonard Bernstein Foundation, the Mellon Foundation and the China National Center for the Performing Arts. His music has been performed by many internationally-acclaimed musicians and ensembles, and he has won awards at renowned music festivals such as ISCM World Music Days, Centre Acanthes, Festival Présences, Tanglewood Music Festival, Aspen Music Festival, Pacific Music Festival, Beijing Modern Music Festival among many others. His music eschews contemporary vogues, aiming for a timelessness and an otherness that exists beyond the standard categories – music for the moment, but also music for then and music for what lies ahead.

J. Alejandro Delgado-Jimenez is a mining engineer and researcher who holds a PhD in Earth Resources Development Engineering from the Colorado School of Mines.

He specializes in the sustainability of the mining industry, and the environmental, social, economic and governance aspects that shape relationships between mining operations and local communities. Alejandro has worked with multidisciplinary teams promoting sustainable mining practices through teaching, consulting, research, and the translation of knowledge into practical applications within the mining sector. He has received several scholarships, including the Australian Leadership Program, the Canadian Emerging Leaders of the Americas, and a fellowship in the PIRE program from the United States National Science Foundation.

Anita Dey Nuttall is the Polar Science and Policy Engagement Officer in the Department of Earth and Atmospheric Science at the University of Alberta. She teaches resource management and environmental policy, and researches science policy issues, the history and contemporary nature of national Antarctic programs, and geopolitics, security and sovereignty in the circumpolar regions. She is a member and past Chair of the Canadian Committee for Antarctic Research, and has been involved in several University of the Arctic (UArctic) initiatives. She has also been a Visiting Researcher at the Thule Institute, University of Oulu in Finland, and previously served as Associate Director of the Canadian Circumpolar Institute, University of Alberta, and UAlberta North, an interdisciplinary office concerned with Northern research and community engagement.

W. Scott Dunbar is a Professor in the Department of Mining Engineering at UBC. His research explores the future of mining, drawing ideas from a range of science and engineering disciplines to develop novel concepts and methods for mining and mineral processing. His recent work has focused on organizational innovation in the mineral supply system. He is a registered professional engineer in the province of British Columbia, and the author of *How Mining Works*, a book that explains the mining industry to non-specialist audiences.

Allen Edzerza is an Elder of the Tahltan Nation, and a member of the Tahltan Elders Council. He has led mining reform discussions with the Government of British

Columbia on behalf of the First Nation Energy and Mining Council, and has served as an advisor on Aboriginal issues to the Premier and Cabinet of Government of British Columbia and the Yukon. For more than three decades, he has worked to advance Indigenous title and rights and the re-establishment of Indigenous sovereign governments, supporting resource projects to address climate change, while protecting the environment and wildlife populations. He is also working with UBC to bring post-secondary education to remote northern communities, with a significant component of land-based experiential learning and Elder knowledge.

Erik Eberhardt is a Professor of Geological Engineering in the Department of Earth, Ocean and Atmospheric Science at UBC. He previously served as the Associate Director of the Rio Tinto Centre for Underground Mine Construction (RTC-UMC), and now serves on the leadership team for the International Caving Research Network (ICaRN). His research integrates geological field measurements with advanced computer modelling to better understand and assess the underlying mechanisms responsible for complex geological hazards, including engineering risks associated with large open pit and deep underground mining projects. He is a registered professional engineer in the province of British Columbia, and recently won the Rock Mechanics Award from the Canadian Institute of Mining in recognition of his significant and lasting contributions to rock engineering.

Jocelyn Fraser is a Research Associate and Sessional Lecturer in the Department of Mining Engineering at UBC. After working for extractive companies on community and stakeholder engagement issues, she completed a PhD in Mining Engineering at UBC on the topic of shared value. She teaches and conducts research on the intersectionality of mining and society, with a focus on social risk and responsibility in the mining sector. She is particularly interested in approaches to increase collaboration, reduce mining-community conflict, and business model innovation to achieve the agenda of the United Nations Sustainable Development Goals. Jocelyn sits on the advisory panel of the Mining Association of Canada's Towards Sustainable Mining initiative and leads a Canadian Institute of Mining and Metallurgy working group on stakeholder engagement.

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Maria Holuszko is an Associate Professor in the Department of Mining Engineering at UBC. She holds both a MASc and PhD from UBC, and is a mineral processing engineer by training, with more than thirty years' experience as a registered professional engineer. Her research focuses on the recovery of valuable materials from both industrial and municipal wastes including the recovery of critical minerals and metals from mining tailings, urban wastes and electronic waste. In 2015, Maria co-founded, with Professor Marcello Veiga, the Urban Mining Innovation Center (UMIC) at UBC, and she is also the current Co-Chair of UNESCO's Sustainable Electronics initiative, led by Professor Clara Santato (Polytechnique Montréal). She recently edited the book *Electronic Waste: Recycling for Sustainable Future*.

Naomi Klein is an award-winning journalist, columnist and the international bestselling author of nine books published in over thirty-five languages, including *No Logo*, *The Shock Doctrine*, *This Changes Everything*, *No Is Not Enough*, *On Fire* and *Doppelganger: A Trip into the Mirror World*, which was published in September, 2023. She is a columnist for *The Guardian*, and her writing has appeared in leading publications around the world. Naomi is also an Honorary Professor in Media and Climate at Rutgers University, an Associate Professor in the Department of Geography at UBC, and the founding Co-Director of UBC's Centre for Climate Justice.

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Vuma Ian Levin is a jazz guitarist and composer, whose music interrogates conceptions of identity, nation, culture, power and being, both globally and in the emergent, post-1994 South African Democratic project. He has been described, by *The Mail* and *The Guardian*, as "destined to be one of South African jazz's greatest musicians". Vuma attended the Conservatorium van Amsterdam where he earned the Non-European-Union Talent Scholarship to finance his study. He currently lives in Johannesburg, where he holds a teaching position at the University of Witwatersrand, and continues to play and record widely. He has been the recipient of numerous award nominations and prizes, including the Keep an Eye International Jazz Awards, the Dutch Eindwerkprijs, Dutch Jazz Competition, the Socar Montreux Jazz Electric Guitar Competition and the Standard Bank Young Artist Award. He has been featured on CNN's *African Voices*, and was included in *The Mail* and *The Guardian*'s 200 young South African's list. Vuma has performed at a number of top venues and festivals in

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Carol Liao is an Associate Professor at the Peter A. Allard School of Law and the Distinguished Fellow at the Peter P. Dhillon Centre for Business Ethics, Sauder School of Business, UBC. She is the Chair of the Canada Climate Law Initiative, dedicated to advancing director knowledge on the latest in climate science and fiduciary obligation. Her research focuses on corporate law and sustainability, climate governance, gender and racial justice. Carol was named as one of Canada's 2024 Clean50 and Canada's Top 100 Most Powerful Women, and is the recipient of the Business in Vancouver Influential Women in Business Award, TELUS Community Service Award, and BCBusiness Women of the Year Award.

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Riz Mokal has researched, taught and practiced insolvency, property and commercial law over the past twenty-five years, and has advised governments on law reform. He currently practices law at the English Bar from South Square in London, and previously held the Chair of Law and Legal Theory at University College London, served as Senior Counsel to the World Bank and headed the Bank's Global Insolvency and Creditor/Debtor Initiative. He has also been a member of the World Bank's and, subsequently, the United Kingdom's delegations to the United Nations Commission on International Trade Law. His work has influenced law reform in several jurisdictions, and has been cited with approval by courts around the world.

Roberto Morales-Manzanares is a musician, composer, performer and Professor of Music at the University of Guanajuato. He holds a PhD in Composition from the University of California (UC), Berkeley. In 1987, Roberto co-founded, with Francisco Núñez, the Laboratory of Computer Music and Digital Synthesis at the Escuela Superior de Música. In 1992, he founded the Laboratorio de Informática Musical at the Escuela de Música de La Universidad de Guanajuato, of which he was Director until 2019. He has won a number of national and international awards as a composer, and his music is regularly performed in Mexico, the United States and Europe. Roberto has been invited as Composer-Researcher in Residence at several universities, including Stanford University, UC Berkeley, UC San Diego, McGill University, New York University and Columbia University. He has organized and directed several international music festivals, including 'La Computadora y la Música', 'Callejón del Ruido, Composición Ideas y Tecnologı'a' and 'Transito_MX04'. Currently, Roberto organizes courses and seminars on composition, music and mathematics and digital art in various institutions across Mexico. His research interests focus on real-time composition generated from mathematical models, learning systems applied to audio and video computing, gesture capture, and real-time processing of image and sound.

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Dave Porter is an Elder of the Kaska Nation, whose traditional territory covers a large part of northeastern British Columbia and southeastern Yukon. He is the CEO of the British Columbia First Nations Energy and Mining Council, and President of the Dena Kayeh Institute. He has previously been a member of the Yukon Legislature, where he served as House Leader, Deputy Premier and Minister of Renewable Resources, Tourism, Heritage and Culture, and Minister Responsible for Constitutional Devolution. Dave has also served as a Deputy Minister and Assistant Deputy Minister in the governments of the Northwest Territories and British Columbia, and as Executive Director of the Yukon Human Rights Commission. In 2002, he was elected Chair of the Kaska Dena Council, with a special commitment to preserve Kaska culture and create greater opportunity for Kaska youth. Over his career, Dave has worked to promote sustainable economic and social development on Indigenous lands.

Trumpeter **Dorival Puccini, Jr.** is an active soloist, chamber musician, orchestral player, producer and educator. Founder of the award-winning Axiom Brass quintet, his interest in chamber music has led him to contribute several musical translations for brass quintet specially written for the Axiom Brass. Dorival has co-produced all of Axiom Brass' albums including *New Standards*, *First Impressions* and *Astor*, which includes ten of his musical translations of Astor Piazzolla's compositions. As a proponent of chamber music, Dorival has commissioned and premiered over fifty new works for brass, and is the founder and chief-editor of *Brass Legacy*, a publication and commissioning consortium dedicated to Brass Chamber Art Music. His works have been performed across the United States, Europe and Asia. He holds a Bachelor's degree from Grand Valley State University, a Master's degree from the Juilliard School of Music and a Doctoral degree from Michigan State University.

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Christopher Sainsbury is an Associate Professor in Composition at the School of Music at the Australian National University, and an Australian Performing Rights Association Luminary. As a scholar, his primary research focus is on regional music and identity. He has received commissions from the Australian Chamber Orchestra, the Sydney Symphony Orchestra, Victorian Opera Company Melbourne, the Canberra International Music Festival, the Sydney Festival and many regional community music groups including Symphony Central Coast (his long-term home group). Christopher is of mixed heritage, as a member of the Dharug (Eora) Aboriginal people of Sydney and the surrounding mountain and coastal regions. He runs the Ngarra-burria First Peoples Composers program in Australia, which mentors and connects Aboriginal and Torres Strait Islander composers with industry. The group has released two albums with the Australian Broadcast Corporation, and the program received an international Classical:NEXT Innovation Award in 2022. Christopher also loves playing guitar and writing for his surf music group Random Earth Band.

Gordon Southam is a Professor of Geomicrobiology, cross-appointed between the School of the Environment and the Sustainable Minerals Institute at the University of Queensland, Australia. His research on bacteria-mineral interactions crosses the traditional boundaries between biological and geological sciences to examine bacterial transformations of materials composing the earth's crust, and the impact of these transformations over geologic time. He has conducted field studies across the globe examining life in extreme environments, from hot springs in Yellowstone National Park, the Canadian high arctic and Antarctica, to ultradeep gold mines in South Africa, iron mines in the Amazon Rainforest, and deep-sea ocean environments. He was previously appointed as a Canada Research Chair in Geomicrobiology, and Director of the Environment and Sustainability program at Western University, Canada.

Augusta Read Thomas is one of the most critically-acclaimed and widely performed composers working in the US today. According to the American Academy of Arts and Letters, she 'has become one of the most recognizable and widely loved figures in American Music'. Thomas was the longest-serving Mead Composer-in-Residence with the Chicago Symphony, for Daniel Barenboim and Pierre Boulez, from 1997 through 2006. This residency culminated in the premiere of *Astral Canticle*, one of two finalists for the 2007 Pulitzer Prize in Music. She has won the Ernst von Siemens Music Prize, among many other coveted awards. Augusta is a member of the American Academy of Arts and Sciences, and of the American Academy of Arts and Letters. Recent and upcoming works include commissions from the New York Philharmonic, Boston Symphony, Utah Symphony, Philharmonic de Paris, the BBC Proms, Wigmore Hall, Martha Graham Dance Company and the Santa Fe Opera.

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John Wiltshire is an Emeritus Professor at the University of Hawaii, former chair of the Ocean and Resources Engineering Department and past Director of the National Undersea Research Center in Hawaii for the US National Oceanic and Atmospheric Administration. He is currently Editor of the journal *Marine Georesources and*

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Introduction

Philippe Tortell

On the corner of Front and Bay Streets in downtown Toronto, two large office towers soar up from the pavement, the taller one with its forty-one floors, reaching nearly two hundred meters into the sky. In a city with many large skyscrapers, what you notice most about these particular buildings is the windows; more than fourteen thousand of them, each tinted with bronze-gold glass set into aluminum frames. On a sunny day, the golden windows reflect a shimmering and slightly distorted image of the bustling city below. At the time the buildings opened in 1979, an ounce of gold sold for about four hundred dollars, and the total quantity of gold in all the windows, close to two thousand five hundred ounces, was worth about one million dollars. At today's price (about two thousand dollars per ounce), the windows contain about five million dollars' worth of gold.

As a boy growing up in a small town near Toronto, I was fascinated by those golden buildings. Coming into the big city from the suburbs, it was the first thing I'd see when I emerged from Union Station—two gleaming pillars towering over the iconic Royal York Hotel. In my young imagination, the buildings represented untold riches; like a pot of gold at the end of a rainbow. In some ways, I wasn't so far off from the truth. The Royal Bank Plaza, as the buildings are known, hosts the headquarters of Canada's largest financial institution. It sits in the heart of the country's financial capital, where

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large fortunes have been won (and lost) in an economy built historically on natural resources—fur and pelts initially, and then agriculture, timber, fish and minerals. One of the early corporate clients leasing space in the building was Denison Mines Incorporated, a major producer of the uranium used in nuclear reactors. In the late 1970s, amidst a global energy crisis, the price of uranium skyrocketed, reaching nearly two hundred dollars per pound. With its large uranium mine near Elliot Lake, Ontario, Denison's profits were booming, just as its hundreds of employees settled into their new offices in the golden towers. One of those employees was my father.

My dad started working as an accountant with Denison Mines in 1979, the year the company headquarters moved into the Royal Bank Plaza. His arrival coincided with what turned out to be the peak of global uranium prices. Shortly after he joined the company, the price of uranium began to drop sharply. During the 1980s, growing environmental concerns—particularly in the wake of the 1986 Chernobyl disaster—led to a public backlash against nuclear energy, causing global demand for uranium to decrease steadily for the next two decades. The year I finished high school, in 1989, a pound of uranium was selling for about twenty dollars—less than 10% of its peak value just a decade earlier. By the early 1990s, the writing was on the wall; the company downsized significantly, and many people, including my father, were forced to look for other jobs. As the uranium mines closed, leaving behind more than a hundred million metric tons of radioactive waste rock, it seemed that my family's connection to the mining industry was over. But things didn't quite turn out that way. Though I didn't know it at the time, my life would intersect with minerals and mining a few more times over the subsequent decades.

By the time I was in university, my father had found a new job with a company that operated a copper and zinc mine in a small Turkish town on the Black Sea coast. The town's name, Çayeli, comes from the Turkish word for tea (*çay*), which is grown in large quantities on its mountainside slopes. As part of its waste management plan, the company, Çayeli Bakır İşletmeleri, was exploring a method to dispose of mine tailings in low-oxygen deep waters of the Black Sea, where high concentrations of hydrogen sulfide would bind up zinc and copper, capturing them in unreactive minerals that would then sink to the seafloor. Such an approach, it was argued, was preferable to the storage of the mine waste on land, where the rocks would create acidic wastewater and release potentially high concentrations of metals into the environment. After my third year of university, on a visit to see my parents, I got a job in Çayeli, working alongside local scientists and a consulting team from Vancouver on an environmental impact assessment of the proposed waste disposal plan. In the end, I believe the plan went ahead, with somewhat mixed results. My role in the project was insignificant, but it connected me, once again, to the mining industry, and also in some small way to Vancouver—a city where I would settle less than a decade later.

Back in North America, I had decided to study oceanography, pursuing graduate school in the United States, and then, with great luck, landing a dream job as a professor at the University of British Columbia (UBC) in Vancouver. When I started that job, in 2002, I wasn't thinking much about mining. In the wake of the ill-fated Kyoto Protocol (a 1997 United Nations agreement to limit global greenhouse gas emissions),[11] the world was just beginning to reckon with the impending threat of global warming. Scientists around the world, including me, were more focused on understanding the impacts of rapidly increasing carbon dioxide (CO_2) concentrations on Earth's biophysical systems, than seeking actual solutions to the problem. Surely, we thought, the increasingly strident warnings from the Intergovernmental Panel on Climate Change (IPCC) would motivate global action to address the root causes of global warming. As it turns out, we were wrong.

Over the next two decades, the effects of climate change became ever more apparent, with rising global temperatures, increasing sea levels, melting glaciers and ice sheets, and more frequent extreme weather events. In the face of these mounting impacts, the world began, slowly, to move towards a broad (though not universal) consensus that we needed to mitigate the worst possible outcomes, shifting from fossil fuels to renewable, low-carbon energy and transportation. With the launch of the Tesla Roadster in 2008, electric vehicles became increasingly common (at least in Vancouver), while renewable energy began expanding more rapidly than fossil fuels for the first time in history. By 2015, the fraction of new electricity generated from renewable sources surpassed 50% globally,[2] suggesting that the world was finally taking steps towards an energy transition. Maybe we were moving too slowly, but we were, at least, heading in the right direction. With determination and political will, it seemed that we had a fighting chance.

But there was a catch—all of those new renewable energy sources required a fundamentally non-renewable resource; minerals and metals needed for batteries, circuit boards, wiring and other components of the digital, carbon-neutral economy. Suddenly, it seemed, everyone was talking about cobalt, lithium, copper and nickel, not to mention rare-earth elements (REEs) like scandium and yttrium that few people had ever heard of before. China, in particular, was quick to anticipate potential future shortages of what came to be known as 'critical minerals', buying up a large share of global mineral resources, and investing in mineral processing facilities. Not to be outdone, other countries including the US, the United Kingdom, Japan, Australia and Canada, began launching their own critical mineral strategies, seeking to secure reliable long-term supplies of minerals to support their future green economies.

As metals became increasingly important in a globalized economy, the world began paying more attention to the true costs of renewable energy, with a spotlight on the potential environmental and social harms of mineral exploration and mining. In Canada, a country rich in mineral resources, another reckoning was also unfolding, as the nation began to examine the dark legacy of its colonial past. In 2015, the Truth and Reconciliation Commission of Canada released its final report, detailing more than a century of abuse perpetuated against the country's Indigenous peoples through forced cultural assimilation in a brutal system of Indian Residential Schools.[3] It wasn't just Indigenous cultures and languages that had been taken; even before the federal Indian Act of the late nineteenth century, Indigenous peoples across the country were displaced from their traditional lands, as the Canadian government sought to expand its control over the vast natural resources within its borders. Today, more than one hundred and fifty years after Canadian Confederation, the impacts of colonialism continue to reverberate, and much of the nation's mineral wealth still lies on ancestral or unceded Indigenous lands.

It was in this context that my life, once again, intersected with the mineral resource industry. In 2019, I became Head of the University of British Columbia (UBC) Department of Earth, Ocean and Atmospheric Sciences, a group of about forty professors and many students and staff working to advance research and education across a wide range of Earth science disciplines. Early on, I came to appreciate the innovative work of my colleagues who were developing better approaches for mineral exploration and mining—from the discovery and characterization of new mineral deposits, to the design of lower impact mines and improved waste treatment methods. I also learned just how important Vancouver was to the global mining industry, as a worldwide hub for mineral exploration and geotechnical companies. But maybe the most important thing I learned was that the challenges of mining were not just scientific or technical in nature. Equally important were the legal, economic and political challenges—alongside the unresolved question of Indigenous rights and title, particularly in British Columbia, where the large majority of Indigenous lands were never ceded in treaties.

Beyond my own department, I began hearing about other mining-related research across UBC. The work was inspired and impressive, but much of it was running on parallel tracks, with relatively little cross-fertilization between academic silos. This seemed to me like a missed opportunity. And so, in 2022, as the world was beginning to emerge from the COVID-19 pandemic, I convened a group of experts from across UBC with deep knowledge of the global mineral resource sector. The group included some of my own colleagues in Earth sciences, but also others from mining engineering, law, economics, public policy and even the School of Music. It also included Indigenous leaders, and those in the mining industry with a practical working knowledge of the business. We called ourselves the Future Minerals Working Group,[4] and set out to understand what we might achieve together, combining our collective experiences and perspectives to re-imagine the future of the mineral resource sector in Canada and beyond.

With some funding from UBC, the Future Minerals Working Group began meeting regularly, over lunch, to hash out ideas. At first, the conversations were a bit forced, with each person presenting their views in language that often felt foreign to others. But eventually, we converged on some critical themes that seemed particularly timely and important. Those themes—from the recognition of Indigenous land rights, to the development of lower impact mineral exploration, extraction and recycling methods—painted a broad picture of an industry in transition. It was an important story, but one that few people understood beyond a small group of insiders. And it was a story we felt compelled to share, not only with other academics, and industry and government experts, but also with the broader public. Otherwise, how would we, as a society, make responsible decisions about the resources supporting our carbon-neutral economic future? And so, as a group, with help from others around the world, we set out to build a new vision for the global mineral resource and mining sector.

As academics, we gravitated naturally towards research and education. We held seminars and panel discussions, wrote proposals and created a new UBC graduate course called *Heavy Metal*. But we also wanted to go further, seeking impact outside the ivory tower. We wrote op-eds, met with government officials, and looked for ways to connect directly with the public, hoping to make complex ideas both accessible and engaging. The book you now have before you represents an important part of that effort.

In putting this volume together, we sought to bring forward a wide range of perspectives, illuminating both the challenges and opportunities facing the future mineral resource sector. The collection begins with an essay by Allen Edzerza and Dave Porter, both Indigenous Elders, recounting the story of Indigenous resistance and land rights in the face of colonial resource extraction. Melanie Mackay's essay complements these ideas, presenting a long-term perspective on mining practices among British Columbia First Nations. Werner Antweiler, Sara Ghebremusse and Carol

Liao each consider the social, economic and legal contexts of mining in an increasingly interconnected world characterized by growing geopolitical rivalries. Writing from the perspective of an exploration geologist, Shaun Barker addresses the question of how and why large mineral deposits form on Earth, while John C. Wiltshire, Sara Russell, Anita Dey Nuttall and Mark Nuttall describe the potential new frontiers of mineral resource extraction on the seafloor, in outer space and in frozen polar regions. Lee A. Groat tells the story of lithium, an essential element for batteries, which has come to symbolize the future energy transition. Gordon Southam, Erik Eberhardt, Marcello M. Veiga and J. Alejandro Delgado-Jimenez discuss new approaches that could be used to access mineral resources—taking some inspiration from ancient practices and organisms. Allison Macfarlane tackles the complex question of community engagement and informed consent, while W. Scott Dunbar and Jocelyn Fraser present a disruptive vision for new business models in the global mining sector. Both Roger Beckie and Maria Holuszko discuss the enormous problem of mining and metal waste, while Nadja Kunz takes on the complex issue of water use and management—often a key flashpoint in the interaction of mining operations with local communities. The final essay in the book, by Naomi Klein, presents an alternative vision that challenges an economic growth imperative based on endless resource extraction.

Interspersed with the essays described above, a number of contributors explore minerals and mining through an artistic lens. The collection includes a series of stunning images and written reflections from the Canadian photographer Edward Burtynsky, whose camera captures the transformation of landscapes through large-scale resource extraction. The theme of transformation is also explored sonically, through the work of eight composers who have created the *Heavy Metal Suite*, each contributing a movement inspired by a metal produced in their country—copper from Chile, lithium from Australia, and platinum from South Africa, for example. In a series of short reflections, the composers provide insights into their creative process, and we include a link to the live premiere of the *Heavy Metal Suite*, which took place at the Vogue Theater in Vancouver on Earth Day (22 April), 2024. These creative interventions—both the photographs and musical scores—allow us to see minerals and mining in a new light, and hear them with fresh ears, inviting us to imagine a different, and better, future.

I hope this collection, with its words, images and sounds, will help illuminate the complex challenges and opportunities ahead as we seek to supply the minerals needed for a sustainable future. To do this, we must better understand the role of metals and minerals in our daily lives, seeing more clearly the invisible resources that are buried underground or in the gadgets we carry in our pockets. The stakes could not be higher, and failure is not an option. And yet, I remain optimistic, even as we confront a rapidly changing climate and uncertainty about how and where we will find the minerals we need for a carbon-neutral economy. As I have engaged with these essays and authors over the past few months, I have learned that we already have many tools at our disposal, and also the collective capacity—if we choose to use it—to be innovative and creative, learning from past mistakes. Perhaps one day, in the not-so-distant future, we will see those golden buildings in Toronto not just as a cautionary tale of hubris, but also as a triumph of the human imagination.

Endnotes

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Colonialism and Mining

Allen Edzerza and Dave Porter

We write these words from the unceded territories of the Stó:lō People to reflect on the history of colonial appropriation of Indigenous resources on Indigenous lands. We write about the past, and also about the present and the future. In some ways, our words tell a long story. But, in others, they tell a short story—a small slice of time against the thousands of years that First Nations have lived on the land and used its resources.

The story of Indigenous land appropriation starts more than five hundred years ago, on 4 May 1493, when Pope Alexander VI (1431–1503) issued the Inter Caetera Papal Bull, forming the foundation of what is now known as the Doctrine of Discovery. The previous year, Christopher Columbus (1451–1506) had 'discovered' America, and the Pope's proclamation was issued to support Spanish and Portuguese claims of exclusive rights to the riches of the New World. The Bull stated that any land not inhabited by Christians was available to be 'discovered', claimed and exploited by Christian rulers, declaring that 'the Catholic faith and the Christian religion be exalted and be everywhere increased and spread'.[1] This 'Doctrine of Discovery' became the basis of all subsequent European claims in the Americas. It would only be officially repudiated by the Catholic Church in 2023, in a formal statement by Pope Francis acknowledging

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that the Doctrine of Discovery 'did not adequately reflect the equal dignity and rights of indigenous peoples'.[2]

As colonization of the New World expanded, European powers jockeyed for position, power and access to valuable resources. In North America, the conflict reached its peak during the Seven Years' War (1756–63), in which Britain and France led opposing alliances seeking to assert global dominance. The war ended with the Treaty of Paris (1763), which was followed that same year by the Royal Proclamation, in which King George III (1738–1820) officially claimed British territory in North America. Importantly, the Royal Proclamation established guiding principles for the European settlement of Indigenous lands in North America. A key element was the explicit recognition of Aboriginal land rights and title, and the stipulation that settlers could only claim land that had been first bought from Indigenous people by the Crown. The Royal Proclamation also asserted that all lands were to be considered Aboriginal unless explicitly ceded by treaty and set out a framework for a treaty-making process.

In 1867, a century after the Royal Proclamation, the British North America Act established the Dominion of Canada. The new consolidated territory was further enlarged in 1870, through Rupert's Land Order, issued by Queen Victoria (1819–1901), which brought in large swaths of land of what is known today as the Northwest Territories. The 1870 Order required the new government to address the 'aboriginee land question' before granting any access to land and resources, effectively beginning the Numbered Treaty process, which is still used today. Over the past one hundred and fifty years, eleven Numbered Treaties have been signed in Canada, but these are not equally distributed across the country. In British Columbia, for example, the majority of Indigenous land remains unsurrendered and unceded.

With the establishment of Canada, the new government began to assert increasing control over the lives of Indigenous people. In 1876, the newly established Indian Act mandated sweeping changes that segregated Indigenous people across the country, re-settling them into reserves, restricting their movements and outlawing their religious and cultural ceremonies. The laws were justified as a means of 'civilizing' Indigenous people under the colonial and Christian society of the new country. But they also gave the government significant control over unceded Indigenous lands and resources. This set up a pattern of systematic appropriation of Indigenous lands that would play out for more than a century, with devastating social and environmental impacts.

Over the past one hundred and fifty years, Canada has grown into one of the largest mining jurisdictions in the world, hosting more than 75% of global mining and mineral resource companies. On an annual basis, mining contributes around one hundred billion dollars to the Canadian economy, and this is expected to grow significantly, as demand for critical minerals increases over the coming decades. While the economic contributions of the mining sector in Canada are beyond doubt, these benefits have also come at a significant cost—particularly for Indigenous communities on whose land much of the country's mineral wealth is located. From the Pacific to the Arctic to the Atlantic, historical mining operations have left a tragic legacy of environmental disasters, such as the Faro Mine, Giant Yellowknife Mine, Tulsequah Chief Mine, and many gold-rush placer mining areas. These harms are not restricted to the pages of history—they continue into the present day. In 2014, the failure of a tailings pond dam led to the release of about eight million cubic meters of mine waste into Polley Lake, Hazeltine Creek and Quesnel Lake, with significant impacts on the health and livelihood of Soda Creek and Williams Lake Indian Bands.

In the face of ongoing mining impacts on Indigenous lands and people, there has been an awakening of the Canadian legal system (and perhaps of the broader society) around the historical legacy of colonialism in this country. The reckoning stems, in part, from the Truth and Reconciliation Commission of Canada, which shed a glaring light on the legacy of the country's Indian Residential School system.[3] In the legal context, a first landmark case regarding Indigenous rights and title was the 1973 Canadian Supreme Court *Calder* decision, named for the politician and Nisga'a chief, Frank Calder. Calder was the first status Indian to attend the University of British Columbia, and the first Indigenous member of the British Columbia legislature. In 1967, he launched a case with the Supreme Court of British Columbia, arguing that the

Nisga'a's land rights and title had 'never been lawfully extinguished', and challenging the provincial government's failure to recognize Aboriginal rights established under the 1763 Royal Proclamation. The initial case was dismissed at trial by both the provincial Supreme Court and Court of Appeal, eventually landing on the docket of the Supreme Court of Canada five years after it was first launched. On 31 January 1973, the court released its decision. Six of the seven judges supported the existence of Aboriginal title under Canadian law, but there was less consensus around the Nisga'a's specific claim; three of the judges argued that the Nisga'a's title had been invalidated by laws enacted before Canadian Confederation, while three others asserted that the land rights had not been surrendered. The remaining judge ruled against the Nisga'a on a technical point, tipping the balance against their legal challenge. Although the *Calder* case was not successful, it was, nonetheless, a watershed moment for the recognition of Indigenous rights and title in Canadian law. In time, the case would eventually lead to the signing of the 1999 Nisga'a Treaty, through which the Nisga'a achieved self-government and control over a large swath of their ancestral territory.

In the years since the *Calder* case, other legal challenges at the Supreme Court of Canada, including the 1997 *Delgamuukw* and 2004 *Haida* cases, have further clarified the existence of Aboriginal rights in Canada. In the *Haida* decision, the Supreme Court justices wrote: 'To unilaterally exploit a claimed resource during the process of proving and resolving the Aboriginal claim to that resource, may be to deprive the Aboriginal claimants of some or all of the benefits of that resource. That is not honourable'.[4] Many of these legal challenges have made specific reference to section 35 of the Canadian Constitution Act (1982), which recognizes and affirms existing Aboriginal and treaty rights, and imposes a duty to consult and accommodate First Nations when those rights may be impacted. The duty to consult and to obtain free, prior and informed consent (FPIC) is further articulated in the 2007 United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP), which has been used as a legal instrument to support the rights and interests of Indigenous people around the world. The Canadian government became a signatory to UNDRIP in September 2007, and subsequently passed Bill C-15, which commits Canada to aligning its laws with UNDRIP. In 2019, British Columbia became the first jurisdiction in Canada to align its own laws with UNDRIP, under the Declaration on the Rights of Indigenous Peoples Act (DRIPA).[5]

The new legal statutes are increasingly being applied in court rooms across Canada in support of Indigenous land rights. The 2014 *Tsilqhot'in* (*Chilcotin*) decision by the Supreme Court of Canada recognized Indigenous title to more than 1,700 square kilometers of land in British Columbia to the Tsilhqot'in Nation. In its ruling, the justices wrote that 'Government incursions not consented to by the title-holding group must be undertaken in accordance with the Crown's procedural duty to consult'.[6] In the 2021 Blueberry River case (*Yahey*), the British Columbia Supreme court ruled that the Province had infringed on the rights of the Blueberry River First Nation through inappropriate mitigation of industrial impacts on Blueberry River's traditional territory. And, most recently, in September of 2023, the same court ruled that British Columbia's Mineral Tenure Act, a gold-rush era 'free-entry' mineral claim regime,[7] breached the government's duty to consult with the Gitxaała and Ehattesaht First Nations whose treaty rights were potentially impacted by mineral exploration activities. While this decision was seen as a victory for Indigenous rights, many are concerned about a potential staking frenzy over the eighteen-month interim period as the Province works to overhaul the Mineral Tenure Act in consultation with First Nations. The delay could be longer if the Province decides to appeal the decision, leading to significant uncertainty in the future of mineral prospecting in British Columbia.

Throughout all these years and legal cases, the courts have repeatedly affirmed the message delivered in the 2004 *Haida* case: 'Canada's Aboriginal peoples were here when Europeans came and were never conquered'. The list of precedents is long and growing: *Morris and Olsen*, *Gitanyow*, *Marshall*, *Klahoose*, *Gray and Sappier*, *Jules and Wilson*, *Sparrow*, *Guerin* and *Gladstone*. These precedents create a new legal context for the Canadian mining sector.

Beyond the legal arguments for Indigenous land sovereignty, there is a strong economic and financial incentive to recognize Indigenous rights and title. As new mining projects come forward, proponents will be making the decision to invest tens of millions, hundreds of millions or even billions of dollars. Such decisions are difficult in the face of significant uncertainty around mineral claims, access to land and permits.

Achieving certainty requires addressing unsurrendered Indigenous rights and title, and aligning legal frameworks to constitutionally mandated statutes. In this context, Indigenous people must play an active role. They must begin to re-establish their Sovereignty and build the capacity to share the decision-making and management of resource development in their territories. In other words, they must govern their lands and resources, in a Nation-to-Nation partnership with the provincial and federal governments. Such a partnership, based on the recognition of Aboriginal rights and title, will give First Nations joint decision-making powers regarding resource development activities, and allow them to act as regulators or co-regulators for resource activities. First Nations must also be able to collect rents and taxes for resource development on their territories and be informed proponents of any new projects. Such a shared governance model will support free, prior and informed consent, as mandated under UNDRIP. It will also provide the best assurance of certainty for First Nations, mining companies and governments in the development of any new resource projects. To help guide this process, the British Columbia First Nations Energy and Mining Council has issued a series of recommendations on how First Nations can work with the Province to achieve greater certainty in the future mining sector.[8]

The mining industry in Canada now sits at a critical juncture. We must hurry up, but we must also slow down. Scientists and environmental organizations have been sounding the alarm about the impact of continued carbon emissions on Planet Earth. We have all watched news stories about severe weather storms, hellish forest fires, scorching summer temperatures and vanishing streams and lakes. We have witnessed the crash of salmon populations, and the displacement of wildlife due to food and habitat scarcity, starving bears and caribou herds nearing extinction. Indigenous traditional knowledge recognizes the interconnectedness of all creatures and provides a long-term, intergenerational understanding of our rapidly changing Earth. The warnings are now finally beginning to be heard by political leaders around the globe, as they struggle to develop a framework to address global warming by 2050. There is no doubt that critical minerals—copper, lithium, cobalt and others—are central to this effort, as we ween ourselves off fossil fuels and transition to renewable energy.

Canada and the United States are concerned that most critical metals are currently being mined in foreign countries, and the two governments have recently entered into a memorandum of understanding to significantly increase North American production of these metals. This is viewed by many as a 'new gold rush', but this new era of mineral exploration cannot look like the last one. In the new era before us, First Nations must take a leadership role in mineral exploration and mining to protect their lands and maximize their benefits from resource development on their territory. This is the only way to ensure environmentally and socially responsible mining practices.

The path forward requires new kinds of partnerships, built on the sharing of expertise and knowledge. Indigenous people hold a wealth of knowledge about the Earth and its natural resources, developed over thousands of years and countless generations. At the same time, Western science has developed powerful new tools to understand the geological processes leading to the formation of mineral deposits. To fully embrace a leadership role in the future minerals and mining sectors, more Indigenous people need advanced education, not just in Earth sciences and mining, but also in law, politics, economics and public policy. Quite literally, we must engage with the resource sector from the ground up, from mining sites to boardrooms. Working with universities, we must redefine new educational approaches, bringing advanced education to our remote northern communities, with an on-the-ground component that includes our Elders and their traditional knowledge. Such an approach will build Indigenous leadership capacity, while also shifting the perspectives of non-Indigenous people working in government and in the mining industry.

Together, we can (and must) transform the global mining industry, through new technologies and methods, but also through a fundamental culture shift towards collaboration and mutual respect between Indigenous and non-Indigenous people.

As we seek to address the existential threat of climate change, we must consider what we will leave behind for future generations. Yes, we must supply critical minerals for renewable energy, but we must also protect our lands, waters, air and wildlife. It is a sacred responsibility that the Creator has placed upon us. The Elders tell us that the Creator is speaking to us. We must stop and listen.

Endnotes

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The Future Demand and Supply of Critical Minerals

Werner Antweiler

Climate change has become a defining challenge of the twenty-first century. Tackling this challenge will require copious amounts of metals and minerals needed for renewable energy and low-emission transportation systems, including wind turbines, solar panels and electric vehicle batteries. At present, it remains unclear exactly how future mineral demand will grow, and whether these raw materials can be supplied in a socially and environmentally responsible manner. Addressing these questions is key to charting a path to future sustainability.

To begin, two important questions need to be answered. Which minerals are deemed critical, and which properties make them so? There are three specific characteristics that make a mineral critical for any country. They must be *necessary* for transitioning to a low-carbon economy and mitigating climate change; *essential* to the economic security of a country and its allies, with few or no substitutes; and *vulnerable* to supply chain disruptions or nation-state interference because of their concentration in specific locations of extraction and/or processing. The list of critical minerals evolves over time as their use changes, expands or declines. Currently, the most widely recognized critical minerals include lithium, nickel, cobalt, graphite and

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rare-earth elements (REEs). This list is not comprehensive and varies by country. Canada's list includes over thirty different elements.

Many of the economic and political risks associated with critical metals result from the concentration of metal deposits and refining activities in a small number of locations.[1] Further complexity in mineral supply chains results from the separation of raw material extraction and downstream processing. This uneven distribution gives significant market power to the limited number of private or state-owned companies that control a large fraction of mineral reserves and metal refineries. Take cobalt, for example. In 2022, the world's largest producing country was the Democratic Republic of Congo (DRC), which accounted for 68% of world supply.[2] By comparison, the next three largest producers, Indonesia, Russia and Australia, accounted for only 5.3%, 4.7% and 3.1%, respectively. The DRC's cobalt deposits are not only the world's largest, but they also have higher ore concentrations than other locations. The situation is even more lopsided for the refining of cobalt. China's output of refined cobalt in 2022 was almost eight times that of the second-largest producer, Finland. Chinese mining companies also hold controlling stakes in the DRC's largest cobalt mines.

Some metals have a more diversified supply base. Of the twenty-two million metric tons of copper produced in 2022, the largest producer country (Chile) accounted for about 28%, and the second-largest producer country (Peru) about 12%. Lithium is produced either from concentrate (derived from hard-rock spodumene) or from precipitating brines. Australia and China respectively produce about 47% and 15% of global lithium from concentrates, while Chile produces about 30% from brines. REEs are a group of seventeen metals that includes neodymium, dysprosium, praseodymium and terbium, which are widely used in the motors of clean-tech applications. By 2010, China had cornered the entire REE market, with 95% of global production capacity. Other countries, notably the United States, responded by increasing their own REE production. Within a decade, China's market share had decreased to about 60%. New discoveries of REEs in other locations (Sweden, Turkey, India) may further reduce China's dominance of REE supplies.

Although the production of some metals may be distributed globally, the processing of mined materials into final products is more concentrated in certain countries, most notably China. This country alone accounts for about half of global copper smelting and refining, and more than half of global lithium processing. The processing of REEs currently also remains concentrated almost exclusively in China. The spatial separation of extraction and processing follows economic considerations, but in China's case it is also a result of an industrial policy that has championed the development of this industry. Whatever the motives for this policy—domestic economic growth or foreign policy ambitions—the resulting concentration of market power could adversely affect markets, and also become subject to political interference and gamesmanship. Amidst rising geopolitical tensions, China's dominance of metal processing has led to a closer examination of supply chain resilience.[3]

Economic dependencies can be reduced by diversifying and controlling potential supply chain risks. Many countries, including Canada, are developing critical mineral strategies that address these concerns. This has become as much a political as an economic goal, but it comes at a significant cost. Considerable investments would be required in Europe and North America to build resilient supply chains for critical minerals that would lessen import dependence. Some Western countries are also making it more difficult for foreign investors to acquire mining operations, with particular restrictions on foreign state-owned enterprises.

Global markets for commodities are defined by supply, demand, prices, investments and various external factors. The supply of mineral resources follows exploration and mine construction, which are influenced by current and expected future market prices. Additional financial risk comes from the fact that exploration activities may or may not bear fruit, and from the high capital costs of developing major mining projects. As with the fossil fuel industry, the mining sector has undergone repeated boom-bust cycles, where high prices trigger new investment, eventually followed by overproduction and falling prices. Despite these fluctuations, metal and mineral prices have remained remarkably steady (in inflation-adjusted terms) over the past century, as exploration has not yet reached the limits of physical scarcity. This long-term stability does not eliminate periodic and short-term price spikes. As an example, nickel prices, which have hovered between 10,000–20,000 US dollars per metric ton in recent decades, jumped to over 48,000 dollars per metric ton for a brief period in March 2022, following the invasion of Ukraine by Russia, the world's third-largest nickel producer.

Over the past century, mineral demand has evolved gradually, driven by patterns of economic growth and development. In contrast, more rapid growth in demand is expected over the coming decades as we transition to renewable energy systems. The International Energy Agency (IEA) has estimated that mineral requirements will quadruple by 2040 if we are to reach the 2015 Paris Agreement targets limiting global temperature rise to 2°C. According to the IEA, the target of net-zero emissions (NZE) by 2050 would increase global mineral demand six-fold.[4] Even larger increases are projected for specific minerals that are essential for the clean energy transition; global output of lithium, graphite, cobalt, nickel and REEs could increase between ten- and forty-fold. These projections are based on currently dominant technologies and do not consider future technological innovations that could change demand for critical minerals.

Most of the projected mineral demand will come from batteries for electric vehicles and utility-scale electricity storage, as well as expansion of renewable electricity networks and transmission infrastructure. Wind and solar power require much larger amounts of minerals than conventional thermal power plants per megawatt (MW) of electricity. Solar power mostly requires copper and silicon. Wind turbines require zinc for the external structures, copper for connecting to the power grid (more so for offshore turbines) and a mix of REEs, manganese, nickel, chromium and molybdenum for electric generators and other components. Onshore and offshore wind turbines require between ten and fifteen metric tons of minerals per MW, with additional copper requirements for transmission grids. Massive expansion of renewable energy also depends on the development of electricity storage to address the intermittent nature of these supplies (the sun doesn't always shine, and the wind doesn't always blow). Among the competing technologies, lithium-ion batteries have taken an early lead, despite their high cost. These large mineral requirements pose a challenge for the expansion of renewable energy. As demand for these minerals increases, supply shortages could drive up prices and increase the cost of the clean energy transition.

Beyond the expansion of renewable energy, the transition to electrified transportation systems will require the replacement of millions of internal combustion engine vehicles (ICEVs) with battery electric vehicles (EVs). A typical EV, with a seventy-five-kilowatt-hour (kWh) battery, requires about five times as many metals and minerals as an ICEV. By weight, most of this extra demand will involve graphite, lithium, nickel, copper and cobalt, as well as some REEs, which are mostly used for motor components. Today, there are an estimated 1.5 billion motor vehicles in the world, with 20% of these in the United States alone. If each new EV requires about one hundred and sixty kilograms of metals and minerals, replacing only one-tenth of the world's vehicle fleet would require an additional metal demand of twenty-four million metric tons. For comparison, current metal demands in the global economy require worldwide production of cobalt, copper, graphite, nickel and lithium ranging from about one hundred thousand metric tons (lithium) to about twenty-five million metric tons (copper).

New technologies could partially offset the high expected mineral demand associated with EVs. Current EVs use lithium-ion batteries with a fluid electrolyte. New types of batteries are now emerging with lower mineral requirements, including lower-cost lithium-iron-phosphate (LFP) batteries, which do not contain nickel, cobalt or manganese. Other new technologies are expected to improve energy density while reducing dependence on various minerals. As a recent example, the US-based company Sparkz opened the first cobalt-free battery factory in Livermore, California in 2022. High prices for REEs could induce similar substitution effects, as motors containing permanent magnets (with high REE requirements) can be replaced by asynchronous induction motors, which use copper and aluminum instead of REEs. Similar technological innovation could also provide alternatives for electricity storage, including vanadium flow batteries and hydrogen electrolysis. Recently, sodium-ion and iron-air batteries have begun emerging as potentially lower cost and less critical alternatives to lithium-ion batteries. These batteries may be particularly suitable for stationary applications where energy density is less important than in mobile applications. The path of innovation will be influenced by the relative cost of material alternatives, and this will introduce uncertainty about the future demand for minerals.[5]

Can the global supply of minerals be scaled up to meet anticipated demand? And can this be done both rapidly and responsibly? The answer to these questions requires an understanding of global mineral reserves, industrial capacity and social and environmental impacts.

Global reserves of minerals are vast; according to the US Geological Survey, there are an estimated 22 million metric tons of lithium, 7.6 million metric tons of cobalt, 1.5 billion metric tons of manganese, 95 million metric tons of nickel, and 320 million metric tons of graphite distributed in countries around the world.[6] And future exploration will reveal new deposits as demand grows. For many metals, except copper,[7] physical scarcity appears unlikely over the short to medium term. A larger constraint on future mineral supplies will result from the need to rapidly scale up new industrial capacity for metal refining and processing. This enhanced capacity will follow demand and prices, although the need for various inputs, including energy and water, may shift competitive advantages among different countries.

For those new mining projects that go forward, the pace of development will not be fast, particularly for large mines. It often takes between ten and fifteen years or more of consultation, planning, permitting, financing and construction to build and begin operating a large mine. Governments should not allow shortcuts through this process, nor should they weaken social or environmental standards for the purpose of expediting projects. Although the development of small-scale mining operations could happen on much shorter timelines,[8] these operations will only be able to supply a fraction of anticipated future metal demands. Scaling up future mineral *extraction* will take more time than is envisioned in Canada's critical mineral strategy; the timeline for scaling up mineral *processing* and downstream manufacturing appears more achievable.

If mining activities cannot scale up rapidly, demand will exceed supply and prices will rise. Higher prices could slow down the energy transition, but they will also spur innovation in alternative technologies or applications that require fewer minerals. The upside of high prices is a greater incentive for recycling, and for the development of more mineral-efficient technologies. Higher prices will not necessarily upend the clean energy transition, but may instead channel the transition into more sustainable directions.

The rapid expansion of mining activities will inevitably lead to increased social and environmental impacts. Such impacts, rather than resource availability *per se*, may be a primary constraint on the future development of the minerals industry, as local communities reject proposed developments. It will become critical to ask how the sector can be transformed to minimize any negative effects.

Among the environmental threats posed by mining, the impacts on water systems are among the most significant.[9] Indeed, water is one of the defining environmental challenges for future minerals growth. Consider the example of Chile, which has the world's largest reserves of copper and lithium, most of which are concentrated in the arid regions of the Atacama Desert in the north of the country. Approximately two million liters of water is needed to produce one metric ton of lithium, which is evaporated from large salt ponds. For copper, 90,000 liters of water are needed for each metric ton produced. Large-scale water use by mining operators can add to local water stress, competing with drinking water needs and agricultural irrigation.

Processing the ore produced at mining operations also generates copious amounts of waste in the form of tailings, a slurry composed of wastewater and solid particles that is fed into an impoundment or enclosure made of earth dams.[10] The dams must be constantly maintained during the life of the mine and beyond. In rare cases, catastrophic failure of these dams can result from poor design or maintenance. The breach of a tailings pond at the Mount Polley Mine in British Columbia in August 2014 spilled an estimated twenty-five million cubic meters of water and tailings into nearby lakes and creeks, impacting local drinking water and salmon spawning grounds. The breach of Vale's Brumadinho tailings pond in Brazil in January 2019 inundated a local community and caused 270 fatalities. Senior Vale staff were indicted on murder charges, and the company was ordered to pay a seven-billion-dollar settlement.

Amidst growing water scarcity, water resources need to be better managed even in the face of higher costs. Instead of treating wastewater in tailings ponds, slurries can be filtered, thickened and dried, and the residual dry tailings can be stored more safely.[11] Dehydrating slurry requires energy, which adds cost, but this method can also save money in the long term by reducing insurance rates and remedial costs during mine closure. Water recovered from wastewater treatment can be reused, decreasing the demand for freshwater, and freshwater can sometimes be replaced with saltwater, or saltwater treated by desalination. The technical possibilities are vast, but the associated higher costs need to be internalized by markets. In recent years, water scarcity has already prompted the development and application of various water-saving technologies. This trend is expected to continue and accelerate.

Ultimately, environmental sustainability will depend on the ability to recycle minerals rather than continuously extracting new sources from the ground.[12] Kickstarting the recycling industry for future minerals is therefore an essential ingredient of the critical mineral strategies of all governments. In the long term, a large share of minerals will have to come from recycled sources. Hydrometallurgical processing of lithium-ion batteries (leaching with acids and metal separation using solvents) and pyrometallurgical alternatives (pre-treatment and reductive smelting) are already well developed. Direct recycling (disassembly, lithium enrichment and heat treatment) could eventually improve recovery rates and lower costs. These technologies are evolving rapidly.

The need for greater environmental stewardship must go hand in hand with the protection of individual and community well-being in mining-impacted regions. History is full of cautionary tales where resource extraction projects have jeopardized or destroyed traditional economic and social foundations of local and Indigenous communities.[13] Indigenous communities around the world—whose ancestral (and often unceded) lands are subject to significant mining activities—have too often been left out of decision-making, and deprived of ownership rights through colonialism or misdirected governmental paternalism.[14] With the development of the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP), there is now a globally recognized mandate for free, prior and informed consent (FPIC) in the development of any new mining project. Increasingly, UNDRIP is being incorporated into the legal framework of countries around the world, who are enacting national and regional laws implementing its principles into resource development projects. The explicit consent agreements mandated by such laws will be a cornerstone of the future minerals industry. Such agreements promote collaboration, define due process for environmental assessments and provide certainty for investors.[15] Relationships between mining companies and local communities can also be strengthened by joint infrastructure projects (for example, water treatment), benefit sharing agreements and co-ownership. Through such partnerships, mining projects can create pathways for Indigenous-led mining operations, with long-term economic benefits to communities.

One can imagine a number of different pathways for the supply of critical minerals to meet growing global needs. Scaling up mining around the world will certainly bring significant new challenges, including geopolitical risks, environmental hazards and growing social impacts. Meeting these challenges will require new approaches based on cross-sector and international collaboration.

New industry standards are beginning to evolve out of best practices adopted by some mining companies. The International Council on Mining and Metals (ICMM) fosters collaboration among mining companies and global organizations (including the United Nations) in the development of industry standards. As an example, the Global Industry Standard on Tailings Management was developed in the wake of the catastrophic tailings pond breach in Brumadinho, Brazil. This standard aims for 'zero harm to people and the environment' across all phases of project development, and requires mine operators to implement specific measures to prevent catastrophic failure of tailings facilities.[16] The Initiative for Responsible Mining Assurance (IRMA) offers independent, third-party assessment and certification of industrial-scale mines, holding them accountable to international standards for the design, operation and management of tailings facilities.[17]

Greater transparency of the global mining industry is needed to allow buyers and investors to make informed decisions that include a careful assessment of potential environmental and social impacts. For example, the Global Investor Commission on Mining 2030 is an investor-led initiative that is trying to develop a consensus about principles for socially and environmentally responsible investment in the mining sector.

Due diligence takes time and effort, and some have argued that this would result in unacceptable delays in the development of future mining projects. This inherent tension is difficult to resolve, but decarbonizing our economies cannot come at the cost of creating other large-scale environmental problems, or infringing on the rights of Indigenous communities on whose land mining often takes place. The key to meeting sustainable development goals in mining will lie in certification: a global standard for determining adherence to sustainable mining practices throughout the entire supply chain. To avoid a 'race to the bottom', where standards are lowered to gain more access to minerals, the global standards must be kept high, especially as mining activities increase globally. The ICMM and IRMA standards are important steps in the right direction for better governance and management of facilities.

There is no free lunch for a more sustainable future. Higher standards for mineral extraction and processing will entail higher costs, and thus higher prices. Markets will react to these through innovation and the development of lower-cost substitutes. Future generations of low-carbon technologies may utilize fewer minerals and metals than current products, but governments will also need to regulate mining activities, incentivizing innovation, and penalizing any negative impacts.

The second step is boosting recycling, which could solve several problems. Once produced, minerals would remain in circulation, lessening the demand for primary extraction. Domestic recycling would also lessen import dependence, providing greater economic security and decreasing geopolitical risks. Most importantly, recycled metals and minerals would significantly reduce the environmental footprint of global mining activities, replacing them instead with recycling plants supplied by renewable energy.

It is also important to ask how we might find ways to significantly reduce global demand for critical minerals. If each internal combustion engine vehicle is replaced by an EV, the demand for minerals will skyrocket because every new EV that rolls off the sales lot contains large quantities of critical metals. Subsidizing EV ownership, as many governments are keenly doing, assumes that the only feasible replacement for conventional cars is a one-to-one swap for EVs. Better public transportation options and improved infrastructure for micro-mobility (including e-bikes and e-scooters) may lessen the demand for individual vehicle ownership. Ubiquitous EV charging infrastructure may reduce the need for large battery packs in EVs. Stationary battery systems used in electricity storage applications, where weight and size are less important than cost, may rely on metals and minerals that are more abundant and less critical.

Governments have a significant role to play in all of this. First, boosting research and development for cleaner mining technologies will lower the environmental footprint through innovation. Second, developing and supporting recycling infrastructure will lessen resource dependence. Third, transparency and recycling mandates can build a system of closed-loop responsible use. And fourth, consultation and accommodation of local and Indigenous communities affected by mining activities can mitigate and avoid social harm, while fostering local economic development and land sovereignty. Because of the global nature of mining and related international trade, governments also need to collaborate to develop global standards and protocols that will support transparency while reducing social and environmental impacts. With determination and creativity, we can create a sustainable path forward.

Endnotes

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

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7 See also ‘The Copper Supply Gap: Mining Bigger and Deeper’ by Erik Eberhardt in this volume.

8 See also ‘Can Small Mining be Beautiful?’ by Marcello M. Veiga and J. Alejandro Delgado-Jimenez in this volume.

9 See also ‘Metal and Water’ by Nadja Kunz in this volume.

10 See also ‘Mine Waste’ by Roger Beckie in this volume.

11 Ibid.

12 See also ‘A New life for Old Metals’ by Maria Holuszko in this volume.

13 See also ‘*Black Panther* and an Afrofuturist Vision of Mining’ by Sara Ghebremusse in this volume.

14 See also ‘Colonialism and Mining’ by Allan Edzerza and Dave Porter in this volume.

15 The British Columbia legislature turned UNDRIP into local law through the adoption of the Declaration on the Rights of Indigenous Peoples Act (DRIPA) in November 2019 (full text available at https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/19044). Yet, implementing DRIPA requires alignment with other statues. British Columbia’s Mineral Tenure Act dates from the 1850s and has not been updated to reflect Indigenous rights (full text available at https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/00_96292_01).

In its current form, the Mineral Tenure Act permits mineral claims to be staked on lands of Indigenous communities without their knowledge and consent.

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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.

Ocean Minerals

John C. Wiltshire

In Jules Verne's 1870 novel *20,000 Leagues Under the Sea*, the ocean explorer, Captain Nemo, describes vast treasures in deep-sea mines of zinc, iron, silver and gold. At the time, Verne could only imagine what lay beneath the great ocean depths. That began to change, however, just two years later, when the HMS *Challenger* set sail from England on a nearly three-year scientific expedition to map the global oceans. The ship's crew brought back thousands of samples, describing many new species and providing the first glimpses of the ocean floor. The expedition report described golf-ball sized sedimentary 'nodules', rich in manganese oxides and other associated metals. This was the first tangible evidence of significant metal deposits in the ocean. Yet, it remained unclear what quantity of minerals might be supplied from the deep sea, or how they might be extracted in a commercially viable manner.

About half a century later, as Germany struggled to pay its massive World War I reparations, the chemist Fritz Haber devised a plan to concentrate gold from seawater. Haber, who had recently won the Nobel Prize in Chemistry for his method of ammonium production, believed that large quantities of gold could be extracted from ocean waters using electrochemical methods. He was not the first to suggest this possibility. In the late 1880s, two men from Edgartown, Massachusetts, Prescott Jernegan and Charles Fisher, published a pamphlet, entitled *Gold from Sea Water at a Profit: The Facts*, in which

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they described a revolutionary new method to extract ocean gold using a copper plate and a thin layer of mercury. After duping more than a few investors, the two men were exposed as frauds, and the idea of ocean gold mining faded from public attention until Haber took up the cause. Based on Haber's recommendation, the Germans undertook a survey of seawater gold concentrations on the 1925 ocean *Meteor* expedition. Initial results seemed to support Haber's assertion, but he eventually discovered an error in his calculations, realizing that he had overestimated seawater gold concentrations by a factor of one thousand.

Modern interest in deep-sea mining was re-ignited a century after the first discovery of manganese nodules during the *Challenger* expedition. By the mid-1970s, undersea exploration technology and marine chemistry had advanced sufficiently to allow accurate determination of potential deep-ocean metal sources. In 1974, ocean floor manganese nodules were first test mined in the Pacific Ocean, while deep-sea hydrothermal vents—metal-rich geothermal fluids rising to the seafloor—were discovered in 1977. Back then, deep-sea mining was largely undertaken as a proof of concept, driven more by scientific curiosity than economic imperatives. At the time, atmospheric carbon dioxide (CO_2) was 25% lower than present-day levels, the world's population was about half the current value, and global warming was not embedded in the public consciousness. And in the pre-digital age, humanity's requirement for mineral resources was significantly smaller than it is today.

Fast forward about fifty years, and things look rather different. As the world now has over eight billion citizens who hope to be wealthier and live longer than their predecessors, it is anticipated that we will require large quantities of minerals to supply our renewable energy needs if the worst impacts of climate change are to be mitigated. Is it now time to rip a page from our past and reconsider exploiting the ocean's potentially vast mineral wealth?

The question of when and how ocean mining might be developed is both a scientific and philosophical one. With current technology, it may now be possible to mine almost every major deep-sea mineral deposit.[1] And while the environmental cost and legal regimes are currently hotly debated, this has not stopped the expansion of potential ocean mining activities in recent years. Indeed, the United Nations International Seabed Authority (ISA),[2] which regulates mining in international waters, has already issued more than twenty ocean mining licenses, and approved mining exploration over more than one million square kilometers, an area twice the size of Texas. In the face of this rapid expansion, there are fundamental questions remaining to be answered.

While there are many types of marine mineral deposits, including specialty sands, phosphates, diamonds, gravel, shells, hydrates and silts, three types of deposits have been the primary focus for ocean mining activities: manganese nodules, polymetallic sulfides (black smokers) and manganese crusts. The nodules are found on the deep seafloor in depths ranging from about four to six kilometers below the surface, while the crusts are somewhat shallower, located on the top and sides of seamounts. The sulfides are found on hydrothermal ridges at tectonic plate boundaries and other geologically active seafloor spreading areas, such as the mid-Atlantic ridges first identified during the *Challenger* expedition.

The idea of sustainable ocean mining is a controversial one. On a global scale, the ocean is generating minerals at a greater rate than we would most likely mine them. But this is a moot point, as any realistic mining operation would be concentrated in a relatively small region, where the rate of removal would vastly exceed the rate of generation. In the case of manganese nodules, for example, the mineral deposits grow through a continual process of hydrothermal input and precipitation on the seafloor. These are slow processes, with nodule growth rates of only a few millimeters per million years. A golf ball-size nodule lying on the seafloor and containing rare-earth metals could be tens of millions of years old. In practice, ocean minerals should be considered as a non-renewable resource.

From a purely economic perspective, the mining of ocean manganese nodules offers the best hope for development in the next decade.[3] This mining is essentially a gathering operation, not unlike picking fruit. The nodules simply sit on the seabed waiting to be harvested; there is no tunneling, blasting or digging—simply collecting. A machine, not unlike a golf ball collector at a country club, picks up nodules from the bottom and conveys them to a lift system for transport to the surface. To a first approximation, the technology seems mundane. The technical complication comes from the fact that the nodules can be found in water depths exceeding six kilometers, and the lifting of mined ocean minerals to the surface is not a trivial endeavor. The lift can occur through buckets, or using pipes that operate like a home vacuum cleaner, using water rather than air to generate the necessary suction. Alternatively, the nodules can be mixed with seawater to create a slurry, which is pushed to the surface with high-pressure mining pumps, analogous to those used in many land-based mining operations. The amount of material in question is enormous. A single mining vessel would release between 2–3.5 million cubic feet of effluent from the slurry every day, a volume equivalent to about three thousand twenty-foot shipping containers. This process could run continuously for thirty years at one mining location.

Despite the obvious challenges of mining manganese nodules, they have the advantage of being relatively widespread across the seabed, covering about 15% of the ocean floor (approximately 10% of the planet's surface). This means that ecologically sensitive nodule areas could be set aside, and that nodule mining operations could be widely spaced from each other, in contrast to terrestrial mining activities, which must be highly concentrated in the specific area of an ore deposit.[4] By comparison with manganese nodules, the two other main ocean deposits, polymetallic sulfides and manganese crusts, are much more restricted geographically, and they must be excavated from the ocean sediment, making their extraction significantly more expensive and complex. As a result, it is likely that ocean-mining activities will focus on manganese nodules for the foreseeable future.

Although technologically feasible, there remain major problems in opening up the deep sea for mining. Historically, the deep ocean was considered remote and largely devoid of life. It was also believed to have an inexhaustible capacity to absorb human pollution. We now know, however, that deep-water ecosystems are complex, diverse and fragile. Beyond their huge potential mineral wealth, these ecosystems may also hold highly valuable biological resources. For example, scientists have discovered thousand-year-old deep-sea corals, and microbes that can treat cancer and infectious diseases, and convert sulfur and methane into energy. These organisms offer a rare glimpse into the origins of life on earth and could provide biologically inspired solutions to a range of critical problems facing humanity.[5]

There are several significant ecological impacts associated with deep ocean mining. First, and perhaps most obviously, the heavy machinery used to collect manganese nodules moves across the seabed like a steam roller destroying all non-motile organisms in its path. There are also significant indirect effects, as the sediment is churned up into a fine-grained plume, blanketing bottom-dwelling organisms within a few hundred meters of the collector. Experiments revisiting test ocean-mining sites have shown only marginal ecological recovery after thirty years, indicating that the impacts on the ocean floor are profound and long-lasting.[6]

The ocean water column above the sediments is also subject to significant mining-related disturbances. On average, the ocean depth is around four thousand meters, more than twice as deep as the deepest point of the Grand Canyon. This vast expanse includes more than 90% of the planet's life-sustaining habitats, and is home to an immense array of creatures, from microbes and worms to jellies and giant squid. When a nodule is vacuumed from the seafloor and pumped to a surface ship, the minerals are separated from a so-called 'dewatering plume', a muddy, metal-enriched fluid that is pumped back into the sea. Heavier particles in this plume sink to the seafloor, passing through thousands of meters of intervening water before settling. An unknown amount of material including heavy metals is dissolved in this plume, and this material will be carried indefinitely by ocean currents. Finer materials within the plume can drift for months, carried over great distances by the ocean currents. This drifting material could have a severe impact on open-water ecosystems thousands of kilometers away from the site of the mining operations.

Deep-sea organisms have adaptations that make them especially susceptible to mining impacts. Many of these organisms feed on a meager diet of small particles that sink down from the surface, and they are extremely sensitive to excessive particle loads, which can clog their feeding systems. In addition, more than half of deep-sea animals generate their own light through bioluminescence to find mates and prey and as camouflage to avoid predators. This system requires clear water to be effective. The challenge of navigating through plume-clouded waters, along with additional gill clogging and feeding disruptions would compound other ongoing stresses experienced by deep-sea organisms, including ocean acidification and deoxygenation. It is reasonable to believe that further disturbance associated with mining activities could push some deep-sea organisms over the edge to extinction. Cumulative ecological effects may be much larger than any site or time-specific problem. What is most worrisome is that the deep-sea environment is so poorly known, we have few baselines against which to compare potential future changes.

Beyond the potentially significant ecological impacts of deep-ocean mining, there are also social and geopolitical realities to contend with. The companies and governing agencies that stand to profit most from mining activities are based in the United States, Canada, Australia, Europe and Asia. In most cases, they are geographically, politically and economically removed from the small island nations that will bear the greatest environmental impact of mining. The governments of these small island states may welcome mining for economic gain as a partial replacement for lost tourist revenue. But if history is repeated, it will be Indigenous peoples and local communities on these islands who may first bear any problems coming from this new industry, with few long-term benefits.

The question appears to be not whether there will be deep-ocean mining, but how this activity should be regulated. In this respect, the ISA is releasing seafloor mining regulations, and seabed developers are waiting for these regulations before mining permits can be issued. Over the last ten years, numerous working groups have had input into the development of a deep-sea mining regulatory system, and there has been progress toward consensus. But the final regulations, initially supposed to be released in July 2023, have just been delayed until 2025. This delay is partly attributable to a desire to protect land-based mining, particularly in developing countries, and by calls for greater deep-sea research to support better environmental protection standards. It is unclear how soon mining on the international seabed might start after regulations are finalized.

The regulatory vacuum surrounding international seabed mining has created an opening for two countries, Norway, and the Cook Islands in the South Pacific, to use existing national legislation to propose mining within their two-hundred-mile exclusive economic zones (EEZs). The Cook Islands, in particular, are moving forward in the development of their own mining industry under the oversight of a local minerals authority, with the goal of exploiting more than ten billion metric tons of manganese nodules that are estimated to lie across an area of about 750,000 km^2 of the country's EEZ. There are currently three companies actively exploring new mining exploration licenses and conducting tests around the Cook Islands, including the deployment of seafloor mining pumps and pipe handling and riser equipment. Proponents of this work argue that it will provide a significant opportunity for long-term sustainable development, with suitable attention to environmental protection. Sensitive areas have been set aside as protected, including fifty-mile buffer zones around sensitive coral reefs. However, such measures will likely be only partially successful, as sediment plumes may travel hundreds of kilometers, and will not respect the neat boundaries defined by a permit.

As exploratory deep-sea mining activities move ahead, more discussions about potential environmental impacts will continue, and could help inform ISA's regulations and decision process. In the best-case scenario, the regulations could address both environmental and economic interests, for example by setting aside large undisturbed areas to protect fragile ecosystems and as a reference against which to gauge mining impacts. As an alternative, mining companies could be required to shoulder the additional expense of depositing their effluent as close to the original seafloor disturbance as possible. Doing so will minimize harmful effects of sinking and drifting plumes on the water column and ocean sediments. At the same time, new innovations in ocean mining technology could help offset some of the worst environmental impacts. For example, modifications to lift systems, using buckets instead of suctioning, could solve much of the surface plume problem. Much can be done, assuming that mitigations are incorporated in equipment design before it is finalized and deployed at a wide scale over the coming decade. Over the next few years, there is still time for considerable improvement.

The future development of deep-sea mining operations will be shaped by a complex interplay of many competing factors and motivations. The demand for cobalt and other green industry metals will loom large, as will the desire to prevent the industrialization of the ocean. While the ISA will certainly be a key regulator in the future, other factors will also likely come into play, such as the growth of the environmental movement in the Pacific, geopolitical realities (such as increasing Chinese control of critical metal markets) and the rapid expansion of new mining technologies. This Gordian Knot of competing issues will be difficult to unravel, but we can only hope that strong science and good governance prevail in the future of ocean mining.

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Mines in the Sky

Sara Russell and Riz Mokal

As resources on our planet dwindle, the gaze of writers, scientists, governments and entrepreneurs has turned upwards to consider whether space might supply some of our ever-growing mineral requirements. Before the mid-twentieth century, this idea lay exclusively in the realm of science fiction, and was often cautionary. Garrett P. Serviss' 1898 novel *Edison's Conquest of Mars* imagined Thomas Edison visiting an asteroid near Mars, only to discover it was made entirely of gold and mined by unfriendly Martians.[1] Sci-fi notions of outer space mining persisted well into the twentieth century. According to *The Encyclopedia of Science Fiction*, an entire subgenre of space opera written over the 1930s to the 1960s imagined the Asteroid Belt as the site of a new gold rush, with 'lawless asteroids' serving as 'the perfect place for interplanetary skullduggery'.[2] The 1979 movie classic, *Alien*, imagined a future where commercial space tugs carried mineral ores around the Solar System. In that story, things did not turn out well.

Life imitated art. As the Space Race kicked off in the 1950s and 1960s, voyages of discovery beyond Earth were motivated, at least in part, by a nebulous promise of untold riches. In 1962, US Vice President Lyndon B. Johnson declared 'Someday we will be able to bring an asteroid containing billions of dollars' worth of critically needed metals close to Earth to provide a vast source of mineral wealth to our factories'.[3]

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LBJ may have been drawing on Arthur Radebaugh's comic strip 'Asteroid Arrester', published only a week earlier, which explained that the National Aeronautics and Space Administration (NASA) would one day use powerful rockets to capture asteroids and harness them both for pure science and for commercial activity.[4] Serious academics were also on board, but it was only in 1997 that the distinguished planetary scientist John S. Lewis made the first careful attempt to quantify potential mineral wealth beyond Earth. In his book, *Mining the Sky: Untold Riches from the Asteroids*, Lewis estimated that a single small asteroid, 3554 Arum, could supply twenty trillion dollars' worth of metals.[5] Today, many people, including Texas senator Ted Cruz and the astrophysicist Neil deGrasse Tyson agree that the first trillionaire will be an entrepreneur in the asteroid mining sector. Such claims have motivated the growth of privately owned space exploration companies, like Elon Musk's SpaceX, seeking to exploit a new economic frontier. Underpinning all this activity is the assumption that space mining is a viable approach to help meet humanity's growing need for critical mineral resources. The reality, it turns out, is perhaps not quite so simple.

The story of outer space mining begins a long time ago. The universe was formed about fourteen billion years ago with the Big Bang, a cataclysmic event that produced all the matter we see today. The Big Bang itself generated only the elements hydrogen, helium and a relatively minor amount of lithium. All other elements have subsequently been synthesized from these simple precursors, mostly through nuclear fusion reactions inside stars, with lighter elements coming together to form heavier ones. (Replicating such a fusion process on Earth is a 'holy grail' for clean renewable energy.) The products of these intra-stellar fusion reactions are dominated by the lighter elements including helium, carbon, nitrogen and oxygen, along with the so-called 'transition' metals, such as iron, cobalt and nickel, which have the most chemically stable nuclei. In contrast, the heaviest elements, such as gold and platinum, are formed mainly in energetic supernova explosions, and as a result, these heavy metals have a significantly lower cosmic abundance.

The overall cosmic abundance of different elements is only one factor that influences their availability on Earth. Elements are divided into iron-loving ('siderophile') and rock-loving ('lithophile') types. In the early history of Earth and all other large bodies in the inner Solar System, heavier siderophile elements sank downwards due to gravity to form a core, leaving lithophile elements to rise to form a mantle and crust. As a result of this partitioning, the siderophile elements such as iron, copper and cobalt are relatively scarce in the accessible parts of Earth's crust (the upper few kilometers). It is this top layer that we currently mine for resources, literally scratching the surface of Earth.

In contrast with Earth, some asteroids may constitute a richer source of concentrated metal deposits. These rocky space objects formed from the early dust and gas precursors of our Solar System, and many are expected to preserve the cosmic abundances of different elements. In our Solar System, asteroids are bodies smaller than planets orbiting the Sun, and are concentrated in the Asteroid Belt, between Mars and Jupiter. A small, but significant number of Near-Earth Asteroids (NEAs) also exist. These objects are much more accessible than bodies beyond Mars, and are the likely target of any initial attempts at space mining.

In total, the combined mass of the Asteroid Belt is believed to be around 0.05% of the mass of Earth; there are over a million known asteroids with sizes exceeding one kilometer, and likely billions of smaller ones. Remote spectroscopic measurements and various space missions have demonstrated a remarkable diversity in asteroid size and composition, with distinct types identified based on various observed properties, including the potentially carbon-bearing C-type asteroids, the rocky S-type asteroids and the dark D-type asteroids, which reflect little light and are difficult to observe. Among these groups, the so-called M-type ('Metal') asteroids are most attractive as potential targets for outer space mining. These asteroids make up around 10% of the Asteroid Belt and are believed to be composed of iron and nickel, although some controversy remains regarding their exact mineral composition. Unlike Earth, which has sequestered enormous amounts of its metal inventory into a deep planetary core, M-type meteorites have near uniform compositions, which are assumed to be comprised almost entirely of metals.

The chemical composition of asteroids can be studied on Earth using meteorites that land on our planet's surface. At present, there are around 75,000 known meteorites, the vast majority of which originally derived from asteroids. Linking a meteorite to its extra-terrestrial parent can be complex, but with careful analysis, these objects provide important clues about the potential outer space mineral resources. For example, some meteorites contain high concentrations of transition metals such as cobalt, iron and nickel. These meteorites (and hence likely their parent M-type asteroids) also contain as much as 1% cobalt, as compared to approximately 0.003% in Earth's crust. The more common chondrite meteorites contain between 0.05 to 0.1% cobalt by weight, values similar to the richest deposits on Earth. Assuming a cobalt abundance of 0.05%, it has been estimated that there are approximately 10^{15} metric tons of cobalt in the Asteroid Belt, enough to supply humanity's needs for ten billion years at current rates. A single metal asteroid with a mass of around three billion metric tons could supply thirty million metric tons of cobalt, along with many other useful metals such as iron and nickel. By comparison, the known cobalt resources on Earth amount to around eight million metric tons, with the majority coming from the Democratic Republic of Congo.[6] Cobalt mining in that country has been associated with a wide array of human rights abuses, political corruption and armed conflict.[7] Some have suggested that asteroids could therefore present an attractive alternative supply for this metal, which is a critical element in the rechargeable batteries needed to support low-carbon economies.[8]

Other metals, including the so-called platinum-group metals (PGMs)—ruthenium, rhodium, palladium, osmium, iridium and platinum—are used widely as catalysts in various technologies, including the automotive and medical industries and consumer electronics. Like iron and nickel, these heavy elements are sequestered deep within Earth's planetary core, and only trace quantities are present in near-surface crustal environments. Earth's crust contains about 0.001 parts per million (ppm) of iridium, meaning that every kilogram of rock holds about one thousandth of a gram of this element. By comparison, M-type asteroids can contain up to 60 ppm iridium, sixty thousand times more than that found in Earth's crust. In chondrite meteorites, platinum group elements exist as tiny nuggets of pure metal.[9] Some of the PGMs on the Earth's surface are believed to have been delivered by meteorite impacts after the formation of the planet's core. As a result, the most productive PGM mining regions on Earth are those that have previously experienced giant meteorite impacts, including Vredefort in South Africa and Sudbury in Canada.[10]

Compared to asteroids and other small extra-terrestrial bodies, planet-sized bodies may prove more challenging for heavy metal mining. Like Earth, these larger bodies are differentiated into distinct density layers, with most of their metals buried deep in an inaccessible core. Mars, for example, may have usable ore deposits, but these are likely similar to those on Earth, and more relevant for potential colonists on the Red Planet than as a source to be shipped back to our Blue Planet.

However, there may be one instance where a larger body—the Moon—could supply some much-needed metals. Rare-earth elements (REEs), such as neodymium and dysprosium, are used for batteries, electronics, lasers, magnets and catalysts, among other applications. The future supply of these elements is of concern, mainly because present-day sources on Earth are restricted to a small number of countries, including China, the United States, Myanmar and Australia.

Unlike iron, nickel and PGMs, the REEs are lithophile elements, meaning that they do not concentrate in planetary cores. As a result, they are not particularly abundant in metal-rich asteroids, but parts of the Moon could provide significant reserves of these important elements. When the Moon first formed, its surface rocks melted entirely, slowly crystallizing into a layered structure with light minerals at the top and dense rocks at the bottom. During this process, the REEs partitioned preferentially into the melt phase rather than solid minerals, becoming increasingly concentrated in the upper layers of the Moon as it slowly cooled and solidified. One of the upper layers of material on the Moon, the last to crystallize, formed a highly unusual rock called KREEP (an acronym built from the letters K for potassium, REE for rare-earth elements, and P for phosphorus), first identified during the NASA Apollo space missions of the late 1960s. If significant deposits of this material are identified on the lunar surface, they could potentially provide a source of much-needed REEs. The upcoming NASA Artemis missions to the Moon aim to address this question, among others.

Beyond the significant challenges of identifying and recovering outer space sources of raw minerals, extra-terrestrial mineral deposits must also be processed into forms that are usable in a variety of applications. Different mineral processing options include the return of raw materials back to Earth, processing metal deposits in space, or transporting asteroids to a safe orbit in the Earth–Moon system for longer-term extraction. In metal-rich asteroids, the elements of interest may already be in a chemical form needed for various applications (i.e., pure metal states), reducing the requirements for downstream processing. In this case, metals can more easily be returned to Earth in usable forms, using non-chemical approaches such as raking and magnetic separation. In other cases, metals may exist in a range of different chemical states that require significant treatment prior to utilization. Any necessary processing will be subject to constraints not experienced on Earth, notably low gravity and the lack of air. For this reason, fundamentally new approaches will be needed to recover usable forms of metal from outer space deposits. Such work may include novel methods of 'biomining', in which bacteria are used to leach metals of interest from a rock.[11]

Growing interest in space minerals has ignited a new twenty-first-century Space Race, with a particular focus on the study of asteroids, and the exploration of the Moon and Mars. In 2010 and 2020, the Japanese spacecraft *Hayabusa* and *Hayabusa2* returned to Earth with material from the asteroids Itokawa and Ryugu, respectively. And just last year, in 2023, NASA's *OSIRIS-REx* space probe returned samples from the asteroid Bennu. Over the past decade, several countries including the US, Russia, China, Japan and India have landed autonomous missions on the Moon or Mars (though some of these were crash landings). Recent interest in the Moon has focused on a region on its South Pole known as Aitken Basin, where suspected frozen water could sustain lunar mining operations and provide rocket fuel for travel deeper into the Solar System. Recently, India became the first country to safely land a probe on the lunar South Pole, marking a significant scientific and geopolitical shift in the new Space Race.

The current surge in outer space exploration is occurring against a backdrop of significant legal and regulatory uncertainty. The 1967 Outer Space Treaty, and the subsequent 1979 Moon Agreement adopted by the United Nations General Assembly, set out broad guidelines for activities conducted in outer space. However, both treaties are of limited effect and uncertain interpretation. By way of illustration, the Outer Space Treaty states that Space is not subject to 'national appropriation' or claims of sovereignty, without explicitly addressing the issue of property rights over resources extracted from outer space.[12] Further, accession to these treaties is patchy, particularly amongst states which are likely to develop the relevant travel and mining capabilities over the coming decades. In fact, many states have argued that space mining should be subject to national laws. In 2015, the US passed the Commercial Space Launch Competitiveness Act, signed into law by President Barack Obama. This Act gives US citizens and companies rights of ownership over resources obtained from outer space 'in accordance with applicable law'.[13] Five years later, US President Donald Trump signed an executive order supporting 'the public and private recovery and use of resources in outer space'.[14] Other states, including Luxembourg, Japan and the United Arab Emirates have since passed similar laws, opening the door to a patchwork of potentially competing national regulations. Such an approach could enable outer space mining companies to operate under a 'flag of convenience', as occurs in international shipping. The present legal framework is thus incomplete and unfair, and international regulations would allow commercial operators to self-servingly choose to operate under a national framework with weak environmental and ethical standards.

In response to the growing influence of national interests, there has been a call for new multi-lateral approaches to the regulation of outer space mining. The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) recently established a Working Group on Space Resources, which has been endorsed by over 130 nations, including Russia and China. Any international treaties developed by this group will not only need to consider property rights for future space mining, but also the potential negative environmental and other impacts of such activities. These include the creation of outer space debris fields, which could pose hazards to satellites and other spacecraft, and potential changes in the orbits of asteroids, which may increase their chances of Earth impact. Other considerations include the inadvertent introduction of novel life forms to planetary bodies, and disturbances that could compromise future scientific studies.

In the not-too-distant future, asteroids and other extra-terrestrial bodies might well become a viable source for at least some of the heavy metals we will require. These outer space objects are remarkably diverse in size, location and composition, but they are all typically metal-rich compared to Earth's near-surface environments. At the extreme, asteroids represent concentrations of almost pure metals orbiting near our planet. It therefore seems logical that they could, in time, be a useful resource. The current economic value of asteroid mining is lower than the huge costs involved in mounting a space mission. But this could change in the future, as technological barriers are overcome and innovative practices reduce costs, while growing scarcity of metals on Earth increases their prices. For now, the logistics and economics of asteroid mining are not established, and any serious discussion of space mining remains part of a long-term solution to the mineral supply issue. In the meantime, missions like NASA's *OSIRIS-Apex* and *Psyche* are visiting asteroids to learn more about our metal-rich neighbors. This type of basic research, combined with investment from the private sector, will enable asteroid mining to become ever closer. Any scientific progress will have to be understood in the context of economic, social, ethical and legal considerations, as humanity seeks to expand its ever-growing footprint beyond Planet Earth.

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Mining in Icy Worlds

Anita Dey Nuttall and Mark Nuttall

As the global economy transitions from fossil fuels to renewable energy, the search for 'critical minerals'—copper, lithium, cobalt and others—has pushed us to explore the remotest and most extreme environments on Earth, from the driest deserts to the depths of the ocean floor. In this global resource race, the coldest and iciest parts of our planet, the Arctic and the Antarctic, have also become the subject of much interest. These two regions, often assumed to be similar, but polar opposites in many ways, could play a large role in shaping the future economics and geopolitics of global mineral resources.

At the top of the globe, the ice-covered Arctic Ocean spreads across the circumpolar North. This body of water is the smallest and shallowest of the major oceans. It covers an area of about fourteen million square kilometers, surrounded by many islands and archipelagos, and the northern parts of the North American and Eurasian continents. Humans have lived on these lands for thousands of years. At the other end of Earth, nearly twenty thousand kilometers away, the southern polar region is dominated by the ice-covered landmass of Antarctica. This is the fifth largest continent (covering about the same area as the Arctic Ocean), and also the coldest and windiest place on Earth. It has a harsh climate, with average annual temperatures ranging from -10°C on the coast to -60°C at the highest parts of the interior. Most of Antarctica is covered by

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a four-kilometer-thick ice sheet, and has much lower terrestrial biodiversity than the Arctic, with no indigenous human population.

Since the early 1960s, human activity and governance arrangements in Antarctica have been subject to an international framework called the Antarctic Treaty System (ATS). This system regulates scientific research, environmental management and conservation, but does not recognize national sovereignty over any portion of the continent. Nonetheless, seven countries have made territorial claims to parts of the Antarctic, based on their roles in exploration and early scientific endeavors. The geopolitical situation is entirely different in the Arctic, which comprises eight nation states—Canada, the United States, the Russian Federation, Iceland, Norway, Sweden, Finland and the Kingdom of Denmark, which includes Greenland. Since 1996, these nations have (mostly) cooperated on matters of governance through the Arctic Council, an intergovernmental, consensus-based forum concerned with environmental protection, conservation and sustainable development. Arctic Council activities have been on hold since Russia's invasion of Ukraine in February 2022, although some work is beginning to resume under the auspices of the Council's working groups.

If there is one Arctic region that is closest to Antarctica, at least geographically and climatically, it is Greenland. Although Greenland is not a continent (it is attached to the North American tectonic plate), it is the world's largest island, covering about 2.2 million square kilometers. Average temperatures in the small town of Qaanaaq, in the northwest, range from around 5°C in July to -25°C in January, while Nuuk, the country's capital in the southwest, experiences an average temperature of 10°C in July and around -10°C in January. Greenland is a self-governing territory, with a population of around fifty seven thousand—of which 80% are of Inuit descent. The population is concentrated in towns and smaller settlements along the island's coastal stretches, mainly on the west coast. Most of the island, some 80% of its land mass, is covered by the world's second largest ice sheet. This ice sheet—known as the inland ice (or *Sermersuaq*, the 'great ice' in Greenlandic)—is over three kilometers thick in parts. A weather station on the topographic summit of the inland ice recorded a temperature of -69.6°C in December 1991—the lowest ever recorded in the Northern Hemisphere.

While there are probably more differences than similarities between Antarctica and Greenland, they are both subject to significant speculation about their resource potential. As global demand for critical minerals rises sharply, and supply chains become precarious and volatile, securing mineral supply has become a matter of economic importance and national security. What this means for Antarctica and Greenland will likely be very different. In the case of Antarctica, any future mining would not probably happen for at least another quarter century due to existing international agreements. On the other hand, the circumpolar North has a long history of extractive resource ventures, with major industry operations in Alaska, Canada, Russia and northern Fennoscandia, as well as the Norwegian archipelago of Svalbard. In these regions, hydrocarbon extraction and mining have had significant environmental impacts and lasting social and economic consequences, especially for Indigenous communities. Increasingly, Greenland is now also being seen as a resource frontier for critical minerals, and many around the world see the island as a new and important source of the materials needed for decarbonization and electrification.

A key motivation underlying Greenland's push for mining is a political desire to reduce its dependency on Denmark, while forging an independent sustainable economy and enhancing its global stature.[1] The self-rule government has affirmed its priority to develop a mining industry, and significant efforts have been put into attracting international investors. The recent focus on mining in Greenland is not entirely new. The history of mineral exploration on the island stretches back to the beginning of the nineteenth century, when geologists first surveyed the potential mineral wealth of the west coast and southern areas. Cryolite, a mineral used in the production of aluminum, was first mined at Ivittuut in southwest Greenland starting in the 1850s, with production continuing for over a century until 1987. In the early 1900s, Danish administrators laid down plans for the industrialization of Greenland's natural resources. Subsurface resource exploitation was included in those plans, even though Danish economic interests were more focused on the trade of marine mammal products, fish and furs. Other early mining ventures included coal extraction at Qullissat on Disko Island from 1924 until 1972, and lead, iron and zinc mining at the

Black Angel Mine at Maamorilik in the northwest Uummannaq district from the late 1930s until 1990. In more recent decades, several exploratory mining and hydrocarbon operations have occurred, and specific government policies have been developed to support mining as a critical component of Greenland's economy. These efforts have intensified since Greenland achieved a greater degree of self-government in 2009. As part of the new self-rule agreement with Denmark, Greenland acquired ownership of its subsurface resources in January 2010, with full authority over the decision-making process concerning mineral resource activities.

In Greenland today, different perspectives are emerging around the future of the region's mineral resources. The increasingly accessible landscape, made possible by climate-driven retreat of the ice sheet, has inspired local politicians to promote the island's extractive industry sector. From an international perspective, this unearthing of mineral resources highlights Greenland's evolving geostrategic position, as various economic and political interests look to invest, establish business relations and forge diplomatic links. China, for example, has expressed interest in funding Greenlandic projects, while the United States and other countries have also been positioning themselves to take advantage of Greenland's resource potential. For its part, the European Union has identified Greenland as a major supplier for most of the critical minerals it needs, including rare-earth elements (REEs).

In July 2021, Greenland's new coalition government announced that it was suspending the granting of new licenses for oil exploration. This move was part of a broader commitment to develop strategies for renewable energy and tackle climate change. Whereas fossil fuels were to be phased out, mining companies were reassured that mineral extraction would be a pillar of Greenland's future economy. Indeed, Greenlandic politicians have declared that the country is open for the mining business, actively welcoming bids for prospecting and exploration licenses. And the world has taken notice. Significant international interest is evident in the numerous ongoing mineral exploration and mining projects, with a focus on cobalt, graphite, niobium, platinum-group metals (PGMs), REEs, tantalum, titanium and vanadium. Companies such as KoBold Metals, supported by billionaires Jeff Bezos and Bill Gates, are also initiating exploratory projects, while the Tanbreez mining project in south Greenland aims to unlock the area's REEs. Other resources such as rubies, pink sapphires and uranium have also become objects of value for the future economy of this increasingly important Arctic country.[2]

Not all mineral exploration ventures in Greenland have been smooth or without controversy. Energy Transition Minerals—an Australian company formerly known as Greenland Minerals—faced a major setback when the Greenland government refused its 2019 application for an exploitation license for uranium and REEs. The proposed project, at Kuannersuit near the town of Narsaq in south Greenland, was subject to considerable public opposition, highlighting concerns over inadequate social and environmental impact assessments, and insufficient consultation with potentially impacted communities. Across Greenland, other mining projects have increasingly provoked highly charged political and social debates about the nature, and even desirability, of resource development. The government decision to deny permits to Energy Transition Minerals could indicate a significant policy shift towards greater scrutiny and stronger regulatory control over the environmental and social impacts of mining. But there can be no doubt that the emerging mineral industry in Greenland illustrates a broader global reimagining of the Arctic as a resource frontier.

Antarctica presents a rather different case study of mining in a frozen world. It is the only continent without a history of mining, and no mineral deposits of commercial interest have yet been identified there. But this has not stopped significant speculation about the mineral resources that might be locked up underneath the vast mass of Antarctic ice. About two hundred million years ago, Antarctica was part of an ancient continent, Gondwanaland, that comprised land masses including present-day Australia, Africa, India and South America. Because of this shared geological history, it has been hypothesized that Antarctica may host large mineral deposits, similar to those found in its ancient continental neighbors. But, even if such mineral deposits were discovered, Antarctica's geography and climate would prevent economically viable and environmentally safe mining. Any consideration of potential mineral exploration would be limited to only a few areas of the continent with exposed rock, such as the Prince Charles Mountain range, where iron deposits have been identified.[3] Things could change, however, under a rapidly warming climate. The Antarctic Peninsula is amongst the fastest warming parts of the planet, and glacier melt across the Antarctic continent is predicted to increase by 25% by the end of this century.[4] Much of this new ice-free area will emerge in the North Antarctic Peninsula, significantly enhancing access to potential mineral resources.

A significant complexity around potential mining in Antarctica arises from the unsettled question of its sovereignty. The continent and its surrounding waters belong to no one. They are governed collectively by a group of fifty-six countries that are signatories to the Antarctic Treaty of 1959. But seven of these countries (Argentina, Australia, Chile, France, New Zealand, Norway and the United Kingdom) claim Antarctic territory, even though the treaty neither recognizes nor denies these claims. Furthermore, three of these territorial claims (Argentina, Chile and the UK) overlap with one another in the potentially mineral-rich Antarctic Peninsula. The United States and Russia do not recognize any of these claims, but both reserve the right to make a claim in the future if the Antarctic Treaty were to collapse.

The Antarctic Treaty was a product of its time. Negotiated at the height of the Cold War, the key and most pressing need was to ensure that Antarctica did not become a stage for war or nuclear testing. Suspending the issue of territorial claims was thus a pragmatic move when the nuclear stakes were so high. The principal provisions of the treaty focused on the use of the continent for peaceful scientific purposes only, prohibiting military activities, nuclear tests and radioactive waste disposal. More than half a century after the signing of the original Antarctic Treaty, there are now around forty-one year-round and thirty-nine seasonal scientific stations in the Antarctic, operated by thirty-three national government agencies. Each year, over ten thousand scientific and logistics personnel work on the continent during the Antarctic summer, and around one thousand in the winter.[5] Tens of thousands of tourists also travel there annually, mainly on cruise ships—just over 100,000 visited the continent during the 2023–24 season.

Since the Antarctic Treaty entered into force in June 1961, the governance of Antarctica has evolved through various measures and conventions that regulate human activities and the conservation of living resources. By comparison, the attempted regulation of non-living resources has been less successful. Starting in the late 1970s, the Treaty parties spent over a decade negotiating the terms for future mining in Antarctica. These efforts culminated in the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA), which ultimately failed to be ratified by all the Consultative Parties (who are the ATS decision makers), and thus never entered into force. Among other nations, Australia, and France, both claimant countries, rejected the process, arguing instead to permanently prohibit mining in Antarctica.

The failure to ratify CRAMRA exposed serious divisions among the treaty parties, threatening to dissolve the ATS as it approached its thirtieth anniversary in 1991. In an effort to save the Treaty, the controversial CRAMRA was dropped in favor of a Protocol on Environmental Protection that came into force in 1998. This underscored the principle that the Antarctic must be regarded as a protected and globally unique wilderness to be utilized only for peaceful scientific purposes. The Protocol bans all mineral exploration activities. Like the Antarctic Treaty, the Protocol has no scheduled end in its text. But after 2048, fifty years following the date it came into force, any Consultative Party can request a formal review process, at which time the parties would have three years to ratify a modified or amended Protocol. If the Protocol is brought under review, any party can withdraw by 2051 if a new Protocol has not been entered into force. This would leave the future of its environmental regulations hanging in the balance.

The growing number of countries involved in Antarctic politics and scientific activities has led to concern over the management of human impacts. Today, there are twenty-nine Consultative Parties and twenty-seven Non-Consultative Parties to the Treaty, and the original signatories have been joined by emerging global powers like China and India as Consultative Parties. Each of these nations is attempting to exert influence over the regulation of Antarctica and striving to increase its scientific presence on the continent. Conducting science in Antarctica is expensive, and not all of it is done for intellectual curiosity alone; countries expect to capitalize on their considerable investment. Resources and infrastructure created to enable science could also, one day, be used to support mineral exploration projects.

The main priority of the ATS has been to ensure that states avoid conflict in Antarctica. But it remains to be seen whether the shared values of scientific cooperation and peace can outlast future demands for strategically important minerals. The rapidly warming Antarctic Peninsula may prove to be an early test case, with its potential mineral deposits and the overlapping territorial claims of Argentina, Chile and the UK. For the moment, it does not appear that any nations are willing to give up their Antarctic claims for a greater common good. If anything, an increasing number of submissions to the Commission on the Limits of the Continental Shelf (CLCS), a body created by the 1982 Law of the Sea Convention, suggests that various nations are attempting to strengthen their territorial claims in preparation for a time when mineral exploitation might be feasible. It is difficult to predict what the global economy and demand for resources will look like in 2048, when the protocol banning mineral activities may face renewal.

The examples of Greenland and Antarctica underscore a critical dilemma. On the one hand, we face an urgent imperative to protect the integrity of environmentally sensitive polar regions, especially in the face of a rapidly warming climate. On the other hand, these regions are increasingly being viewed as current or, in the case of Antarctica, potentially future extractive zones for the mineral resources needed for renewable energy systems. Ironically, the effects of climate change are making these polar regions more accessible, and geopolitically significant for an overheating and more populated world. Continued scientific research in Greenland and Antarctica is crucial for understanding global climate change but increased human activity and interest in resource extraction also pose environmental risks.

Greenland is becoming firmly part of the 'planetary mine',[6] undergoing a process of state formation in which mineral resources have become central to a political and economic strategy for a prosperous, and possibly independent, future. In the face of economic and geopolitical pressures, the Greenland self-rule government must also grapple with environmental and social concerns, seeking to balance prosperity and a drive for self-determination with the preservation of fragile and unique landscapes. Half a world away, the mineral resource potential of Antarctica may someday emerge to provide raw materials needed to support a future global economy. The future use of any Antarctic minerals will likely put significant strain on a unique form of international cooperation and environmental governance that has existed for more than half a century.

Both Greenland and Antarctica have growing strategic assets, with expanding scientific and technological expertise, and improving infrastructure, including harbors, airfields, research stations and ice transportation networks. These assets open new opportunities for current or potential future mineral exploration, putting Greenland and Antarctica at the forefront of geopolitical discussions about resource utilization and environmental conservation in an era of rapid climate change. And, more than ever, as we move toward a post-carbon Anthropocene future, we need both these regions to be at the forefront of global discussions about sustainability, environmental impact and the future of resource management.

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Landscapes of Extraction

Edward Burtynsky

I have come to think of my preoccupation with the Anthropocene—the indelible marks left by humankind on the geological face of our planet—as a conceptual extension of my first and most fundamental interest as a photographer. To this end, I seek out and photograph large-scale systems that leave lasting marks. I believe there is much we can learn from deciphering such marks upon the landscape. It's as if I am creating a visual archeology, but rather than digging into the past, I'm preserving the present moment. One of the things I want to show is the scale of the impact—what is left behind as the human enterprise transforms our planet.

Over the course of my career, the subject of mining has intrigued me over and over again. In the mid-1990s, I was working in Elliot Lake, Ontario, taking photographs of large-scale mine tailings ponds. By the time I got there, more than half of the original uranium mines and tailings management areas in the region were no longer in operation. The year prior to my arrival, four of the biggest mines had been shut down. They were producing uranium—specifically yellowcake—for nuclear power plants, at a time when Russian supplies of this product were saturating the market, making it impossible for other countries to compete. Decommissioning of the remaining uranium mines in Elliot Lake had already begun in 1992, and would continue for a decade, leaving yet another community in financial and environmental devastation.

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One of the sites that drew my attention was owned by Denison Mines Incorporated. The mine's tailings pond had a towering wall made of ground quartz. About ten years earlier, a torrential rain had caused a tailings breach, flowing much of that quartzite and other waste material into the landscape, suffocating the trees and other flora in its path. The landscape I captured in my photographs still hadn't recovered after a decade.

Another area that caught my eye was the Copper Cliff Mine in Sudbury, Ontario. The area of this mining complex was expansive, about twenty square kilometers in total, including a tailings pond with walls that reached over seventy meters high in some places along the highway. In 1996, I managed to get access to the top of this tailings area, providing me with an expansive perspective from which to photograph the massively disturbed landscape. When looking at the resulting images—bright orange rivers against a stark black background—a lot of people think the colors are manipulated. They aren't. The orange color results from the residual iron ore left behind in the tailings. During the mineral processing steps, nickel and copper are concentrated out of the mined rocks, along with traces of silver and other precious metals. Iron, however, is much less valuable, and there is no economic incentive to strip it from the ore. The iron oxide gets flooded into the tailings as waste, creating literal rivers of rust.

Not long after my work in Sudbury, I started exploring recycling facilities in Toronto and Hamilton, as an extension of my mining series. Urban mining was intriguing to me, in its approach of going back into our industrial and urban waste streams to harvest materials that have already been taken from nature. In my previous work, I'd focused on primary mining—going to the land, blasting and extracting ores. In contrast, recycling and urban mining represented a source of secondary extraction; rather than harvesting from the earth again and again, it was an opportunity to reclaim high-value materials that already existed in the recycling stream. I was interested to see large-scale e-waste, at a time when businesses were buying post-consumer goods in anticipation of cheap technologies that would enable conversion and repurposing of the embedded copper and other metals. But soon after I took these pictures, the city forced the closure of the e-waste depot. The recycling technology wasn't available yet, the waste couldn't be burned, and there was no efficient way to process it. Instead, they put it in containers and shipped it to China. Years later, when I decided to do a China project, the journey of urban mining and scrap recycling became one of my subjects. I followed the e-waste halfway around the globe.

In 2006, I was approached by the Fremantle Photo Fest, which was commissioning a series of images from Australia. I decided to accept the commission because I saw Australia as very similar to Canada in many ways—a former British colony, largely known for its expanse of natural resources, with a significant focus on mining. I wanted to showcase the Australian mining industry, and ended up visiting Perth and Kalgoorlie in 2007. During my trip, I looked at a variety of different mines, from the super pits in Kalgoorlie to the mines in the Silver Lake area. The Silver Lake Mines are located on salt flats, with a surreal-looking surface. I'd photographed mines for many years at this point, but I wanted to take these pictures differently, shooting them from a helicopter with the door off. I'd already perfected the technique for other projects, and wanted to bring it to the subject of mining.

As luck would have it, an uncommon rainfall had occurred the day before, leaving lots of water sitting on the salt flats. At the same time, the day was unusually cloudy. The combination of the cloudy skies and water on the salt flats presented a serendipitous moment that allowed me to create a body of work that's been very special to me. I remember coming back from this shoot feeling very excited about what I'd seen, and having a whole new way of looking at mining. This was the first successful aerial shoot that produced a complete series, informing the subsequent aerial work I've done over the last thirteen years.

The Australian mining shoot also stimulated my photographic interest in water—the most fundamental aspect of life on Earth. I wanted to find ways to make compelling photographs about the human systems employed to redirect and control water. Through this work, water took on a new meaning for me. I realized that water, unlike oil, is not optional. Without it we perish. Human ingenuity and the development of its industries have allowed us to control the Earth's water in ways that were unimaginable just a century ago. While trying to accommodate the growing needs of an expanding and very thirsty civilization, we are reshaping the Earth in colossal ways. Not just through mining, but also through agriculture and other large-scale activities.

As my interest in water grew, so did my appreciation for salt and other non-metallic minerals that we extract from the earth at industrial scales. In 2017, I visited the large underground potash mines in Berezniki, Russia. Potash is a combination of the potassium-containing minerals halite, carnallite and sylvite, and is a critically important fertilizer supporting global agriculture. Three hundred and fifty meters beneath Berezniki, massive tunneling machines reveal vividly colored layers from an ancient seafloor. As they dig, the machines leave behind impressions in the soft sedimentary rock that look like fossils of the ancient sea life from which they were formed. Completely enveloped in darkness, these tunnels were incredibly difficult to film. They are stable for the most part, and will leave behind a record of our presence through anthroturbation (large-scale human tunnelling under the earth).

Two years after my trip to Russia, I was in Senegal working on my *African Studies* project. A notable highlight of this work was a 2019 visit to the salt ponds near Fatick, Naglou Sam Sam and Tikat Banguel. Here, small-scale harvesters dig shallow depressions by hand, which are then filled with salt water from nearby canals. Once the water has evaporated, the remaining salt is cleared away, leaving residual minerals, pigments and various algae that combine with reflections of the sky to create a spectacle for the eye. Seeing these landscapes from a bird's-eye view is breathtaking; their intricate, organic structures become almost hypnotic.

Having explored many different types of traditional ore mines, from copper, gold, nickel, salt and coal, I have recently been investigating a new type of mining for rare-earth elements (REEs). These elements have unique magnetic and electrochemical properties that make them extremely useful in a wide variety of new technologies, yielding greater efficiency, performance and durability, while reducing weight and energy consumption. Rare-earth magnets, in particular, are used extensively in a wide range of applications, from computer hard drives and wind turbines to medical scanners and electric motors.

This year, my interest in these REEs took me to the MP Materials operation in Mountain Pass, California, an open-pit mine on the south flank of the Clark Mountain Range about a hundred kilometers southwest of Las Vegas. The mine first opened in the 1950s, and expanded quickly to supply a growing need for the element europium, which was used in the color televisions that were becoming increasingly common at that time. For several decades, the mine supplied the majority of the world's REEs, before China came to dominate global production in the 1990s. In response to growing geopolitical tensions, mining operations at Mountain Pass have recently re-started, as the United States seeks to secure a reliable domestic supply of these critical elements.

The photographic study of mining illuminates larger truths about humanity's impact on Earth. All living species must take from nature to survive and we are no different; we need water and salt, we need protein, we need calories, we need shelter. That hasn't changed, but what has changed is the incredible technology that we now have at our disposal. The problem is that we have expanded well beyond the limits of what the planet can sustain, and we're waking up to that fact a bit late in the game. We're working at a level that nature never anticipated.

As artists, we can help, visually and intellectually, in understanding a collective human impact that is putting our planet in jeopardy. I feel that by showing those places that are normally outside our experience, but very much a part of our everyday lives, I can add to our understanding of who we are and what we are doing. Ultimately, I'm looking for interesting places and moments to embody my poetic narrative of the transfigured landscape, the industrial supply line and what that means in our life.

Morenci Mine #1

Clifton, Arizona, USA, 2012

Morenci Mine #2

Clifton, Arizona, USA, 2012

Tailings Pond #2

Wesselton Diamond Mine, Kimberley, Northern Cape, South Africa, 2018

Phosphor Tailings Pond #4

Near Lakeland, Florida, USA, 2012

Phosphor Tailings #5

Near Lakeland, Florida, USA, 2012

Highland Valley #8

Teck Cominco, Open Pit Copper Mine, Logan Lake, British Columbia, Canada, 2008

Mines #43

Berkeley Pit, Anaconda Copper Mine. Butte, Montana, 1985

Sishen Iron Ore Mine #2

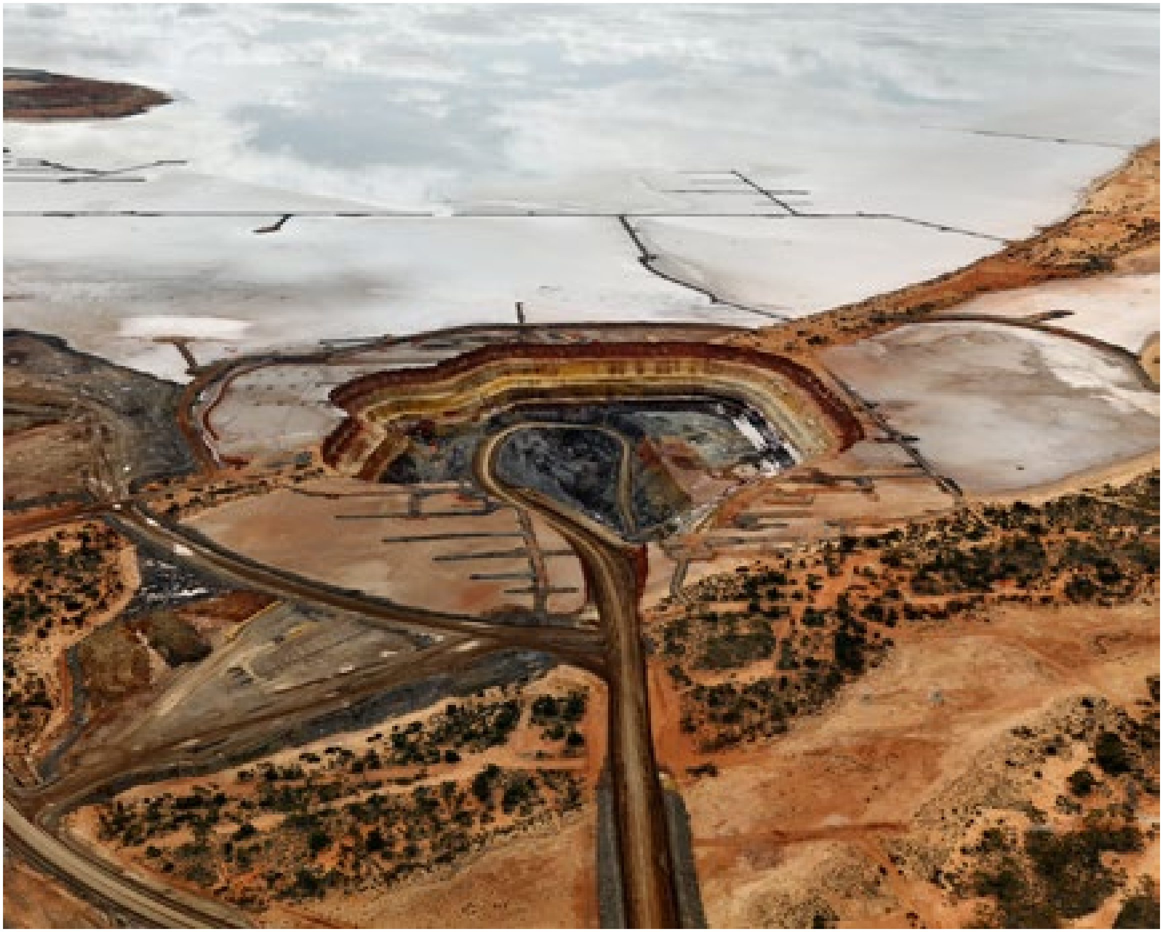
Overburden, Kathu, South Africa, 2018

Densified Oil Filters #1

Hamilton, Ontario, 1997

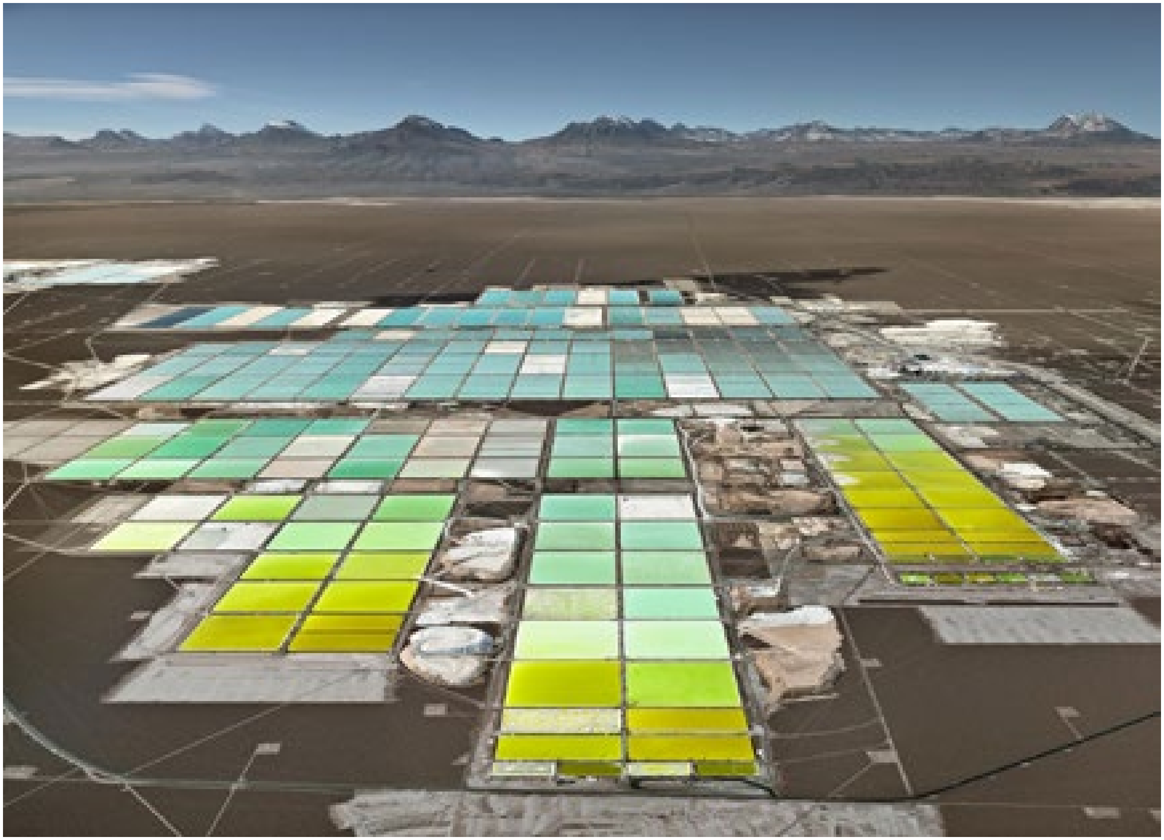
Non-Ferrous Scrap Metal #5

Hamilton, Ontario, Canada, 1997



Silver Lake Operations #5

Lake Lefroy, Western Australia, 2007

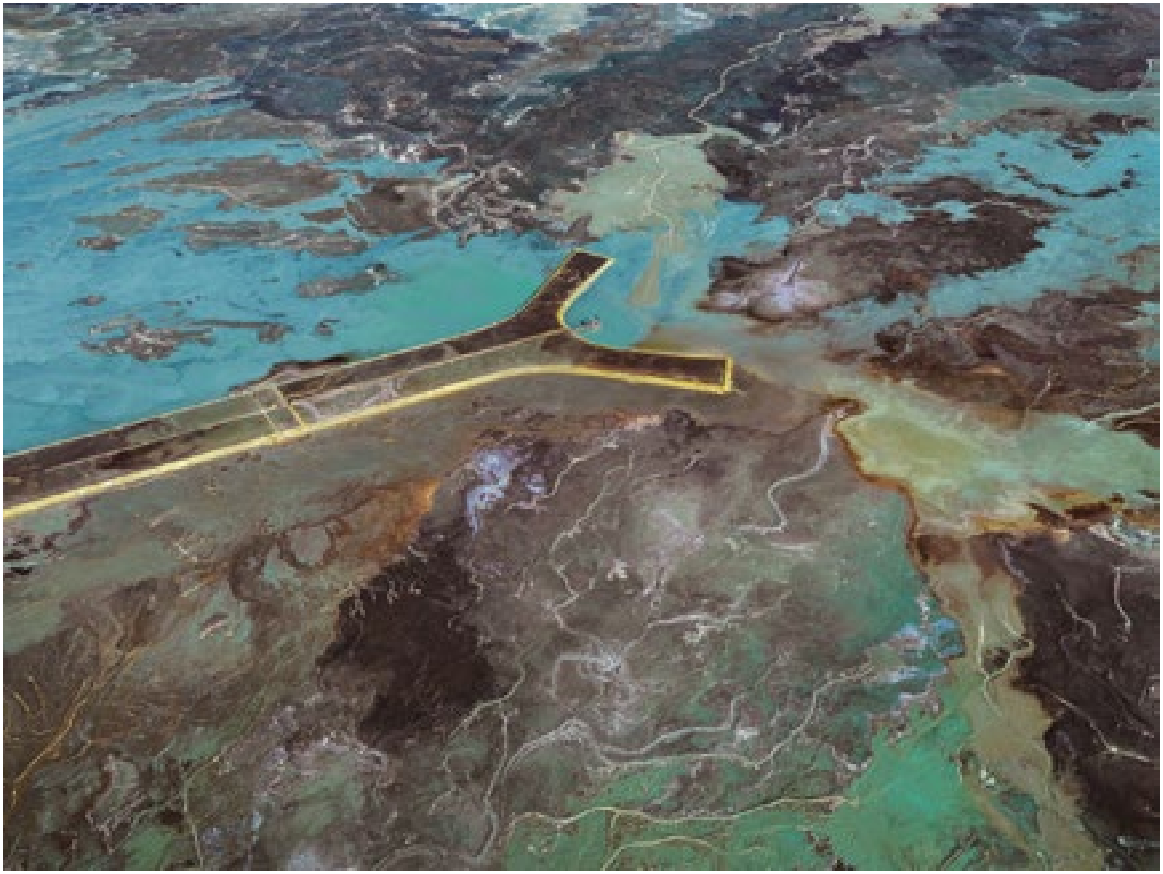


Lithium Mines #1

Salt Flats, Atacama Desert, Chile, 2017

Uralkali Potash Mine #4

Berezniki, Russia, 2017



Gold Tailings #1

Doornkop Gold Mine, Johannesburg, South Africa, 2018

MP Materials #6

Mountain Pass Mine, Mountain Pass, California, USA, 2023

Black Panther and an Afrofuturist Vision for Mining

Sara Ghebremusse

In the 2018 Marvel Studios film, *Black Panther*, General Okoye flies a vibranium-powered ship to Wakanda, the fictional African home of King T'Challa, the Black Panther and protector of the country. As the ship pierces the invisible barrier shielding this mythical land from the outside world, viewers get their first glimpse at a country that is unlike anything that exists in present-day Africa. With the visual enhancements made possible by computer graphics, the scene is breathtaking—like no other representation of an African society ever brought to life on the big screen. Wakanda is home to tall skyscrapers, flying aircraft and advanced technologies, all built sustainably, using the mineral vibranium to advance the socioeconomic interests of its people, rather than those of colonial powers. It was the first time that the Marvel world of Wakanda was brought to life by African American creators in Hollywood. The movie presented a distinctly 'Afrofuturist' vision of mining, which delighted both audiences and critics around the world. To date, the movie has earned gross profits of more than a billion dollars.

The term Afrofuturism, first used by the American writer and culture critic Mark Dery, represents a cultural aesthetic that weaves science fiction and fantasy

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to critically re-examine the historical and present experiences of people of African descent.[1] Through its fantastical imagining of an isolated, mineral-rich African society, *Black Panther* is steeped in the aesthetic and ethos of Afrofuturism. Seeing Wakanda depicted on screen for the first time, I was awestruck by the images of a self-sustaining African society built on mining. Of course, vibranium is like no other metal that exists on Earth. It is powerful enough to fuel aircraft and high-speed trains, and used in technology that allows the people of Wakanda to develop advanced weapons, while also hiding in plain sight. This image of an African nation thriving despite its reliance on mining stands in stark contrast to the reality faced by many countries across the African continent today.

Four years before *Black Panther* was released in theatres, three Eritrean refugees filed a class action lawsuit in Vancouver, Canada, alleging that a Canadian mining company, Nevsun Resources Limited, had been complicit in the torture, forced labour, and cruel, inhuman and degrading treatment they experienced as workers at the Bisha Mine, a joint venture between the company and the government of Eritrea. The lawsuit explicitly detailed mistreatment suffered by the mine workers, including beatings, long working hours in the desert heat and low wages.[2] Eritrea is one of the world's most brutal countries, which has been dubbed the 'North Korea of Africa'. For years, the government had sought to capitalize on the country's immense mineral reserves. But despite this vast wealth potential, few foreign investors dared enter Eritrea's minerals market, due to its poor record on human rights and democracy.

As *Black Panther* enjoyed a long cinematic run, villagers living near the North Mara Mine in northern Tanzania were being subjected to beatings and shootings by mine security for attempting to enter the mine. Lawsuits filed in Canada and the United Kingdom against the mine's operators, Barrick Gold Corporation and its subsidiary, have laid bare the extent of the violence; at least seventy-seven people were killed by police and security forces hired to guard the mine. In Tanzania, as in Eritrea, the locals have not received significant socio-economic benefits from mining. What has taken place in both countries is emblematic of the reality faced by many mining-affected communities throughout Africa, and around the world.

The stark contrast between the fiction of Wakanda and the reality of African countries like Eritrea and Tanzania paints a dark picture of mining across much of the continent over the past one hundred and fifty years. In the early days of colonial expansion, it was the quest for natural resources that brought Europeans to Africa's shores, upending traditional knowledge and governance systems. From gold in the Gold Coast in the modern Republic of Ghana, to diamonds in the South African Transvaal, minerals were part of the political, economic and social currency of European conquest that displaced and dispossessed local populations.[3] The exploitation of Africa as a source of natural resource wealth for foreign powers did not end with colonization. Since the mid- to late-twentieth century, when formal colonial rule was abolished across much of Africa, local populations across the continent have continued to be marginalized in the global mining sector, garnering little benefits beyond minimum royalties and other related tax revenue.

Drawing inspiration from the *Black Panther* movie, it is interesting to re-imagine mining in Africa through an Afrofuturist lens, exploring an alternative reality that does not prioritize the interests of capital over those of communities and the environment. Such a reimagining of mining in Africa is vital as the world increasingly relies on minerals to combat climate change and transition to a carbon-neutral economy. Continuing with the status-quo operations of the global mining sector will likely only exacerbate the harmful effects of this industry. What vision for mining can Afrofuturism offer? *Black Panther* highlights three interconnected principles that could radically transform the future of mining in Africa and around the world: the disruption of hierarchies,[4] sovereignty and decolonization.

The realities of mining today can be traced back to the political and economic conditions of late-nineteenth- and early-twentieth-century colonization. By then, most of Africa, and the New World of the Americas had been largely colonized for the natural resource wealth they contained. Whether it was cotton and sugar cane in the Americas, or gold and diamonds in Africa, colonization drastically altered how land was demarcated, recognized and valued. A reimagined mining future must therefore dismantle several of the colonial principles that continue to define the modern conditions of mining and other resource industries. In practice, achieving such a transformation will be a challenging task, as certain economic and political actors benefit tremendously from the status quo. But even in the face of significant resistance, the sci-fi ideals of Afrofuturism allow us to consider the 'what-ifs',[5] and reimagine a world wholeheartedly different from the present.

Several harmful impacts have almost become synonymous with mining today. As an industry and practice historically built on the dispossession and displacement of Indigenous peoples and local communities, thousands have suffered negative human rights and environmental consequences of mining in their backyards. Mining is an inherently disruptive economic activity that upends the lands, people and environment in which it is taking place. The peoples whose lives and traditions are disrupted by mining are often granted little to no say in how the mining takes place, or whether it can even proceed in territories they have inhabited for centuries. At its core, an Afrofuturist vision of mining would reconsider the relationships of communities, states and corporations to challenge power dynamics and give more authority and jurisdiction to those who are negatively harmed by the practice. This shift in power necessitates disruption of the current hierarchies that privilege the interests of corporations and political elites over the concerns of communities.

The Afrofuturist vision of upended political and economic hierarchies portrayed in the *Black Panther* reflects an alternative reality where Africa was not colonized or subject to interference by Western powers. Unlike most African countries, Wakanda remained untouched by empire, allowing it to maintain independence and autonomy within a global political economy dominated by former colonial powers. The country and its people went about their business because the world did not care about a small, unimportant monarchy in Africa that seemingly offered little of value to the outside world. But when the world learned of Wakanda's vast vibranium deposits, outside powers rushed in to secure their own supplies of this valuable resource.[6] By the time the world took notice, Wakandans were able to defend their supply of vibranium because they had already used the mineral's power to create the means to protect themselves and their interests.

As in Wakanda, some communities are attempting to challenge the hierarchies that dominate the global mining industry, increasingly asserting their rights to ownership and access to the lands on which mining companies seek to operate. Community consultation, and, in some instances, obtaining consent, has become a significant part of the mining sector's social license to operate and of its environmental, social and governance (ESG) priorities. Litigation has also been used in some cases by communities looking to protect their land rights. In landmark cases in South Africa and Canada, Indigenous communities have taken governments to court to reaffirm their constitutional rights to be consulted.[7] In the South African case, the Xolobeni people of the Amadiba area in the Eastern Cape successfully asserted their right to free, prior and informed consent (FPIC) in relation to any resource projects on their land. Similarly, the Gitxaała and Ehattesaht First Nations in British Columbia, Canada, were recently successful in challenging the constitutionality of the province's mineral license system, which grants mining licenses on their traditional territories without due consultation. Such legal challenges are likely to become increasingly common in the future, and their outcomes will have a significant impact on the global mining sector.

Beyond disrupting political and economic hierarchies, the Afrofuturist principle of sovereignty could also radically transform the future of mining around the world. In the Afrofuturist sense, sovereignty goes beyond the nation-centric understanding of political independence that has shaped the world over the past six hundred years. Rather, the Afrofuturist vision of sovereignty involves 'reclaiming approaches, methodologies, and ways of thinking'[8] that predate colonial interference. In essence, sovereignty entails looking forward by first looking back to reclaim traditions, identities and cultural practices that were lost due to enslavement and colonization.[9]

By reclaiming the past, the future can be built upon systems freed from historical experiences of political and economic oppression.

Black Panther reveals, in vivid form, what sovereignty and reclamation could look like in a mineral-rich country. Wakanda's use of vibranium was rooted in traditional knowledge intended to advance the well-being of all citizens. The material benefits of vibranium were not solely enjoyed by those who were able to wield power. Rather, the mineral and the technology it enabled was used equitably to advance the welfare of all those under the jurisdiction of the ruling monarchy. Vibranium was of the people's land and was used for the people. The film's seamless blending of past traditions with present governance and future ambitions illustrates sovereignty as an Afrofuturist ethos. Through the portrayal of a traditional democratic system of governance representing all the people in Wakanda, *Black Panther* makes it clear that sovereign peoples, using their self-determined processes, are best positioned to make decisions affecting their present and future lives. By portraying traditional approaches to governance and decision-making, Afrofuturism affirms sovereignty as a means to recover and restore a lost past.

Modern mining communities around the world are increasingly exerting their own sovereignty, returning to their history and traditions to shape the present and future. As an example, some Indigenous peoples in Canada and around the world have begun insisting that mining companies engage with them on their terms through traditional governance systems that pre-date colonization and may be distinct from state-recognized methods. Several First Nations in Canada have developed their own environmental assessment processes based on traditional knowledge, Indigenous laws and historical relationships with the environment. Similarly, Indigenous peoples in Latin America and Africa have resurrected traditional governance systems, rather than accepting state-appointed representatives and processes. This approach fundamentally recognizes the rights of Indigenous people to self-governance, as outlined in the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP).[10]

The final lesson we can learn from the Afrofuturist vision is grounded in decolonization. This not only considers the 'what-if' scenario in which colonization never occurred, it also imagines the active 'undoing' of existing colonial structures. Such decolonization has attracted significant recent attention, as institutions, individuals and corporations seek to demonstrate their commitment to Indigenous peoples in the spirit of truth and reconciliation. In Afrofuturist art and literature, decolonization is often depicted through a complete reordering of the status quo, and the restoration of Indigenous knowledge systems and ways of being.[11]

In *Black Panther*, Wakanda is synonymous with decolonization. Having never been colonized, decolonization was unnecessary in Wakanda itself; its vibranium mines, processing and production relied exclusively on traditional Wakandan knowledge and technological systems. Wakanda used its vibranium-generated wealth and technology to support decolonization in the African diaspora. The re-imagined flow of aid, resources, technology and knowledge from Africa to the rest of the world represents an active form of decolonization. This Afrofuturist vision of society elevates Indigenous knowledge to ensure prosperity and collaboration for globally marginalized communities.

In today's world, decolonizing mining is perhaps the most difficult Afrofuturist principle to achieve. Ownership, control and access to land are central considerations of mining; only a small fraction of current mining activities occurs on land that is fully controlled by Indigenous peoples and mining-affected communities. Without control of land resources, it will be difficult for such communities to decolonize the mining sector and fully restore their legal, political and economic rights. Entrenched political and economic interests in mineral-rich countries around the world will continue to challenge decolonization in mining. A truly decolonized Afrofuturist vision for mining would require nothing less than the complete reordering of contemporary legal and economic systems. And that is no small task.

Afrofuturist literature and art are treated as fantasy and speculative fiction. No doubt, most of the world envisioned by Afrofuturism does not exist today.

Achieving this vision will require a radical transformation of society as we have come to know it. Such radical transformation is difficult, sometimes seemingly impossible, to achieve. But imagining a radical future is the necessary first step. As the world requires ever increasing amounts of mineral resources, the global mining industry must evolve to avoid the harms of the past. Communities around the world impacted by mining will likely lead the way forward. Indigenous peoples and mining-affected communities around the world are reclaiming and asserting their traditional rights and knowledge to shape new approaches in the mining sector. Afrofuturism offers further understanding of what a future mining industry could look like. The principles of self-sufficiency, sovereignty, self-determination and decolonization should not be restricted to a Hollywood fantasy world. They are necessary steps on the path to a better future for mining.

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The Face of Mining

Carol Liao

The seminar room is too small for the growing crowd of people who pack themselves in, ever tighter, hoping to find a spot with an unobstructed view of the front. It is December 2018, before the COVID-19 pandemic, when a warm, crowded room was fathomable without a second thought. One group of people, the lucky ones who arrived early, is seated around tables arranged in a circle. Another row of latecomers is pressed tightly along the walls. At the invitation of a friend, I had made a special trip from Vancouver to the University of Victoria to attend a talk on China's investment in the green economy. The presenter is a newly minted PhD graduate whose doctoral research focused on a Kenyan mine acquired by a Chinese state-owned enterprise (SOE). Her talk showcases some of China's accomplishments in building community-engaged green energy infrastructure, and the message feels surprisingly uplifting—there is a lot to be said about green improvement, and China is seemingly emerging as a globally-important player in the clean energy transition. If you had left the room at that moment, you would have thought all was rosy.

Then a woman in the audience raises her hand. She introduces herself as a PhD student from Kenya and begins asking some pointed questions that reveal a different side of the story. 'What about Chinese mining companies controlling the economic livelihoods of Kenyans?', she asks, 'and what about the enormous financial debt and

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debt-trap diplomacy that the Kenyan government now finds itself in with China?' What followed was a riveting discussion about the challenging future of global mining. As interesting as the discussion itself, were the people engaged in it—two young women, one from China and the other from Kenya. Together, they represented a glimpse into the changing face of mining, an industry that was once dominated by the West, with a long history of colonialism, white supremacy and misogyny.

Today, five years after that seminar, the geopolitical arena has changed rather significantly. China's ascendancy as a global superpower has forced the mining industry and its observers to adapt to shifting and often uncomfortable realities. The country's growing investment and soft power around the world, particularly in Africa and Latin America, is redefining the key players in the global mining sector. But the stage itself and its notable actors still include some big question marks. How does an industry reconcile a racist, colonial history with a rapid geopolitical shift in global power to China—what some are calling 'a new colonialism'? The face of mining is trying to undergo a significant makeover, but entrenched power disparities within the industry have ensured that some groups remain at the margins.

The very same month of the seminar, Chinese Huawei executive Meng Wanzhou was arrested in Vancouver for financial fraud, and nine days later, Canadians Michael Kovrig and Michael Spavor were detained in China. These arrests set off a chain of diplomatic disputes that left Canada–China relations in tatters, abruptly ending the growing cooperation the two countries had been enjoying in legal and economic matters. Layered onto these political tensions, a global pandemic originating from Wuhan, China, forced the world into crisis, lockdown and transition. Donald Trump, then-President of the United States, touted COVID-19 as the 'Kung flu' and 'China virus', and anti-Asian hate crimes in North America reached record heights.

In the wake of the Huawei affair, trade woes between Canada and China increased significantly. By 2022, Canada had introduced new rules governing foreign investment in critical minerals, with a particular focus on restricting the influence of (Chinese-dominated) SOEs in this sector. Tensions were further heightened by subsequent accusations of foreign influence and meddling into Canadian elections, with Canadian politicians of Chinese descent finding their loyalties increasingly, and offensively, questioned.[1] The presence of suspected Chinese surveillance balloons over Canadian airspace in 2023 did not help matters.[2]

As a resource-rich, but relatively small, player on the world stage, many worry that Canada's growing conflicts with China will leave it poorer, and less able to address long-term global threats such as climate change.[3] The Canadian government's 2022 Indo-Pacific Strategy (IPS)—with its notable shift away from the term 'Asia' to 'Indo-Pacific'—is the country's first policy document focused on expanding trade, security and green economic partnership with the region's forty nations. Collectively, these Indo-Pacific countries are projected to host a third of the world's middle-income population by 2030, and half of the global gross domestic product (GDP) by 2040.[4] Both China and India feature prominently, but very differently, in the IPS. India is portrayed as a cheerful and promising ally, and a noteworthy counterweight to China, the troublesome, long-awakened giant.

Not surprisingly, critical minerals are conspicuous in Canada's 2.3 billion-dollar IPS. In terms of global demand for minerals, there is 'no market more important than China'[5] and a significant portion of the IPS focuses on how Canada will negotiate with that country, at a time when Western nations are looking to shift their industrial supply chains towards more 'like-minded' and 'friendly' partners. Yet, many of the most important drivers of climate change are found in China. With an immense population quickly shifting into the middle class, and hundreds of millions of people adopting consumption-driven lifestyles, China is placing growing demands on global energy supplies. By 2035, little more than a decade from now, the Asian Development Bank predicts that the demand for electricity in India and China alone will exceed 75% of the world's total.[6] These energy needs are increasingly met by coal-powered plants, producing high greenhouse gas (GHG) emissions that significantly contribute to climate change.

In the face of an ongoing climate crisis linked to global GHG emissions, the political and economic relationship between China and Canada sits at a precarious juncture. Canada is a global powerhouse for mineral resources, with several large mining companies and thousands of small 'junior' exploration companies. Most of these mining and mineral resource companies are based in Toronto and Vancouver, cities which both have large Asian populations. Vancouver is also a major international port city, situated on ancestral and unceded First Nations territories. The reach of Canadian mining companies extends far beyond Toronto and Vancouver, with mining and mineral processing operations spread across the world—collectively these companies contribute to Canada's position as one of the world's top ten largest producers of platinum, titanium, gold, nickel, cobalt, iron ore, lithium and copper. Building on this current position, the Canadian Critical Minerals Strategy (CMS), released by the federal government in 2022 (the same year as the IPS), seeks to establish Canada as a global supplier of choice for critical minerals needed for electrification, wind turbines and solar panels, enabling the country to play a leading role in the clean energy transition.[7] At present, the CMS remains aspirational, and realizing its vision will require significant international cooperation to develop the entire value chain from minerals to refined metal. But recent events suggest that economic and geopolitical factors may pose increasing challenges to such cooperation in the face of mounting governmental interventions into Canada–China business relations.[8]

Climate change is forcing fundamental shifts in how companies around the world conduct their business, creating systemic and interconnected risks that amplify financial uncertainty. To its credit, China has anticipated many of these risks, pre-emptively securing global critical mineral supply chains through its Belt and Road Initiative and other efforts. Over the past several decades, China has slowly, but surely, acquired about 60% of worldwide critical mineral production, buying up mines like properties in a game of *Monopoly*. The country now also accounts for the vast majority—about 85%—of critical mineral processing capacity (the conversion of raw mining products into refined metals used in various applications). Chinese SOEs have taken ownership positions in countless mining companies across five continents. For instance, China now owns almost all of the producing mines in the Democratic

Republic of Congo, which supplies 70% of the world's cobalt.[9] Chinese mining and battery companies are also behind most of Africa's lithium projects, as well as major mining projects in Latin America exceeding one billion US dollars.[10] By 2035, it is estimated that China could secure one-third of the world's lithium mining capacity.[11] These ownership positions are not limited to the developing world. Chinese SOEs are the biggest single shareholders in Canada's three largest mining companies: Teck Resources Limited, First Quantum Minerals and Ivanhoe Mines.

The rise of China as a dominant force in the global mineral supply chain has been facilitated, in large part, by governments and corporations around the world hungry for foreign investment. So why is there now so much concern about the dominance of Chinese SOEs?

Surely, other global superpowers like the United States would have beaten China to the punch if they had the foresight and determination to corner the world's market on critical minerals. Is it mainly the economic stress of failing to capitalize on opportunity that is driving angst over China's growing dominance of the critical mineral supply chain? Or perhaps the vulnerability of economic dependence on an authoritarian state? Or maybe there is something else; the sense that an Asian country, and not the great Western powers, might lead the world towards renewable energy systems.[12] American commentary on China's dominance of the global mining sector routinely invokes Orientalism stereotypes, and assumptions that African nations would certainly prefer to deal with Uncle Sam as opposed to Yellow Peril.[13] But the United States, itself, also has a violent history of pillaging and corruption in its search for natural resources.[14] And the track-record of other competing countries has also not been particularly good, with several notable legal cases exemplifying egregious human rights abuses by Canadian mining companies in developing countries. Over the past century, the history of the global mining industry has had more than a few examples of violence and racism.

Alongside economic and political considerations, there has been increased pressure for a new post-pandemic era that embraces a green recovery, while also promoting social justice, equity and anti-racism. In the face of mounting reputational risks and social movements including Truth and Reconciliation, #MeToo, Black Lives Matter and Stop Asian Hate, the mining sector has been obliged to take a hard, unflinching look at itself. Mining companies have begun to reckon with their historic lack of women, Black and Indigenous leaders, and growing expectations regarding free, prior and informed consent (FPIC) for Indigenous rightsholders. Advocates argue that the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) should be more than a symbolic statement—its words should hold the global mining sector to higher standards of engagement with Indigenous peoples from whose territories they extract significant profits.

The statistics on gender, Indigeneity, race and other forms of diversity, already stark within the corporate sector, are particularly egregious in mining, where underrepresented groups are often counted in single digit percentages. There are complex historical reasons underlying this reality, including exclusionary colonial practices, and systemic biases in the fields of science, technology, mathematics and engineering.[15] But understanding the 'why' does little to alleviate the daily realities of this underrepresentation, or its ripple effects on racial dominance and inequity. With its acquisition of Western mining companies and large operating footprint in developing nations, China has disrupted this historical trend, significantly increasing racial (if not gender) diversity in the global mining sector. Nonetheless, significant interracial power disparities persist.

Reflecting on the discussion emerging from that 2018 seminar, many intersectional issues arise from China's growing dominance of the world's mineral supply chain. In the case of Africa, it is questionable how much benefit is actually received by those countries where China is a major investor. Mining contract concessions are typically opaque, and often heavily tilted in China's favour.[16] While there is no doubt that Chinese mining companies have created significant local employment opportunities (African employees make up 70–95% of the workforce in these companies), China's resources-for-infrastructure agreements have often sent billions in minerals to China, with comparatively little local infrastructure actually developed from these deals.[17] Critics argue that China deliberately increases its political leverage by lending large sums to African countries that will never be able to repay the loans, as was noted by the young Kenyan scholar at the seminar. But the reality is somewhat more complicated; over the past two decades China has restructured or refinanced fifteen billion dollars of debt and canceled 3.4 billion dollars in debt in Africa. Nonetheless, accusations of financial exploitation in Africa, said to have 'infuriated' China, led to its decision, in 2022, to cancel twenty-three loans to various African countries.

China's role in the global mining sector may be on the cusp of significant change. The country's economy has begun to destabilize, with record-high youth unemployment and a property market in crisis. This economic trouble is having ripple effects across Asia, which is now facing its worst economic outlook in over half a decade.[18] In response, China is ramping up its coal production to meet energy demands, and actively divesting from the Canadian mining sector in the face of tightening foreign ownership restrictions.[19] At the same time, China's accelerated investment in the green economy worldwide has greatly reduced renewable energy costs, showcasing the nation's unparalleled ability to scale up zero-carbon generation. Even as its coal production increases, China continues to lead the world in installed wind, solar and nuclear capacity.[20]

Some are calling the future of critical minerals 'the New Cold War', as countries battle for ownership of resources and prepare for a net-zero carbon future.[21] As this global economic competition unfolds, the impacts of climate change and mining are likely to expand around the world into previously unaffected areas. Amidst a global climate emergency and sustainability crisis, it seems clear that the economic situation in China will have a major impact on the mining sector. But what that means, in practice, is far from certain.

As we look towards the future of mining, it is important to keep our eyes on the bigger picture. A stable climate underpins the development of our human civilization; climate data inform where it is safe to live, where we can grow food and where to build critical infrastructure. Climate change also continues to exacerbate inequality, with disproportionately negative effects on Indigenous and racialized people, women and the Global South.[22] Within the power vacuum of a global critical minerals sector and a rapidly accelerating climate crisis, how do we combat the ongoing, harmful effects of racism, misogyny and colonialism? One thing is clear. No sole country can address climate change on its own; international cooperation is imperative, and this requires representation of many different faces and voices around the table. The trick will be in supporting the national security and economic interests of countries around the world, while maintaining the vibrancy of international partnerships and trade. Whether we like it or not, the future of mining is deeply intertwined with the wicked problems of climate change and social inequity. As we seek a responsible path forward, dialogue addressing these complex geopolitical and intersectional issues must continue, even if it is in a warm and crowded room.

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Indigenous Mining: Ancient Wisdom and Modern Practice

Melanie Mackay

As the sky settles in the warm glow of the autumn twilight, a family settles down after a satisfying dinner of roasted venison and root vegetables. The lighting around them takes on the flickering glow of the fire as the children slowly get ready for bed. One family member, an artist, settles close enough to the fire to work by its soft light, gently sanding a piece of jade, smoothing the bumps and ridges. The jade will eventually be fashioned into a chisel meant for woodworking and carving. As it slowly takes form in the dancing light of the fire, the jade reflects different shades of green, from chartreuse to mint to emerald.

In another village, by a similar firelight, a mother cradles her crying daughter as she applies a healing clay ointment to a cut on the child's arm. Time and time again, the clay has proven itself useful in healing cuts and wounds. As a child, the mother applied the clay ointment to many of her own cuts and scrapes. Her mother, the child's grandmother, also used it as a medicine to help her ailing stomach. As the clay is applied to the child's cut, her cries stop, and she soon falls asleep in the loving arms of her mother.

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One might imagine that the scenes above are set in the Middle Ages, somewhere in Europe perhaps, or maybe Asia. In fact, they represent people who lived many thousands of years ago on the lands that we now call British Columbia, Canada. The scenes describe First Nations using minerals for sanding and carving, and for medicinal purposes. They provide a glimpse into the deep connection of Indigenous peoples with Earth's resources.

Over the past two centuries, Indigenous knowledge of Earth's resources has been marginalized in colonial societies. Today's students in Earth sciences and mining learn their subjects through a distinctly European lens, with a focus on published scholarly works. In the Western scientific tradition, the Danish geologist Nicolas Steno (1638–86) is famous for his studies in the 1600s dating rock layers, while James Hutton (1726–97), a Scottish naturalist, is known as the 'father of geology' for his work observing rocks in the 1700s. And in the early nineteenth century, the English engineer and geologist, William Smith (1769–1839), produced the world's first modern geological map, depicting the distribution of surface and subsurface rocks (and coal) across the British Isles. Smith's efforts were the subject of Simon Winchester's 2001 book, *The Map that Changed the World*.[1] This book, along with many other written works and maps, have shaped Western concepts of geology and mineral resources. They do not, however, tell the whole story.

Traditionally, Indigenous knowledge and science were verbally passed down from generation to generation over thousands of years, leaving no written record behind for the future. This oral tradition sits alongside another form of Indigenous knowledge that is inherent within the individual, and not explicit, measurable or recordable. These Indigenous philosophies interweave the spiritual, the natural and the self into a holistic worldview where the emotional, spiritual, cognitive and physical cannot be separated.[2] With the arrival of European colonial powers, the production and intergenerational transmission of explicit and inherent Indigenous knowledge was gravely threatened.

In Canada, it is thought that between 225,000 and 375,000 Indigenous peoples died because of European colonization. Some estimates are as high as 1.9 million. In North, Central and South America, it is estimated that more than fifty million Indigenous people (about 90% of the existing population) died after the arrival of Europeans in 1492. This 'Great Dying' of Indigenous people had a significant effect on land use and forest cover. As the population plunged, lands were abandoned, and the pre-existing vegetation grew back, creating a natural carbon sink that contributed to a decrease in atmospheric carbon dioxide (CO_2) associated with the so-called Little Ice Age.[3] Beyond its profound social and ecological impacts, the catastrophic effects of colonialism on First Nations in the Americas (and globally) also led to the loss of invaluable scientific knowledge recorded in the minds of Indigenous peoples. This lost knowledge encapsulated Earth history over thousands of years, passed on across countless generations.

Several examples serve to illustrate Indigenous knowledge in the context of Earth's mineral resources. In the scenes depicted above, the artist sanding jade by the firelight uses a rock type known as schist, which contains the silicon-containing mineral garnet. Garnet provides an abrasive texture that is well suited to sanding and polishing. Today, garnets are used in sandpaper and industrial sandblasting. The jade being fashioned into a chisel does not break apart easily, making it well suited as a cutting surface. Evidence for the use of garnets and jade was discovered at an archaeological site of an ancient Stó:lō Nation village in the upper Fraser Valley in British Columbia, which was occupied between 2,500 and 2,000 years ago. Even earlier evidence of jade and garnet use in Indigenous cultures comes from creation stories that pre-date many archeological sites.

The mother tending to her child represents the Heiltsuk Nation on the central coast of British Columba. The 'healing clay' she used was deposited during the Last Ice Age and has been known to the Heiltsuk Nation for thousands of years as a topical ointment to treat cuts, wounds and skin ulcers. It was also rolled into tiny balls and taken every day like a vitamin, helping to treat stomach ailments. The clay was a valuable commodity that was traded to other tribes outside the Heiltsuk territory. A study at the University of British Columbia found that the clay has antibacterial and antifungal properties that are effective in treating infections by multi-drug resistant bacteria commonly found in hospitals, as well as the bacteria commonly infecting cystic fibrosis patients.[4] The clay contains a rich diversity of bacterial taxa which, along with various metal ions, are thought to contribute to its healing properties.

There are many more examples of First Nations in British Columbia using minerals in their everyday lives. In addition to garnets, jade and clays, Indigenous people have used quartz crystals, geodes, mica, ochre, copper, obsidian, graphite, coal and opal, to name a few. They have also used a wide variety of rocks and minerals for medicinal, ornamental and fabrication purposes, including jewelry, blades, spear points, arrowheads, houseware, paint, medicine and grinding tools. Indigenous use of native copper (pure copper in a metallic state) is a particularly interesting case in point. Today, massive quantities of copper are used around the world in the wiring of electrical devices, and the demand for this metal is expected to grow significantly over the coming decades.[5] Thousands of years ago in northwestern British Columbia, the metal represented wealth and status, and had both supernatural and healing roles in First Nations culture. Copper featured prominently in many myths and legends told by First Nations, including one story from the Tsimshian people, where salmon were magically transformed into this metal. According to this legend: ‘Our people call this copper “living” copper. They say that spring salmon went up this river, and when they reached the deep water at the upper part of the river, the salmon became copper’.[6] The legends of the Kwakiutl and the Nuxalk First Nations also connected copper to the supernatural world. The legends speak of Quomaqwa, an undersea deity, that was the supernatural source of copper, living in a copper house surrounded by a wealth of copper possessions. The Kwakiutl and other Indigenous peoples also understood that copper had curative properties and associated it with the quality of “purity”. Copper implements were handled with respect, and reserved for specific purposes, such as the use of three-pronged copper needles for ceremonial tattooing by the Haida. These uses of copper pre-dated modern understanding of the anti-microbial properties of this metal. Today, thousands of years later, the metal is commonly used as a ‘self-sanitizing’ substance in health-care facilities and various public, commercial and residential settings.

Over thousands of years, Indigenous people developed methods to mine mineral resources from the earth. The Arrowstone Hills provide a well-known example. This quarry site exists in south-central British Columbia in the traditional, ancestral and unceded territories of the Secwépemc and Nlaka’pamux Nations. These Nations mined a silicon-rich volcanic mineral known as dacite, which was used to make toolstones. The high-quality dacite deposits at Arrowstone Hills are fine grained and black in color, with physical properties that make them hard, yet easy to shape. The dacite deposit would have been visited year-round, excavated by hand from pits measuring several meters across. Archaeological surveys of the area show that tools were often produced right at the mine site, eliminating the need to transport large rocks away from the mountain. The finished dacite tools were widely traded and have been found 200 kilometers west of the Arrowstone Hills, on a site along the Harrison River. The dacite deposit was large enough to provide First Nations with an unlimited supply of toolstones during the 11,000 years prior to European contact, and over the subsequent half millennium. Today, dacite is still collected from Arrowstone Hills for tool shaping by First Nations.

The Tahltan Nation in northwestern British Columbia have also depended on Earth’s minerals for thousands of years. Mining has always been part of Tahltan culture, and this Nation has historically prospected for and mined obsidian, a silicon-rich mineral derived from volcanic lava. Tahltan obsidian was fashioned into tools and traded with other First Nations. Studies of the chemical composition of obsidian artifacts have identified material from Tahltan territory in archaeological sites as far away as Alberta, Canada. Today, mining continues to be an important part of the Tahltan Nation. Their territory is in a region of British Columbia known as the Golden Triangle, which hosts a 500-kilometer belt of copper, gold, silver and other precious metals. The business arm of the Tahltan Nation, the Tahltan Nation Development Corporation, provides services to five different mineral projects and mines, and many

Tahltan members work on these projects. Increasingly, the Tahltan have exerted their constitutional rights over the resources situated on their territories. And through this activity, they are working to reverse more than a century of destructive colonial mining practices.

In the early years of gold-rush mining, there were few regulations. Mineral deposits were exploited in a haphazard fashion, leaving behind abandoned sites with catastrophic environmental impacts on Indigenous lands. In British Columbia alone, over 1,700 abandoned mine sites have been classified as having the potential to generate acid leaching of toxic metals into the environment,[7] with significant impacts on watersheds and traditional food sources, including salmon. These environmental threats come from the large-scale accumulation of waste rock piles, derived from colonial mining operations based on the principle of 'bigger is better'. Many current surface mining activities usually include large open pits reaching kilometers in width and hundreds of meters in depth, where thousands of metric tons of rock are mined each day.[8] The large size of these mining operations has been driven by an 'economy-of-scale' approach to the provision of infrastructure (power lines, roads, buildings, tailings storage facilities) and equipment (shovels, excavators, haul trucks), where large size and scale are leveraged to spread fixed costs over a significant output.

By comparison with modern operations, traditional Indigenous mining sourced small quantities of materials from streams and riverbeds, rock formations or mineral deposits, with limited need for large excavations or hazardous waste piles. As the world's largest, richest and most accessible deposits become increasingly rare, the mining industry will be forced to focus more attention on smaller, lower-grade and remote deposits in the future.[9] Perhaps First Nations could contribute to the development of a new model for mining, which incorporates the development of small mineral deposit resources. Such a model requires active participation, and indeed leadership, of Indigenous peoples in the future mining sector. At present, several significant challenges stand in the way of this goal.[10]

In British Columbia, a key challenge facing the mining sector is the outdated legislation regulating mineral claims and staking. The provincial Mineral Tenure Act, which dates back to the early days of the gold rush, allows any person today with less than one hundred dollars and an internet connection to stake mineral claims without regard to First Nations land sovereignty.[11] When claims are selected for staking, paid for and registered, the permit holder is given the right to enter and occupy an area for the exploration and development of mineral resources, even if the land holds potential cultural or spiritual importance to Indigenous landowners. The duty to consult First Nations is not triggered until an exploration application is submitted to the government, creating confusion and conflict, and leading to the false conclusion that mining rights trump Indigenous rights.

Recently, the Gitxaała and Ehattesaht First Nations of northern British Columbia initiated a legal case against the province's Chief Gold Commissioner, seeking to overturn several mineral claims made within their territory under the Mineral Tenure Act. The legal challenge cited a failure of the mineral claimants to achieve free, prior and informed consent (FPIC) of Indigenous landowners, and highlighted the potential negative impacts of mineral exploration on traditional and cultural practices. The Ehattesaht have a spiritual connection to crystals within their traditional territory, while the Gitxaała have collected ochre at a traditional gathering place called Ksgaxlam, where legends tell of supernatural dens. The Gitxaała and Ehattesaht argued that these important spiritual connections to the land would be disturbed through mineral exploration. The court agreed.

In its ruling, the British Columbia Supreme Court concluded that the Mineral Tenure Act does not include an appropriate consultation framework, and violates the government's constitutional obligations to consult Indigenous peoples with rights and title prior to the granting of mineral claims. The province has been given eighteen months to revise the mineral tenure system and will do so in consultation with First Nations and the mining industry. Many now worry that the eighteen-month period prior to the anticipated change in legislation will open a frenzy of new mineral staking claims. The next few months could significantly shape the long-term future of mineral exploration and mining in British Columbia, with ramifications across Canada and beyond.

Despite the outdated Mineral Tenure Act, several mining companies and First Nations have collaborated proactively in the development of new mineral projects in British Columbia. As an example, the Tahltan Central Government has built a new partnership with Skeena Resources Limited, a Canadian mining and mineral exploration company that is working to re-activate a legacy mining site at Eskay Creek in Tahltan territory. The company has developed several initiatives to support this collaboration, including financial support for community-based programs, and the establishment of mentorship and entrepreneurship programs with Tahltan youth. In addition, the company relinquished several mineral tenures to help establish a nature conservancy in Tahltan territory. In turn, the Tahltan Central Government has invested five million dollars into Skeena Resources. In a news release, the president of the Tahltan Central Government said 'Ownership provides the Tahltan Nation with a strong seat at the table as we continue our pursuit towards capacity building and economic independence for the Tahltan people'.[12]

Two metallurgical (steelmaking) coal exploration companies have gone even further in developing partnerships with First Nations in British Columbia. NWP Coal Canada Limited has signed an agreement with Yaq'it ʔa·knuqⱡi'it (Tobacco Plains Indian Band) whereby Yaq'it ʔa·knuqⱡi'it will act as a regulator and reviewer of the Crown Mountain Coking Coal Project. This oversight role for the Yaq'it ʔa·knuqⱡi'it implies that the Band can effectively shut down the project if they are not satisfied with the results of the Environmental Assessment. This represents a profound shift in the industry, as First Nations currently do not have veto rights on projects, and mine permits can be issued even in the face of community opposition. North Coal is another exploration company that is working to develop a steelmaking coal project in Yaq'it ʔa·knuqⱡi'it territory. The Band has developed a letter of intent to form a partnership with North Coal and its owner, Pacific Road Capital, to jointly develop the Michel Project. The partnership is based on the principles of co-ownership, co-management and co-governance. Chief Heidi Gravelle was quoted as saying 'This partnership has been built on mutual respect, collaboration, and integrity, while working with our community members, elders, and leadership to create a sustainable future built on strong traditions and culture. By working together with Pacific Road Capital, we will have set a precedence for other companies looking to partner in economic ventures on unceded territory'.[13] This project, and others, are laying the foundations for new mining business models in British Columbia, providing examples of new collaborative opportunities between mining companies and First Nations.

For thousands of years, First Nations have prospected for minerals and metals in lands now known as British Columbia, and in other territories around the world. Rocks and minerals were in high demand and used in many aspects of Indigenous life, from medicinal and 'purity' purposes to spiritual and cultural practices. Indigenous mining was driven by local supply and demand, and oral knowledge and technologies were passed down over countless generations. Although colonialism has had led to the loss of significant Indigenous knowledge, it is not too late to learn from the knowledge that still exists. At a time when innovation is needed in the mining industry, incorporating Indigenous perspectives into mining theory and practice could promote more sustainable mineral extraction, with lower environmental impacts and greater social and economic benefits for communities. New exploration companies are showing the world that deep collaboration with First Nations can exist in the development of mineral resource projects. In any path forward, the mining industry will need to embrace more holistic approaches to mineral development, incorporating Indigenous cultural, spiritual, environmental, social and economic values. Such an approach will help restore long-standing relationships between Indigenous peoples and the resources on their territories.

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Can Small Mining Be Beautiful?

Marcello M. Veiga and J. Alejandro Delgado-Jimenez

In the 1973 book, *Small Is Beautiful: A Study of Economics as if People Mattered*, the economist Ernst Friedrich 'Fritz' Schumacher outlined a vision for future sustainable development. He emphasized the use of local resources, and criticized the nascent process of globalization he saw unfolding around him. Schumacher embraced the use of small-scale technologies, and argued against the mainstream notion of 'bigger is better'.[1]

Half a century later, globalization, built on large-scale industries, has become the de facto economic imperative for the supply of all major commodities, including minerals needed for renewable energy and other technologies. But even before the 1970s, the discovery and extraction of mineral deposits was dominated by so-called Conventional Organized Mining (COM) companies, medium to large multinational corporations with operations spread around the globe. Today, COM companies employ as many as four million people globally, and have annual revenues between two and three trillion US dollars (on par with the gross domestic product (GDP) of Germany and France). Much of this profit is distributed among a small number of particularly large companies, some of which are among the biggest corporate entities in the world. One American company, Newmont Corporation, has about four thousand metric tons of gold reserves (almost 8% of the total global reserves).[2] The Brazilian company,

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Vale, has iron ore reserves of approximately thirteen billion metric tons (about 7% of the global total), producing 320 million metric tons in 2023.[3] With their significant market shares, COM companies control most of the mineral titles on Earth. For this reason, they exert a strong influence on global mining practices, directly impacting commodity prices and even geopolitics.

The dominant economic model for COM companies relies on the discovery or acquisition of large, 'word-class' ore deposits. The discovery and development of such deposits requires enormous up-front capital investments, and depends on an 'economy-of-scale' approach (the notion of *bigger is better* that Schumacher criticized). But increasingly, the main challenge to this economic model lies in finding large deposits, which are becoming rarer and more inaccessible, buried deeper underground.[4] Take gold, for example. In 2010, approximately five gold 'mega-deposits' with more than six million ounces (oz) of gold were discovered. In 2018 and 2019, no such large deposits were found, although many smaller deposits were identified, including thirteen new deposits ranging from 0.1 to 1 million oz of gold, and over three hundred deposits with less than 0.1 million oz.[5] Looking for 'elephants', the geologists instead found lots of 'mice', which are not large enough to justify large up-front investments of COM companies. And even with a significant investment in geological exploration, the discovery of potential mineral deposits often does not translate into a significant number of new mines entering into operation. On average, out of every 10,000 mineral exploration projects, only one becomes a large-scale working mine.[6]

In the face of dwindling mega-deposits, the COM companies have responded by putting their faith in technological innovation, and in market forces that keep commodity prices high. Most of these companies focus on technical approaches to develop new or improved methods for mining exploration and processing of complex ores. These include automated, deeper underground mining methods,[7] seafloor mining[8] and the use of microbes to access low-grade ore deposits.[9] Even asteroid mining has attracted the attention of COM companies.[10] These technological approaches are used to justify the strategies of the COM companies, but they don't necessarily address other environmental, social and geopolitical realities that might constrain large-scale mineral exploration and recovery. They also don't address the significant time-lag from the discovery of a large mineral deposit to the production phase. In some cases, this delay can range from fifteen to twenty years, and significantly longer if there are disputes with local communities. Such long delays make large COMs slower to respond to altered demand and potentially rapidly shifting market factors, with significant implications for commodity prices.

Sometimes, large proposed mining projects can be shut down all together, often over significant environmental concerns among potentially impacted communities. In the municipality of Tambogrande, Peru, for example, the Canadian company Manhattan Minerals obtained a reserve of close to fifty million metric tons of copper, zinc, gold and silver ore, proposing a mine to extract one billion dollars' worth of minerals. The community was concerned about insufficient revenue sharing and inadequate services associated with the proposed mine, and also about potential impacts on local lime and mango production (the region produces more than half of the country's limes). In addition, half of the 16,000 town inhabitants were to be displaced by the open pit. In a referendum, 93% of community members expressed opposition to the mining project, and the company left the town two years later with a sixty-million-dollar loss.[11]

All types of mining operations have potential negative impacts on the environment, and on the health and social fabric of local communities.[12] But the focus of most environmental groups has been on the COM operations, whose large-scale projects have the most significant potential impacts. In 2015, a tailings dam breach in Brazil released forty-four million cubic meters of iron ore waste rock, flooding the downstream villages of Bento Rodrigues and Paracatu de Baixo. The resulting pollution spread over more than six hundred square kilometers, and nineteen people lost their lives in the flooding. Four years later, also in Brazil, the failure of the Brumadinho tailings dam unleashed a mudflow that destroyed houses, roads and farms, killing 270 people and creating a devastating environmental catastrophe.[13] Such environmental impacts fall disproportionately on vulnerable communities in remote or developing regions. They are one of the most significant barriers to the acceptance of large-scale mining operations.

With its focus on finding mega-deposits, the COM sector does not take into consideration the mining of metals from a large number of small deposits found every year by geologists. The majority of these deposits are discovered by local prospectors or junior exploration companies, many of which are located in Canada. These small companies explore and drill small deposits using sophisticated geological expertise. They do not, however, typically move beyond the exploration phase, leaving the development and operation of mines to others. A number of these small deposits could be profitable given sufficiently high metal grades, but the low tonnage does not entice investors interested in large discoveries and financial windfalls. If large COM companies have interest only in large deposits (elephants), and if the junior companies are not interested in mining small deposits (mice), who will do it?

The answer may lie in artisanal mining. This informal economic activity, which directly involves forty-five million people,[14] is based on the use of rudimentary techniques to extract and process more than thirty different types of minerals, with a particular focus on gold, diamonds and other gemstones, but also increasingly on critical metals, such as cobalt, niobium, tin and tantalum. These practices go back thousands of years, to the time well-before European colonization of Africa and the Americas, but their contribution to the global economy has increased significantly in recent decades. Today, the sector employs approximately forty-five million workers in more than eighty countries around the world, with the greatest activity concentrated in developing countries in Africa, Asia and Latin America.[15] Artisanal miners represent about 90% of all mining-related employment in the world, with significant representation of both women and children.[16] In sub-Saharan Africa, artisanal mining is second only to agriculture as a contributor to local economies.

The involvement of child labor has underscored human rights concerns around artisanal mining, and these activities have often intersected, and perhaps even fueled, local armed conflict. During the five-year civil war in the Democratic Republic of

Congo (1998–2003), the region's minerals were used to finance rebel groups, foreign militias and the national army, leading to large-scale violence and human rights abuses.[17] Significant attention has also been focused on the potential environmental and health impacts of artisanal mining. These are particularly well studied in the case of gold extraction, which involves the burning of gold amalgams in open pans to evaporate the mercury.[18] The inhalation of highly toxic mercury vapors has been linked to neurological, kidney and autoimmune impairment, as well as respiratory failure and death, while environmental release of mercury leads to bioaccumulation across the food chain. Artisanal miners also face significant exposure to other potentially dangerous substances, including arsenic, lead, methane, sulfur dioxide, nitrous oxide, carbon monoxide and cyanide.[19] Biological health risks include increased exposure to sexually transmitted diseases, and other pathogens such as cholera, malaria and dengue fever associated with often poor sanitation and unsafe drinking water.[20] Physical risks include injury associated with over-working under conditions of high temperature and humidity, as well as the high prevalence of accidents, including landslides and the collapse of unstable mining tunnels. Typically, health services are either rudimentary (at best) or inaccessible in the vicinity of informal mining camps.

Despite its obvious challenges, the economic calculus and social context for artisanal mining is vastly different to that of COM operations, allowing it to potentially fulfill an important role in the global mining sector. Artisanal miners have very low up-front costs, allowing them to exploit small deposits, and rapidly shift their activities between sites. Following the collapse of the Tambogrande Mine project in Peru, for example, thousands of local artisanal miners began excavating the streets of the town to manually extract gold using mercury. This activity was accepted by the community as a means of providing socio-economic benefits for unskilled workers.

The broader question is how artisanal mining activities can be developed in a way that supports human and environmental well-being, while also supplying much needed raw materials. Many of the environmental and social challenges facing artisanal mining reflect the illicit nature of this sector, with few (if any) regulations and little (if any) oversight. Thus far, governments of developing countries have proved incapable of effectively regulating the methods used by artisanal miners, or even developing simple and expedited mineral legislations. This does not reflect a lack of interest or effort. In Ghana and Mozambique, for example, governments have attempted to formalize the practices of artisanal mining, yet these efforts have been hampered by limited financial and human resources, complex bureaucracy and ineffective enforcement regimes.[21]

Little assistance is given to artisanal mining communities by the governments of developing counties. Rather, the presence of such primitive miners seems to be a source of embarrassment for the authorities, and most governments prefer to establish awkward and unenforced laws that stifle the development of this sector. In Colombia, for example, an artisanal miner seeking formal recognition from the government must work through 380 bureaucratic steps. As a result, less than 1% of artisanal miners operate legally in Latin America,[22] with unsanctioned miners often portrayed as bandits or criminals by local media. There is no doubt that money laundering and other illegitimate activities exist in artisanal mining (as in many other black-market economies), but the large majority of poor mining workers in rural areas are simply struggling to feed their families. A United Nations study concluded that much of the disorganization and pollution caused by artisanal miners is attributable to a lack of understanding, skills and equipment, and cumbersome legal and bureaucratic in developing countries facing dire economic circumstances. Nonetheless, there may be a path forward in transforming artisanal miners into small-scale operators adhering to acceptable environmental, safety and human rights standards.[23] And in this transformation, it may be that the COM companies can play a fundamental role, though a shift in their business models.[24]

Some progress is already evident. In Latin America there are an increasing number of local and foreign investors building small-scale, responsible mining operations. Chinese companies, in particular, have understood the profitability of these small mines, and have flocked to Africa, making significant economic contributions to local communities, but also generating conflicts with pre-existing artisanal miners.[25]

The model increasingly being developed is one of economic co-existence, in which artisanal miners sell their ores to COM operating plants, which have the capacity to process and refine these into higher-value metals. Such a model has already been implemented (albeit at a limited scale) in Colombia, Costa Rica, Ecuador, Nicaragua, Peru and other countries. In these countries, there are at least two dozen medium-sized COM companies either buying ores or tailings from artisanal miners, or allowing these small-scale miners to exploit part of the companies' mineral claims.[26] Through this cooperative model, the miners focus on extraction, while the companies focus on processing. The miners receive higher payments, and avoid the many health and environmental risks associated with low-tech extraction methods, including the use of mercury. This approach reduces environmental and health impacts, increases metal recovery and the overall profitability of the artisanal mining sector, with more economic benefits flowing directly to local communities. In addition, a more formalized artisanal mining sector can provide access to credit and more clearly defined property rights. Governments, in turn, can derive greater economic returns from their mineral resources.

There are other potential advantages of well-regulated artisanal mining, developed in partnership through mining companies and local communities. For one thing, new alternative technologies can be much more easily tested and implemented in small projects than in large operations. For example, using a liquid waste-product from cassava flour production, known as 'manipueira', it was possible to extract up to 84% of gold from an artisanal mining ore.[27] This home-made solution can be used as a substitute for mercury in artisanal gold mining, but would not be suitable to process hundreds of tons per day of ore from a large mine. And even if such technologies prove inviable, failure on a small scale results in a minor setback, as opposed to a major disaster. Other potential synergies with local communities include the use of traditional knowledge combined with modern prospecting methods to help focus exploration efforts.

The development of artisanal methods to exploit small ore deposits, using appropriate technologies and innovative business models, holds significant potential economic and social benefits for communities. Tangible benefits include direct employment and even ownership stake by locals, and the development of entrepreneurial initiatives. The small scale of these operations means that projects can start more quickly and experiment with the latest technological innovation. Depending upon the production rate, small-scale mines can remain viable for longer periods than rapidly exploited large mines, creating longer-term benefits. If adequately regulated, the environmental footprint of these small operations can be minimized, and they are likely to be much less energy intensive, with significantly lower carbon emissions.

The global mining sector is certainly different today than it was in 1973, when Schumacher published his famous book. It is likely that we have already located and mined most of the planet's easily accessible, large-scale deposits. With the growing scarcity of such deposits, large COM companies, and the global mining sector more broadly, will need to evolve quickly. No doubt, the development of new technologies and increasing commodity prices will support ongoing efforts to find and exploit ore deposits of various sizes and complexity. But in our ongoing search for elephants, we will surely find many more mice. These mice will not be able to meet our full demand for minerals, but if they are exploited responsibly—with appropriate oversight and regulatory frameworks—they can contribute significantly to the economic and social development of millions of people around the world. If we follow such a path forward, perhaps small can, indeed, be beautiful.

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A Closer Relationship with Our Metals

W. Scott Dunbar and Jocelyn Fraser

Why does society need metals and where do these metals come from? These questions are not likely top of mind for most people. Rather, the existence of metals is taken for granted, their sources unknown, but assumed to be reliable. This perception will be challenged over the coming years as growing metal demands and shifting geopolitics begin to threaten global metal supplies, with significant impacts on standards of living and economic development. In the face of such challenges, society will have to fundamentally alter its relationship with metals.

As a starting point, we need to understand how and why we use metals, and how our needs will evolve. At the most basic level, as income and population grow, so does the demand for metal-containing infrastructure and products—the 'stuff' we accumulate as our standard of living increases.[1] For example, the demand for various machines increases as people with growing incomes seek to do less manual labor. Urbanization and the concentration of populations in cities also increases the demand for metal-intensive transportation systems and other large-scale infrastructure. But the increase in metal consumption with income is not linear and can vary between countries. Assumptions about urbanization, industrial expansion and the corresponding demand for vehicles, electronic products and other equipment can be used to develop scenarios from which estimates of future metal demand can be made. These estimates

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vary, depending on the specific assumptions made in different scenarios. What is clear, however, is that the predicted demands are disturbingly large.

One scenario of particular importance is based on the Paris Agreement,[2] a treaty signed by 196 countries aimed at reducing greenhouse gas emissions to limit the global average temperature increase to 1.5°C above the pre-industrial (1880–1900) level. Achieving this target requires a net-zero emissions (NZE) scenario, where all human-derived carbon dioxide (CO2) emissions are matched by CO2 capture and removal from the atmosphere. In the NZE scenario, solar and wind power will have to supply 70% of global electricity demand by 2050.[3] This will lead to significant increases in the demands for several metals, most notably copper, which is a major component in solar and wind power generation technologies, and for the wiring connecting these (and all other) power sources to electrical distribution grids. Clean transportation systems will also increase metal demand. By 2050, the global number of electric vehicles (EVs) is expected to grow to two billion globally,[4] with each vehicle containing forty to eighty kilograms of copper.[5] Between renewable energy systems, electric vehicles and other copper-containing equipment, the copper demand associated with the NZE scenario is expected to be about forty million metric tons per year by 2040,[6] almost double the copper production from mines in 2022.[7] A similar argument can be made for nickel, which is used in solar and wind power systems, and, to a much greater extent, in EV batteries and in hydrogen technologies. By 2040, nickel demand for clean technologies is expected to reach seven million metric tons per year,[8] more than double the global nickel production from all mines in 2022.[9]

The projected metal demands will be exceedingly difficult, if not impossible, to achieve by 2040 within the current metal supply paradigm. Existing mines might be a source of additional supplies, but the concentrations (grades) of metals in these mines are decreasing, meaning that more rock must be extracted to yield the metals of interest. This results in the accumulation of larger amounts of mining waste,[10] with potentially significant environmental impacts. Increased metal demand could be satisfied by developing new mines, but economic factors, geopolitical complexities, together with social and environmental concerns can significantly limit the feasibility of new mining projects.[11] At present, only half of identified mineral resources are successfully turned into mines, and new mining projects typically take ten years or longer to begin operations. An additional consideration is that geology has placed large amounts of metal resources in developing countries that have limited capacity to regulate the social and environmental impacts of large industrial operations. The result is an inequitable global distribution of benefits and harms from mining. Unless transformational changes are made to the way minerals are extracted and metals are produced, issues related to the environmental and social footprints of mining will become unresolvable as demand increases. The problems cannot be easily mitigated, and they are projected to create a significant constraint on metal supply before 2040.

How can we address our metal supply dilemma? One goal would be a fully circular economy, where future metal demand is secured from recycling and reuse of metals.[12] The question is, how do we get there? An approach that has not yet been explored is an innovative change to the global metal supply system. The current system can be represented as an assemblage of mining companies, equipment and service suppliers, metal processors, metal exchanges and traders, and manufacturers and recyclers; each of these plays a distinct and quite separate role in the supply of metals and metal-containing products. Governments, communities and financial institutions also contribute through regulations, and the supply of labor or capital. The current supply system evolved during the early twentieth century to accommodate the metal demands of a rapidly growing global economy. It is rigid, inflexible and cumbersome, based on the extraction of metal from large mineral deposits, and dominated by large corporations with enormous capital resources. Over the past one hundred years, the system has not undergone any notable change, even though the availability and quality of large mineral deposits have decreased significantly around the world. Moreover, the system has created a strong disconnect between society and the metals it requires. Closing this gap is an important first step towards addressing our future metal demands.

In the typical case, mining companies are responsible for extracting primary ore and its initial processing to a concentrate, which is shipped (often over long distances) to smelters and refineries that produce useful forms of the metals that are traded on international markets. The refined metals are then distributed throughout the economy, embedded into all manner of useful products, from cars and cell phones to wind turbines. Once these products reach the end of their life, they are often discarded in landfills, resulting in significant amounts of unrecovered metals.[13] Efforts to extract or recover these metals—like gathering breadcrumbs on a kitchen table—have not been considered economically viable. Soon, however, these 'crumbs', if collected efficiently, will become increasingly important in overall metal supply.

Many opportunities exist along the supply assemblage to access more sources of metal, while also providing economic benefits to more companies, communities, and individuals. Such opportunities can give rise to new businesses that operate alongside the traditional supply assemblage to produce metal that would otherwise be lost. The key to success is actually a form of innovation—finding new points of entry to the metal supply assemblage, identifying and removing barriers to entry, introducing necessary (possibly new) technologies, and organizing more efficient business models.

The concept of a supplier (or a group of suppliers) providing distributed services to mining companies offers several avenues for broader participation in metal supply. Such distributed service providers are already present in the mineral resources industry, particularly in equipment maintenance, and new models of Mining as a Service (MaaS) are under development. In these new economic models, a wide range of suppliers and service providers, both existing and new, become more dominant participants in various stages of metal production, each working in one or more parts of the metal supply assemblage.

Small ore deposits provide one example of an innovative approach to metal supply assemblages. Collectively, these small-scale deposits could provide a significant source of metals, and their limited size leads to a reduced mining footprint. But the ore bodies can be widely dispersed, with variable geometry and mineral properties over short distances, making them difficult to access with conventional mining equipment and techniques. An additional barrier is the perception of financial risk associated with high capital and operating costs relative to the small size (and thus anticipated profits) of the deposits. A novel approach to accessing small deposits involves the use of small-scale mining (SSM), based on mobile and modular machinery for mineral extraction and processing.[14] (These small-scale operations should not be confused with artisanal mining practices, which rely on manual labor with little technology.)[15] The use of mobile and modular equipment provides the flexibility needed to adapt to changes within a small-scale deposit, and the ability to quickly change location. The modular equipment also makes smaller-scale mining operations easier to manage, allowing them to be developed in stages, with options to reduce financial risk.[16] Globally, there are many examples of small-scale mining, but two examples illustrate the importance of flexibility and adaptability in this approach.

Mineco,[17] a company based in the United Kingdom, operates a portfolio of small, underground mines in south-eastern Europe. Each of the deposits is composed of irregularly shaped, high-grade ore bodies containing various metals. These mines produce about 1,000 metric tons per day or less, which is about 10% of the amount extracted from a typical large underground mine. The scale of the mine is small enough to enable almost continuous adaptation to local changes in ore body geometry or geotechnical conditions. Extracted ore is processed locally to produce a mineral concentrate that is shipped to smelters in Europe, where it is refined into a pure metal product.

Vital Metals[18] provides another example of a small-scale, flexible and adaptable operation. The company mined a rare-earth deposit in the Northwest Territories, Canada, generating a metal concentrate from the ore by separating heavy rare-earth minerals from the lighter silicate minerals. The company employed a portable X-ray density separator to sort the material on-site, without the use of water. Mining and operation of the density separator involved members of the local Indigenous community. The concentrate was initially processed at a plant in Saskatchewan, prior to final refining in Norway into rare-earth oxides that were sent to an automotive plant in Germany. The contract terms of the supply chain, from mined ore to a final product, were developed and negotiated by the mining company. The small scale of the mining operation allowed it to adjust and operate in 'switch on-switch off' mode, depending on short-term market requirements. Such flexibility is a hallmark of small-scale mining operations.

Beyond the primary extraction and processing of mineral resources, there are also many opportunities to efficiently recover metals from various waste streams. Mining operations produce huge amounts of waste, in the form of tailings consisting of ground rock and effluent from the processing plant.[19] Tailings from active and 'legacy' mines can contain significant amounts of unrecovered primary metals, with typically higher concentrations in older mine sites where less efficient processing methods were used. The recovery of metal from mining wastes is usually found to be technically and economically unviable. Increasingly, however, improved technologies (including biological methods with bacteria)[20] are being used to extract metals from tailings and wastewater. As an example, waste material (slag) from steelmaking has been found to contain high concentrations of twenty-seven elements typically included in current lists of critical minerals,[21] while coal tailings and coal by-products contain significant amounts of rare-earth elements (REEs).[22] Feasible methods for recovery of metals from these waste streams are under development and could be offered as a service by specialized suppliers, working in partnership with communities, mining companies and manufacturers. This is one example of a creative assemblage of communities and businesses working together to increase metal supply.

End-of-life industrial and consumer products, such as cars, machinery, electronic waste and batteries also contain significant quantities of metals that can be recovered and recycled for further use.[23] However, end-of-life products are typically widely dispersed, and current collection methods are inefficient. In addition, some components of waste products are considered hazardous and subject to transport restrictions from collection points to a processing facility, especially across international boundaries. Contaminants in metal waste also include unwanted non-metallic materials that decrease value and make recovery less economical. One solution is to separate unwanted or hazardous materials from metal waste using combinations of shredding, dismantling and sorting in mobile plants located at or close to collection points. Mobile processing plants,[24] provided as a service, would offer the possibility of minimizing transport of waste and increasing the efficiency of metal recycling systems.

Several methods for recovery of metals from waste have been developed,[25] but separating metals from complex mixtures of materials remains a significant challenge. The organizational and regulatory systems in which metal recycling operates also cause barriers to efficient metal recovery and reuse—the key parts of a circular metal economy. For example, there are no regulations in place to ensure that metal waste is directed to a recycling operation, let alone to an operation that uses the best available technology. Policies to mitigate or remove these barriers are possible and would provide many opportunities for service suppliers who could recover metal from any location where metal waste is produced.[26]

The above examples demonstrate that innovative modifications to the metal supply assemblage can provide more access to the metals needed for the energy transition, while also creating broader opportunities for individuals, communities and businesses to participate in mineral supply. But more effort is needed to take full advantage of these opportunities, which are expected to increase. For example, when renewable energy systems, such as EV batteries and wind turbines, reach the end of their useful life, the metals within them will become available for recycling. Well-crafted policies should recognize and incentivize all types of organizations—national and international, public and private, non-governmental, academic and individual—to contribute their expertise, skills and ideas at the various stages of metal extraction, processing and recovery. Both local and regional initiatives would result, but it must be recognized that what works in one country or region may not work in another and may also change with time. Policies must therefore be flexible to adapt to local conditions and evolve as new opportunities and participants emerge.

Mining companies can play a vital role as owners or supporters of a metal supply assemblage, developing collaborative partnerships with entrepreneurs, innovators, and communities working across the industry.[27] Examples of such a collaborative approach could include joint ownership of mineral processing plants, tailings reprocessing plants or recycling facilities. Companies could also support 'intrapreneurship', where self-motivated employees are incentivized to pursue innovative projects, products or services within the organization. This could lead to spin-off endeavors led by employees with ideas for an alternative metal supply business. Such collaborative innovation sits at the heart of the various national critical mineral strategies,[28] highlighting the need for changes to the current metal supply assemblage.

To maintain economic prosperity and improve standards of living in developing countries, current barriers to entry into the metal supply system (legal, regulatory, financial and technical) must be identified and removed or mitigated. This will provide a path for anyone in society to become more engaged with the metal supply system and contribute to the supply of the metals needed for the energy transition. It is a daunting challenge, but also an exciting opportunity to embrace the social, technological and organizational changes that will transform the way we relate to and interact with metals.

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A Matter of Trust

Allison Macfarlane

Picture a large, windowless room in a modern community center, with rows of folding chairs facing four Indigenous drums and a speaker podium. Picnic tables are set up at the back of the room, laden with breakfast foods and coffee fixings. The chairs are occupied by members of the local First Nation who are hosting the event, as well as representatives from the Nuclear Waste Management Organization (NWMO) and the Canadian Nuclear Safety Commission. A few members of other Indigenous communities are also present, along with a sprinkling of academics, and a few non-Indigenous people from nearby towns. The morning ceremony has ended with the burning of sage, and a sweet aroma lingers in the air.

The audience is focused on a PowerPoint presentation describing the potential impacts of a mined geological repository for high-level nuclear waste that is being proposed near their land. They are just a year or so away from deciding as a community whether to agree to host the repository. This courtship, if you could call it that, between the NWMO and the First Nation has gone on for years. For some in the potentially affected areas, it has gone on far too long. For others, who are just beginning to learn about the proposed project, there is a need for more information—and perhaps a more direct role in the decision-making process. This meeting, a Sharing and Learning Gathering, is one of hundreds of meetings, webinars and open houses used for public

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engagement on the siting of a nuclear waste disposal facility. But such events alone do not guarantee that a community will accept a mined waste repository. There are many other factors at play, and perhaps the most important is the establishment of trust.

As the energy transition proceeds and nations around the world begin moving away from fossil fuels towards renewable energy, the need for critical minerals and mining is expected to increase. New mining projects will be disproportionately located on rural and Indigenous lands, including areas not previously impacted by this extractive activity. These new projects will certainly face a range of technical challenges, but it may be that the largest challenge lies in obtaining informed community support. With growing demands to engage impacted communities in consent-based siting and collaborative decision-making—especially in light of the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP)—there is an urgent need to approach the siting of new mines in an intelligent, effective and respectful way.

Nuclear waste repository siting has some important lessons to share with the mining community about public engagement and the siting of a 'difficult' facility. Several countries, including the United States, Canada, Sweden, Finland, France, Switzerland, Japan and Belgium, have actively been siting nuclear waste repositories for years. These geological repositories are similar to mines in that deep underground tunnels must be excavated to make room for large waste canisters. Eventually, the tunnels are closed and the site, in theory, is monitored for hundreds of years. Because countries with nuclear power plants have been searching for mined waste repositories for decades, history is replete with lessons about how to be successful and, of course, cautionary tales.

The US provides a particularly notable case study of how things can go wrong. The country started the process of nuclear repository siting in the 1970s, and today, fifty years later, is no closer to operating a repository. In 1982, the US passed the Nuclear Waste Policy Act, outlining a fair and reasonable process to find a site for a national nuclear waste repository. Five years later, however, the US Congress amended the law, effectively giving itself sole decision-making power in the siting decision. They selected the Yucca Mountain site in the Mojave and Great Basin Deserts, near the Nevada Test Site, where 928 nuclear bombs were detonated from 1951 to 1992. The selection of the Yucca Mountain site met with fierce opposition from the State of Nevada, as well as from local communities, including the Western Shoshone and the Southern Paiute, and powerful politicians, such as Nevada Senator Harry Reid. The fate of the site remains at a political impasse. Since 2010, the US Congress has refused to appropriate funds for any further work on the repository.

The story of Yucca Mountain provides a clear example of the 'decide-announce-defend' method of site selection. It is exactly the opposite of a consent-based process, and the resulting debacle speaks for itself. Of course, no country has ever been able to find quick and easy solutions to the complex process of nuclear repository siting. Rather, the process has been an iterative one, where successive policies are tried, lessons are learned from failure, and new approaches developed.

Sweden tried three different approaches before finally finding one that worked. Like the US, they began with a decide-announce-defend type process, sending geologists out to the countryside to assess the suitability of various locales. Once the locals got wind of what the geologists were up to—looking for a site to mine a repository for nuclear waste—they sent them packing. Critically, Svensk Kärnbränslehantering Aktiebolag (SKB), the independent, industry-based waste siting organization, never contacted the local municipalities to let them know what was happening. As a next step, communities were asked to voluntarily host a repository site. Perhaps not surprisingly, this approach was also not successful. In the end, SKB approached municipalities that already hosted nuclear power reactors and waste facilities, and found two communities willing to host the new proposed waste storage site. After years of technical studies of both potential sites, the small coastal village of Forsmark, about one hundred and fifty kilometers north of Stockholm, was selected due to its more favourable geological environment. The village (with a population of less than one hundred inhabitants) has had long experience with nuclear power. It has hosted three separate reactors since the 1980s, and currently produces about 15% of the energy used in Sweden. The reactors are equipped with highly sensitive instruments that can detect low levels of radioactivity. In 1987, these instruments provided the first evidence of the Chernobyl nuclear accident outside of the Soviet Union. With the blessing of the community, the long-term waste disposal site at Forsmark has now been approved by the nuclear regulator, and construction will begin soon.

Another path to certain failure is the assumption that a well-informed and educated public will happily accept the risks of a mining project if they understand the underlying science. This fallacy, known as the 'deficit model of public understanding', continues to be accepted today, often by those in industry. The underlying idea is that opposition to a particular technology or facility simply reflects a deficit in scientific knowledge among potentially impacted communities. Proponents of this idea argue that public opposition can be reduced if the knowledge deficit is addressed through communication by experts. But social scientists have shown that such deficit-filling exercises rarely, if ever, produce support for a technology. And this begs the question of where opposition to technologies actually originates.

The public perceives risks from technologies as part of a larger spectrum of risks in their lives, which are informed by social relationships, life experiences and educational backgrounds. The people who communicate the risk and the way in which it is communicated play an important role in determining how it is perceived by the public. In particular, the level of trust that exists between those who communicate the risk and those who are being asked to assume it significantly influences people's understanding of risk and their willingness to accept it. To be effective, those voices communicating risk must do so in an accessible and culturally appropriate manner. If the messenger is not trusted, or the message unclear, no amount of education will alleviate the public perception of risk. On the other hand, clear information, delivered by a trusted source can go a long way to informing communities about the risks they are being asked to assume in hosting a mining project on their land.

Recognizing the importance of trusted sources of information, most successful nuclear waste siting efforts have provided affected communities with funds to hire their own independent experts to perform technical and social analyses of impacts and risks. This arms-length appraisal can help avoid the existence, or even appearance, of a conflict of interest for project proponents in governments or industry. To ensure robust public debate and informed discussion, some countries have even gone as far as funding public interest groups that oppose a project. This 'red-teaming' approach is used to critically examine any oversights around the safety case made for a site, helping to identify potential blind spots. In the end, risk is best understood and managed when a shared understanding emerges from a range of voices and perspectives.

Over the past half century, there have been some successes in nuclear waste repository siting, although no repository for high-level nuclear waste is yet in operation. Finland has a repository under construction; Sweden has licensed their repository site at Forsmark and will begin construction in the coming years; France and Switzerland have both selected sites and await licensing; Canada and Japan will select sites in 2024–26; Belgium has successfully sited a low-level waste repository using a consent-based process. All these countries share one ingredient in common; they have used some type of participatory process for selecting a repository site. Their success holds important lessons, not just for other nuclear waste repositories, but also for the development of new mining projects.

What can we learn from successful waste repository siting efforts? Perhaps most importantly, it is clear that a participatory or consent-based process is essential to success. And this requires three key ingredients: time, people and resources. Though there is urgency around mine siting, the participatory process cannot be rushed. The process should begin as early as possible, and it cannot be a race against the clock. It is also important that the same set of individuals remain engaged with potentially affected communities over the long term, developing robust relationships with community members and demonstrating their commitment to the project. This requires appropriate technical expertise, no doubt, but also compassion and empathy to understand a range of community perspectives. And all of this requires resources—of both time and money—as the partners work to meaningfully address community concerns and needs.

Another key element to success is the ability of communities to veto or opt out of the siting process. These opt-in/out decisions should be made democratically, through a culturally appropriate process. In some communities, this could be achieved through a referendum; in others, elected or hereditary leaders or Elder's councils could be empowered to make decisions on behalf of the community. No matter what the actual process, it is important to determine which voices are heard, by clearly defining the boundaries of a potentially impacted area, and applying the same rules to all communities within that boundary. In its search for a low-level nuclear waste disposal site, Australia ran into trouble when different Aboriginal communities were given unequal access to the decision-making process. In one case, a municipality allowed traditional Aboriginal landowners near the affected community to participate in the vote. In contrast, a second community, Kimba in South Australia, did not include the Barngarla People, who had held their own separate ballot unanimously rejecting the proposed site. When the government eventually decided to situate the waste disposal site in Kimba, the Barngarla mounted a successful court challenge to block the planned site, arguing that they had not been appropriately consulted over a project that would negatively impact their traditional lands. In her court ruling, justice Natalie Charlesworth said that the government had displayed a 'dismissive attitude' to the Barngarla's concerns. Eventually, the government abandoned the Kimba site.

Appropriate compensation is also critically important for affected communities that agree to host challenging facilities. In some cases, this will be in monetary form, but compensation can also be in the form of useful infrastructure, such as community centers, medical facilities and new local businesses, such as banks, shops, restaurants and hotels. In Finland, for example, the nuclear waste management organization, Posiva Oy, built a new Elder's home that also housed a community gym and meeting rooms to maximize interactions between younger and older community members. Sweden used a unique structure for compensation for the two communities that were considered as waste site hosts. The majority of the compensation funds (75%) were to be allocated to the community that was not selected for the site, leaving the remaining 25% for the community that was ultimately selected. This approach kept both communities in the game, as it was assumed that the selected community would enjoy increased business associated with a new repository facility.

In generating trust between communities and project proponents (a mining company or government, for example), both transparency and openness are required. Transparency means that the proponent shares its analysis, and is transparent about how it makes decisions. Currently, environmental impact assessments for mining projects are often based on proprietary data obtained by third-party contractors with limited connection to the affected communities. A better approach is to build capacity within communities to support their role in the collection and interpretation of key environmental data. In the case of Indigenous communities, this can involve the incorporation of traditional knowledge and Elder wisdom alongside technical data. In Canada, the Indigenous Guardians program supports First Nations community members involved in ecosystem protection and land stewardship. Through this program, community members gather environmental data and participate in monitoring activities in the context of Indigenous laws and teaching. The program is currently active in more than a quarter of First Nations in Canada, and could be further expanded to play a significant role in environmental monitoring and oversight of future mining projects on Indigenous lands.

Openness means that project proponents listen to residents' concerns and address them in a meaningful way, demonstrating a willingness to change plans accordingly. It also means a willingness to truly share responsibility—and benefits—with communities. Some communities have formed legal partnerships with implementing organizations, providing them with a formal voice in planning and implementation of the facility. In some cases, it can be important for the local community to retain some operational control over the facility. In Belgium, the local community formed a partnership with the waste agency on the design of a low-level nuclear waste facility. Among other things, the community partners requested that cameras be installed near the repository. The waste agency did not see the point of this additional expense, but eventually agreed to install the cameras. In the end, the cameras proved useful in ensuring the safety of the repository, highlighting the benefits of the collaborative design process that was used.

In the development of future mineral resource projects, it will not be only companies that need to work closely with communities in the siting of new mines. Regulators and the mining industry at large will also have to adopt a participatory approach to mining. Regulators will need to develop their own relationships with affected communities, so that they can provide trusted analysis and decisions on particular facilities. The mining industry will have to move beyond its reputation as an extractive enterprise with a history of challenging relations between companies and the communities in which they operate. This can only happen through tangible examples of partnership and collaboration, where companies work with the local communities for the betterment of all parties involved. In the end, many different people will need to work together to build a more responsible mining sector. A key element in this will be ensuring that risks are properly communicated and mitigated, and that communities reap tangible benefits from resource extraction on their lands.

The *Heavy Metal Suite*

Introduction

Philippe Tortell and Dorival Puccini, Jr.

Over much of human history, art and artists have been at the forefront of social movements for change, holding up a mirror for us to critically examine our triumphs and failures. In the words of the poet Cesar A. Cruz, 'art should comfort the disturbed and disturb the comfortable'. Like the arts, mining has also created comfort and disturbance. The industry generates enormous wealth for some segments of society, and provides the mineral resources necessary for work, transportation and leisure in our digital age. At the same time, mining has left enormous environmental and social impacts that continue to this day. In the face of these challenges, the creative and performing arts can be a powerful vehicle to open dialogue and help us reimagine alternative possibilities.

The *Heavy Metal Suite* provides a creative and collaborative approach to explore the future of minerals and mining. We first conceived the project in 2022, as an offshoot of a collaboration that began the previous year, when Axiom Brass, led by Dorival, performed a concert at the University of British Columbia (UBC), where Philippe is a Professor and Head of the Department of Earth, Ocean and Atmospheric Sciences (EOAS). The show, *Limitless*, was a multi-media exploration of the place of

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humankind in the cosmos. For many years, Axiom has worked with researchers from across disciplines to explore the intersection of art and science, so it was only natural for the quintet to connect with local scientists during the stay in Vancouver. We first met through a mutual contact in UBC's Pacific Museum of Earth, and we soon began working together, along with other EOAS faculty members to incorporate powerful visual projections into the show, alongside short presentations, interspersed with the music, exploring a range of topics from climate change and extreme weather to mineral resources.

From this initial collaboration, things developed quickly. The following year, Axiom returned UBC to hold a 'collaboration fair' with students from EOAS and the School of Music who were working on a new project called *Earth Sounds*—a series of original musical compositions inspired by Earth System processes. At some point during the visit, we began chatting about a new, much larger and more ambitious project—one that would eventually lead to the *Heavy Metal Suite*. The idea was both simple and complex; how could we use music to explore the challenges and opportunities in supplying the world with much needed mineral resources? From the outset, we knew the project had to be international in scope, with representation from composers around the world who could bring a global perspective to the work. We thus began searching, far and wide, for composers who had the creativity and talent to rise to this occasion; composers who were not only outstanding in their own right, but who would be willing to work together to form a whole that was more than the sum of its individual parts. The search was neither quick nor easy, but in the end, we managed to assemble an extraordinary group of artists from across the globe; Valeria Gisel Valle Martinez (Chile), Christopher Sainsbury (Australia), Yao Chen (China), T. Patrick Carrabré (Canada), Augusta Read Thomas (United States), Roberto Morales-Manzanares (Mexico), Chris Chafe (United States) and Vuma Levin (South Africa). Collectively, these individuals represent some of the most important countries in the global supply of copper, lithium, zinc, gold, silver and platinum. In addition to these minerals, we also wanted to represent water, an element that is essential for mining, as well as silicon, which is critical for the digital chips that underpin our metal-intensive technologies.

Over a period of several months, we held regular video conferences, often joined by members of the UBC Future Minerals Working Group, to discuss artistic representations of Earth's minerals. The researchers shared insights about mineral resources and mining, from Earth sciences and engineering, to economics, law and public policy. The composers took these ideas, turned them around playfully, and reshaped them into sonic abstractions. Strong themes surfaced, encompassing the legacies of colonialism, capitalism and consumption, along with the significance of recycling and circular economies. We also explored the theme of conductivity as a common musical motif running through each movement, weaving together the diverse compositions into an over-arching work. This concept has multiple expressions, each of which is relevant to the themes of the *Heavy Metal Suite*. Electrical conductivity, the ability of a material to carry an electrical current, is a key characteristic of metals such as copper and silver that are used in electronic devices. Hydraulic and thermal conductivity represent the flow of water and heat, properties that are fundamental to the formation of mineral deposits in the Earth's interior. At a societal level, conductivity represents a fundamental inter-connectedness among individuals and nations. Tackling the climate crisis and supplying mineral resources for the future green economy will require global connections, as represented by the diverse composers who came together for the creation of the *Heavy Metal Suite*. Building on these themes, Augusta Read Thomas created a short *conductivity* motif, offering the composers an expansive sonic canvas to explore this concept in their individual movements, melodically, harmonically, rhythmically, or in any way that supported their artistic vision.

After much inspired effort, the composers created a truly unique piece of music, which is both highly individualistic and yet somehow integrated into a larger narrative. The *Heavy Metal Suite* premiered on Earth Day (22 April), 2024 in a performance by Axiom Brass at the Vogue Theater in downtown Vancouver. A recording of the performance is available at https://doi.org/10.25740/hw495rk5901, along with a short documentary describing the creative process driving the work. Everyone involved in the conception and creation of the *Heavy Metal Suite* has come away with a new perspective about the foundational elements needed to support society's renewable energy transition. We hope that the work will open a broad global conversation, and inspire listeners to think differently about the future of Earth's mineral resources.

Diloo

T. Patrick Carrabré

I was born Ronald Joseph Nault. My other family names include Bruneau, Elémond, Racette, Landry and Lagimodière. These names all have deep roots in the unique Indigenous culture that developed in the Red River region, before it became Manitoba, a province in what is now known as Canada. My people have been known as *Otipemisiwak* (those who rule themselves), *Bois-Brûlé* (burnt wood) and, more recently, as Métis. I am a survivor of the Sixties Scoop, a mass removal of Indigenous children into the Canadian child welfare system. Along the way, I have been processed and refined through the colonial education system, studying the practices of Western art and music. But since being reclaimed by my community, I have embarked on a voyage of unlearning, trying to craft an identity that reflects the complexity of my personal truth.

I grew up near the waters of the Red River, which, along with the Assiniboine and the Winnipeg Rivers, helped define my relationship to the land. I'm now a guest in xwməθkwəy'əm (Musqueam) territory, where I can look out each day at the stal'əw' (the Fraser River) and the Salish Sea. Water means many things to Indigenous peoples. Not only is it a source of food and an avenue for transportation, it is also an integral component of many ceremonies.

Canada has more available fresh water than any other country on Earth, and Canadians are the second-highest consumers of freshwater after the United States.

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Yet, access to water is not equal across the country. Like other natural resources, water has been commodified; it is bought and sold, bottled for drinking in plastic containers, harnessed for the generation of electric power, and used in manufacturing and mining. Water can produce great profits for some, while others lack basic access to this resource. Today, a significant number of First Nations communities in Canada cannot drink their tap water; they are deprived of a fundamental human right defined by the United Nations. Future generations will likely experience growing pressure on their fresh water supplies as a result of climate change and pollution.

In recent years, I have been drawn to a number of musical projects that connect to water, including my compositions *100,000 Lakes*, *Snewíyalh tl'a Staḵw* (*Teachings of the Water*) and *Clear Lake*. In the *Heavy Metal Suite*, *Diloo*, which means water in our Michif language, opens and closes the larger musical work, setting the stage for the exploration of the future of minerals and mining. Water is critical for mineral resource extraction, and the impacts of mining on water, often on Indigenous lands, are among its most significant environmental harms. The catastrophic failure of the Mount Polley tailings dam in northern British Columbia provides a particularly vivid example of this.

In writing *Diloo*, I was inspired by the many forms that water can take, as well as its seemingly infinite flexibility. Water can be soft yet powerful. It can move slowly and quickly, flowing, rushing or falling, lightly or with incredible power. Since water can take so many different forms, I wanted to reflect a range of feelings within this short movement. There are some passages that try to capture the grandeur of nature, and others that push the music forward like a rushing stream. There is harmony and dissonance, comfort and disturbance—all the things that make a piece of music (and life) interesting. This is territory where I feel right at home, as my life has been defined by a similar binary. I was taken from my family and have now been reclaimed.

I chose to start with calm. Growing up near water, I have always felt the beauty of its seeming stillness, and I can feel myself relax looking out on a placid expanse of water. I also grew up playing the trombone (alongside piano and voice), and this has given me a very personal and physical connection to the sound of brass instruments.

Like the stillness of water, the flow of breath and sustained musical tones take me to a meditative space. *Diloo* begins with these long tones, building a tight pyramid that slowly expands, like flowing water, to fill the musical space. As the music unfolds, you may hear descending motion, a reflection of the gravitational flow of water down the Coast Mountains near my home in Vancouver. This water falls as snow in the mountains and flows towards the sea through our rivers. The cycle is an integral part of life in a temperate rainforest.

I was inspired by this project, and most of this music came out of me rather quickly. It wasn't until more than half of the piece was completed that I received Augusta Read Thomas's *conductivity* motif. I was truly amazed at how well it blended into the music that I had already created; not only her musical ideas, but even the pitch content. I was able to place the conductivity motif exactly as written into the unfolding water movement, and this turned my mind to other themes of the *Heavy Metal Suite*, including the legacies of colonialism, capitalism and consumption, and the importance of recycling and circular economies.

As I enter into the later, more 'mature' stages of my career, I find myself returning to musical ideas that appeared earlier in my compositional work. This form of musical reuse and repurposing runs contrary to my modernist training, which called for each new piece to be autonomous and self-referential, perhaps reflecting the colonial hunger (and thirst) for an ever-expanding world. As I work to unlearn certain components of my education, I try to embrace the value of multiple musical truths, reflecting perspectives that are historical, Indigenous, popular and, at times, uniquely personal. I hope to let the music flow from me, creating sounds that serve as a point of intersection for complex ideas, like humanity's evolving relationship with water. Water can take on an almost infinite variety of shapes, adapting to its surroundings and flowing around obstacles. By comparison, societies are less adaptable. But like the unexpected power of water, humanity has an amazing capacity for survival. I hope this work will help us re-imagine a future where we are in harmony with Earth and each other.

Kypros 29

Valeria Gisel Valle Martinez

For thousands of years, humans have relied on the unique properties of copper, a reddish-brown metal with an atomic number of 29, located between nickel and zinc on the periodic table. Alchemists represented copper with the symbol ♀, which was also used to denote the goddesses Aphrodite and Venus, and to signify the female gender. The metal was imbued with mystical properties, and used in a wide range of applications, from tools, jewelry and cookware to anti-microbial medicines. Today, copper is arguably the most important metal in the transition to renewable energy. With its high electrical conductivity, the metal is used in massive quantities for wiring. It is also used widely in pipes and plumbing, serving to conduct water, rather than electrons. Over the past century, copper production has increased rapidly across the globe, reaching more than twenty million metric tons in 2023. This massive quantity of extracted metal is associated with an even larger amount of waste rock—more than three billion metric tons annually—with the potential to create significant environmental and health impacts.

My country, Chile, is the world's largest producer of copper, accounting for about one third of global production, and more than twice that of the second biggest producer, Peru. Of the ten largest copper mines in the world, three are in Chile (Escondida, Collahuasi and El Teniente). My home in the central part of Chile is located near the Río Blanco Mine (Saladillo, Andes Mountain Range), where large amounts of copper are extracted from both underground and open-pit mining operations. As with all copper production in Chile, the Río Blanco Mine is run by the National Copper Corporation of Chile (Codelco), a state-controlled enterprise created following the nationalization of copper production by President Salvador Allende in 1971. Within a year of this nationalization (and partly as a result of it), Allende was dead, and his government replaced by a military dictatorship led by General Augusto Pinochet.

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Despite his regime's strong tendency towards privatization, Pinochet maintained national control over the country's copper production, which remains to this day.

Beyond geography and nationality, I have another, more personal, relationship with copper. My family carries an altered gene that causes Wilson's Disease—a rare inherited disorder that causes a buildup of copper in the liver, brain and other vital organs. If undetected and untreated, the excess copper can create a wide variety of health problems, including tiredness, loss of appetite, fluid build up in the limbs, and sleep and speech disorders. My cousin Rodolfo died from this disease; it was tragic to see his body transformed and his life extinguished through copper poisoning.

When I was invited to participate in the *Heavy Metal Suite*, I jumped at the chance to represent my country in this international project, bringing my own perspectives to a global exploration of Earth's mineral resources. Since 2019, my work as a composer has focused on using music to mobilize scientific information in a manner that is creative and accessible to broad public audiences. In collaboration with marine scientists at the San Ignacio del Huinay Foundation, I have recorded soundscapes at a coastal marine field station in central Chilean Patagonia, creating sonic representations of a changing ecosystem impacted by rapid glacier retreat. I have also worked at the Federico Albert Taupp fish farm, creating sound maps of the artificial aquatic environment and its captive salmon population. This fish farm, established in 1905, is the oldest in Chile, and one of the oldest in South America. It also happens to be very close to the Río Blanco Mine, and this has allowed me to closely see (and hear) how copper extraction operates.

In composing *Kypros 29*, I wanted to represent the different stages of copper extraction and processing. The piece consists of eight parts: exploration, extraction, crushing, grinding, flotation, smelting, electro-refining and tailings management. Each part is interconnected melodically through the incorporation of repeating notes, A♭, B♭, F, G♭, C, E♭, taken from Augusta Read Thomas's *conductivity* motif. I also wanted to reflect the intrinsic chemical properties of copper, and the need for large quantities of water in its extraction and processing. The movement is written in the key of C (also known as Do), representing the chemical symbol of copper, Cu. Water is represented through the use of the base note H (for H_2O), which is the German representation of the note B (also known as Si). Within the C major scale, the notes C (Do) and H (B or Si) represent the 2^{nd} and 9^{th} intervals, together forming 29, the atomic number of copper. The distance between these notes forms a major 7^{th} interval, which is associated with musical dissonance, and can be taken to represent the conflicts that have arisen from the social and environmental impacts of copper mining in Chile. At the same time, the note Si resolves musically back to the root note of the C major scale. This resolution can provide inspiration in our quest for a truly circular economy, where metals can be reused and recycled, rather than continuously extracted from primary sources.

Kypros 29 is infused with the exploration and layering of various melodic elements, derived from the chemical properties of copper and the nature of its extraction and processing. At the same time, the music reflects the particular geography and climate of Chile's northern mining regions. Much of this territory lies in the high mountainous region of the Atacama Desert—one of the driest places on Earth, in a landscape of barren rocks shaped by sun and wind. This interplay of climate and geology is reflected in the instrumental sounds of the brass quintet, which range from light and airy to grounded and solid. This provides a metaphor for the challenges ahead, as we seek new mineral resources to harvest energy from the sun and wind.

Zinc

Yao Chen

In seeking to explore the relationship between humans and the environment, the *Heavy Metal Suite* bears features that reflect elements of a globally interconnected social and ecological system. There are threads of conductivity running through all the movements, written by composers from around the world who represent the

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increasing globalization of our societies. Each composer takes a different mode of expression for their work, with the individual movements coexisting aesthetically through a set of common brass instruments (shared resources) and subject to a limited duration in time (finite supplies).

Like the other movements in the suite, *Zinc* takes its cues from the physical and chemical nature of the element itself. The metal is lustrous and bluish-white, and is brittle at room temperature, but malleable when heated to temperatures between 110 and 150°C. The pure metallic element is soft, yet hyper-reactive when placed in contact with other metals. At the same time, zinc is also used to protect other metals from corrosion, forming 'sacrificial' galvanized coatings that react with oxygen. This duality is reflected musically as somber moments interspersed with flashes of vivid interaction. As zinc is a component in all brass instruments, I had the fanciful idea that one might hear the resonance of the element itself, an idea that led me to a surprising musical representation near the end of the movement.

Augusta Read Thomas's *conductivity* motif, with its dominant six-note structure (A♭, B♭, F, G♭, E♭, C), links all the individual movements together. This motif leads naturally to a pentatonic scale (A♭–B♭–F–E♭–C), which is a common intervallic structure in the folk songs of China, my homeland, and the world's largest producer of zinc. Inspired by these facts, my piece incorporates some brief transfigured descending fragments from the famous Chinese folk melody *A Little River Flowing*. By doing so, the music reflects *water*, another overarching theme of the *Heavy Metal Suite*. This water-related folk melody originates from Yunnan province located in southwest China, in the center of the Asian continent. This province has the largest lead and zinc reserves in China, and plays a crucial role in the country's smelting (metal refining) industry. A resource-recycling industrial chain has been built in Yunnan to promote cross-regional, collaborative utilization of renewable resources. Here, again, we see an inherent duality; between primary resource extraction and recycling.

My work, *Zinc*, is itself cyclical, opening and closing with a solo trombone. The speed and intensity of the music gradually increase and decrease, in an auditory parallel of chemical reactions. The two trumpets play bustling, almost breathless material midway through. At the end of the movement, the activity slackens, and the instrumental lines thin out until only one remains. This is a metaphor for surplus and scarcity, and a call to action for global environmental stewardship.

Platinum

Vuma Levin

The history of mining in South Africa, particularly platinum mining, is intertwined with settler colonialism and apartheid. The industry was built on a continuous supply of inexpensive migrant labor, which formed the backbone of a racist economic system supporting a whites-only social welfare state in South Africa. Over time, mining in South Africa evolved from a disorganized, informal arrangement into the cornerstone of apartheid in the early twentieth century. In the post-apartheid era, the South African political landscape has shifted with the extension of voting rights to people of color. But the economic model and demographics of the mining system have endured: labor remains cheap and racialized. Workers reside in makeshift townships near mines, sending money to their families in the rural periphery. Calls for social justice and racial equality in the sector have been met by state repression, as epitomized by the Marikana massacre on 16 August 2012, where thirty-four miners advocating for improved working conditions were killed by the South African Police Service.

The *Platinum* movement of the *Heavy Metal Suite* seeks to critically engage with issue of historical and contemporary exploitation of Black bodies in service of the South African mining industry. Conceptually, the movement aims to reclaim the narrative and creative space surrounding the future of platinum mining and production. Drawing inspiration from the Kenyan academic and author, Ngũgĩ wa Thiong'o, Black Indigenous forms and practices were employed as a 'liberating perspective', providing a creative lens to reinterpret the essential features of platinum. The movement is also infused with the concept of *conductivity*, drawing on the motif written by Augusta Read Thomas.

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The composition incorporates several repeated rhythmic patterns, which are characteristic of African music in general and, in their timbral-pitch-inflected form, Black South African music in particular. Numerical values related to the chemical properties of platinum, such as isotope numbers, thermal conductivity and electrical resistivity, served as the foundation for generating rhythmically accented patterns, which formed the basis of each timeline. A rhythmic exposition at the composition's outset introduces each of these timelines. The intensity of percussive sounds also mirrors the history of violent struggles associated with mining in South Africa. As the piece progresses, various polyphonic techniques from traditional Indigenous vocal music are incorporated, including antiphony, non-simultaneous entry and ending of multiple voices, parallel harmonization, and melodic imitation and counterpoint. The conductivity motif is channeled through the filter of hexatonic scales predominant in certain mining regions of South Africa. Ultimately, the piece aims to give voice to previously marginalized Black African musical cultures and histories, envisioning a future where such acts of empowerment are not only expressed via artistic abstraction, but also through meaningful change to the material circumstances of those most affected.

Aura Tenebris (Radiant Darkness)

Augusta Read Thomas

Music for me is an embrace of the world, a way to open myself to being alive—in my body, in my sounds and in my mind. I care deeply about musicality, imagination, craft, clarity, dimensionality, and I seek to achieve an elegant balance between material and form, while expressing empathy with the performing musicians and all those who make the performance possible. Collaborating with the Axiom Brass Quintet and the University of British Columbia's Future Minerals Working Group has been one of the most exhilarating experiences of my creative life. I am deeply grateful to everyone who nurtured this relationship.

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With *Aura Tenebris*, I have sought to sculpt music that allows our individual and collective work to turn freely in the air. The name of the composition, inspired from the Latin words for radiance (*aura*), gold (*aurum*) and darkness (*tenebrae*), reflects the duality of the element. For thousands of years, the beauty and radiance of gold have captured the human imagination. This element has come to symbolize wealth, privilege and power, and its main use is in decorative jewelry—a luxury for those who can afford it. Yet gold also has a darker side—a story of environmental and social disruption, political corruption and conflict. Its extraction involves the use of poisonous chemicals, including mercury and cyanide, creating significant health impacts and pollution, particularly in the developing world where informal artisanal gold mining is common. And the low concentration of gold in Earth's crust results in large volumes of waste rock; about twenty metric tons of waste are produced to extract the gold needed for a single wedding ring. And yet, the high value of gold makes all this effort worthwhile, while also fueling violence that disproportionately impacts marginalized communities.

Aura Tenebris is by turns elegant, lyrical, prayerful, contrapuntal, flexible, fluid and buoyant. The composition delicately glows like a golden orb, with its radiant aura. The use of two flugelhorns, instead of trumpets, lends a mellow, dignified darkness to the hue of the music. The notes are generally in the lower register of the brass quintet's collective ranges and registrations, allowing the musicians ease in sculpting their graceful aura. Organic and concerned with transformations and connections, the carefully sculpted and fashioned musical materials of *Aura Tenebris* are agile and resonant. Their flexibility allows pathways to braid harmonic, rhythmic, timbral, and contrapuntal elements that are constantly transformed, layered, and reverberating with overtly cantabile, melodic resonances and pirouettes.

Although my music is meticulously notated in every detail, I like it to sound as though it was being spontaneously invented; continuously in the act of becoming. I have a vivid sense that the process of the creative journey (rather than a predictable fixed point of arrival) is essential, and I love performances that spiral forth with natural musicality. *Aura Tenebris* unfolds an expressive labyrinth of musical interrelationships and connections that showcase the five world-class musicians of the Axiom Brass Quintet in a display of rhythmic and timbral dexterity, counterpoint, dynamic and articulative range, precision, and teamwork. Each of the five musicians is featured in several brief soloistic phrases.

Music's eternal quality is its capacity for change, transformation, and renewal. No one composer, musical style, school of thought, technical practice, or historical period can claim a monopoly on music's truths. I believe music feeds our souls. Unbreakable is the power of art to build community. Humanity has worked, and always will work, together to further music's flexible, diverse capacity and innate power. In reflecting the duality of gold through my music, I sought to express a prayer and plea for worldwide equity, seeking economic, environmental and social justice for everyone, and allowing radiance to illuminate the darkest corners of our planet.

Iztacteocuitlatl (Silver)

Roberto Morales-Manzanares

For many centuries, silver held great cultural and economic importance to the Indigenous civilizations of Mexico, including the Aztecs, Mayans and other Mesoamerican cultures. In the Aztec Nahuatl language, which is still spoken today by more than a million Indigenous people in Mexico, the metal is known as *iztacteocuitlatl*, derived from a combination of the words white (*iztac*), power (*teo*) and solar excrement (*cuitlatl*)—quite literally 'golden poo'. Silver was highly prized for its shiny, reflective qualities, making it popular for crafting ornamental and religious items, as well as decorative jewelry. Indigenous artisans in Mexico developed sophisticated techniques for working with silver, including casting, embossing, engraving and filigree, in which intricate designs are created by weaving fine silver wires together. Silver objects were used in rituals and ceremonies to honor deities or celebrate important events in

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Indigenous societies, and the metal held symbolic meaning representing the moon, femininity and purity.

With the arrival of Spanish colonial rulers in the early sixteenth century, the production of silver from Mexico began to increase significantly, creating enormous wealth that fueled the Spanish crown for more than two centuries. But the colonial extraction of silver in Mexico also had significant and enduring negative consequences for Indigenous populations and the environment. These included forced labor and enslavement of Indigenous peoples working in silver mines under harsh and often brutal conditions; depopulation resulting from the introduction of diseases; breakdown of traditional cultures and the loss of Indigenous languages, knowledge and social structures; wealth extraction and economic disparity favoring the Spanish crown and colonial elites; and environmental degradation resulting from deforestation and water pollution with chemicals used for silver extraction. The colonial harms associated with silver extraction have had a lasting impact on Mexico's social, economic, and environmental landscape. They have contributed to the systemic inequalities and challenges faced by Indigenous communities that persist to this day.

In writing a silver-themed movement for the *Heavy Metal Suite*, I wanted to reflect the long and complex history of this metal in Mexico. As a starting point, I took inspiration from the five large Indigenous silver mining regions that still exist in the country today; Zacatecas, Guanajuato, Taxco, Pachuca–Real del Monte and Capulálpam de Méndez. Silver mining in these regions goes back at least two hundred years and, in the case of Taxco, can be traced to the pre-Columbian era. Four of these regions all played crucial roles in Mexico's history of silver production, and their mining activities have influenced the cultural and economic development of the country. Today, Taxco is still renowned for its silver jewelry and craftsmanship. Capulálpam (Nahuatl for 'land of capulins') is currently facing a legal battle to cancel all mining concessions granted in its territory, and to close a gold and silver mine located two kilometers from its urban center, in the neighboring municipality of Natividad Ixtlán.

I also took inspiration from the chemical properties of silver, and from the Nahuatl language itself, with its intricate pattern of syllables, consonants and vowels. In this respect, I am grateful to Gabriel Pareyón for his knowledge of the Nahuatl language, which made it possible for me to articulate the musical motifs, and his inspiring work[1] mapping the periodic table of elements to musical frequencies, corresponding to 440 hertz (Hz) for silver.

Using a rhythmic structure inspired by the sounds of Nahuatl, I explored overarching themes in my musical composition, including abuse and labor exploitation, insecurity, conductivity, recycling and water. For example, some of the rhythm patterns used in the score are derived from Nahuatl words, such as:

Atl = water; 1 syllable

Tla-le = land; 2 syllables

Mejtsintle = moon; 3 syllables

Tonaltsintle = sun; 4 syllables

Iztacteocuitlatl = silver; 5 syllables

And some phrases like:

No ikniuan kitoga tlaol-le = My brothers grow corn (*Mis hermanos siembran maíz*); 8 syllables

Siguin gualaske an siguin yaske = some will come and others will go (*Algunos vendrán y otros se irán*); 9 syllables

Some of these words and phrases were extracted from the book *Ejercicios para el aprendizaje de la lengua Náhuatl de Hueyapan y diccionario Español-Náhuatl*.[2] I played with notes in the score to represent these words musically. For example, in the figure below, you can see the accent on the E♭ (the 4th note in the bar) to match the natural accent of the word silver in Náhuatl.

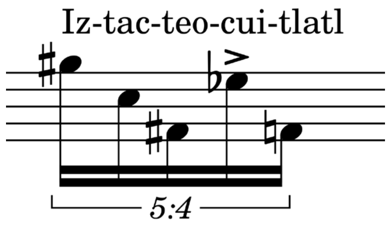
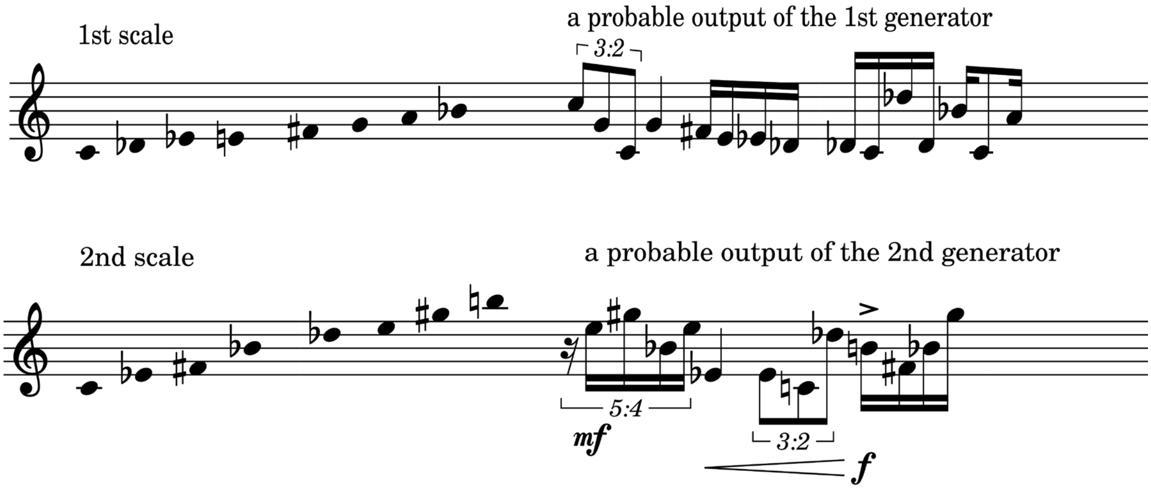


Fig. 1 Extract from *Iztacteocuitatl* score, showing the correspondence between musical accenting and the rhythmic structure of Náhuatl words. Image created by Roberto Morales-Manzanares (2024), CC BY-NC.

The rhythmic elements were placed on top of five different scales (one for each of the mining regions), including octatonic or symmetrical (8 notes per octave), major, chromatic, whole-tone and a split scale with four notes in the first octave and five notes in the second octave. I then used a series of statistical probability functions to choose rhythmic elements and notes from the different scales. From each scale, I generated a set of one hundred notes to reflect the one hundred protons contained in an atom of silver.

To further reflect the five mining regions, I designed the general structure of the score based on five groups of musical motifs, corresponding to each group as shown below:



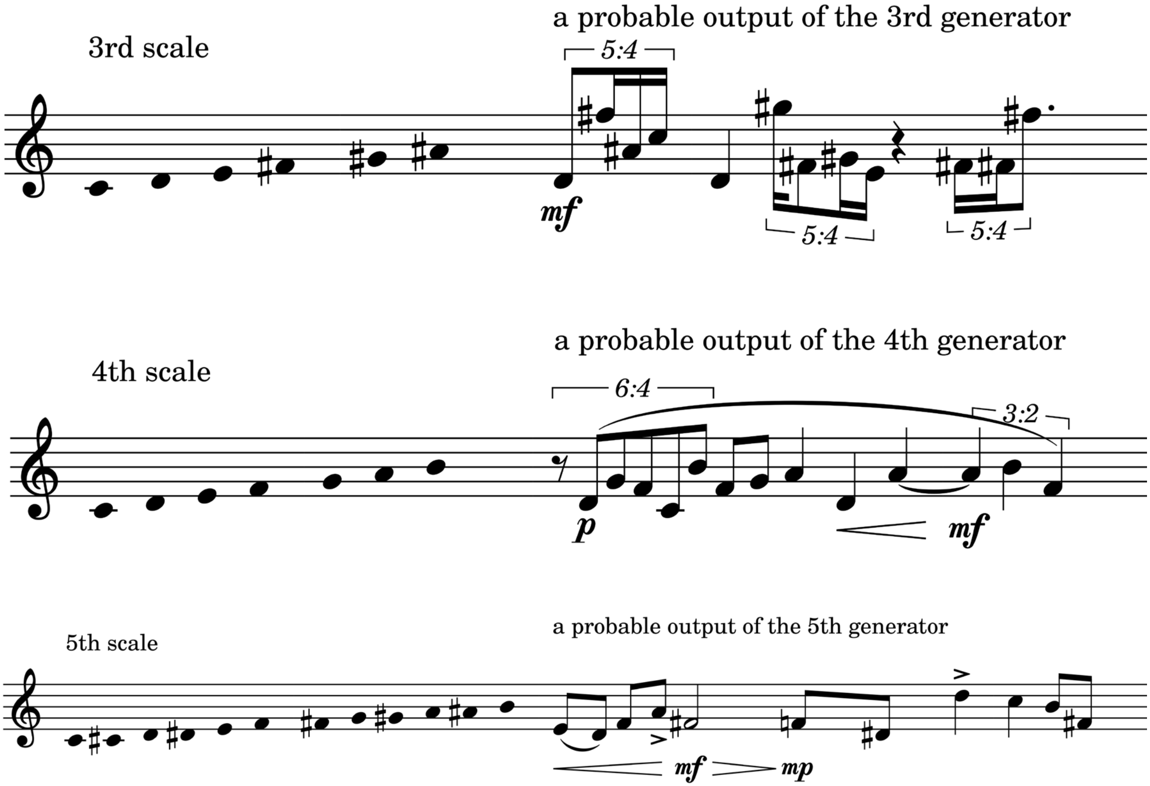


Fig. 2a–e Extracts from *Iztacteocuitatl* score, showing five groups of musical motifs that correspond to five mining regions in Mexico. Image created by Roberto Morales-Manzanares (2024), CC BY-NC.

Recycling and conductivity are represented in the score as bars that make a smooth transition between sections, and by the repeated use of certain musical phrases in slightly altered form throughout the piece. As an example, the musical fragment below uses a hammer and anvil performed by the two trumpets to recombine different scales and motive generators in distinct ways.

Fig. 3 Extracts from *Iztacteocuitatl* score, showing groups of repeated musical motifs that represent the concepts of conductivity and recycling. Image created by Roberto Morales-Manzanares (2024), CC BY-NC.

It is my hope that the *Iztacteocuitlatl* movement of the *Heavy Metal Suite* will allow listeners to enjoy beautiful sounds that emerge from the innate chemical properties of silver and its long history with the Indigenous people of Mexico. I hope, also, that we will be able to reimagine a future for silver mining in Mexico that embraces human and environmental well-being.

Endnotes

1 Gabriel Pareyón, 'Music as a Carbon Language: Clarifying Methods, Results, Fresh Data, and Perspectives', *Journal MusMat* 7 (2023): 1–25, https://musmat.org/wp-content/uploads/2023/09/01-Pareyon.pdf

2 Marcelino Montero Baeza, *Ejercicios para el aprendizaje de la lengua Nahuatl de Hueyapan y Diccionario Español-Nahuatl* (Mexico City: CDI, 2016).

A Lithium Fascination

Christopher Sainsbury

These days, cell phones are perhaps the most ubiquitous expression of our portable digital age. The rechargeable batteries in these devices contain about two grams of lithium, creating a very personal and immediate connection to this element, which I wanted to reflect in my musical composition. Along with their instruments, the members of the brass quintet are asked to use their phones at various parts of the movement. This is meant to signify our fascination with (and perhaps addiction to) lithium, an element which has enabled new means of communication, work, mobility and entertainment.

I also wanted to reflect the place-based nature of lithium production in Australia, the country where I work and live, and where my ancestors, the Dharug (Eora) Aboriginal people, have lived for thousands of years in the mountain and coastal regions surrounding Sydney. The Mount Cattlin Mine in Western Australia contains an estimated twelve million metric tons of lithium ore, in a hard rock deposit that must be excavated, crushed and processed. The mine contains an estimated 150,000 metric tons of lithium oxide (Li_2O), which can be extracted to yield around 60,000 metric tons of metallic lithium; enough to produce batteries for about one million Tesla Model S electric vehicles, or about thirty billion cell phones.

The Mount Cattlin Mine is located near 33° South and 120° East, situated on the traditional lands of Aboriginal people to my west. I used these geographic coordinates to anchor the musical tones of my composition.

The notes of a C major scale are:

C – D – E – F – G – A – B – (C)

1 – 2 – 3 – 4 – 5 – 6 – 7 – (8)

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Here, the note B is scale tone 7, yet B is also inherently below the first C (1), and I took the liberty of designating it as zero (0). Mapping these geographic coordinates against the C major scale results in the following notes:

33 (EE) and 120 (CDB)

This mapping of geography into music gives us the mine's coordinates in the pitches of C major. In a happy coincidence, these pitches align nicely with those used in Augusta Read Thomas's *conductivity* motif (1, 2, 3 and a flattened 7), which was written to tie the individual movements together.

To give the music more complexity and nuance, I represented E (latitude) and CDB (longitude) with a set of pitches drawn from a bi-tone series (F F# G A B C# E G C F#). This formed one melodic theme (a pitch hub) within the piece. The use of the bi-tone series makes up much of the lithium movement, and is something of a signature sound in many of my works. One can simply listen for the emergent soundscape without having to understand the theory behind it. The sounds are like blocks of color, whose juxtaposition and progression within the composition moves between directed action, repose and mystery.

Comparing the bi-tone series against the chromatic scale, we see that four tones are excluded, A♭, B♭, D and E♭. I use these 'leftover' notes as a second pitch hub, constituting a sub-section of the movement that represents the hidden and forgotten 'labor' of the mining sector. My use of two distinct pitch hubs in the composition can also be taken to represent different societal attitudes towards lithium mining, while also reflecting my own mixed European and Indigenous heritage.

My musical representation of the Mount Cattlin Mine is inherently nuanced and abstract. I did not attempt to capture a sonic signature of the mine. Rather, I wanted to signal my knowledge of the mine (and others like it in Australia), while also exploring how modern colonial societies use lithium, and extract it from the lands of Aboriginal people. The form of the work arches between dawn and dusk, with a performance note to the musicians of first dust stirring as they begin to play, and dust settling at the end of the piece. The geographic coordinates are represented throughout, and there is a theme exploring labor, and a chorale for reflection. Near the end, some notes are interrupted, like the intermittent reception of a cell phone. The final chord is restful, yet also has an element of the unresolved, for there is lots yet to discuss and negotiate. Through this composition, I hope to articulate our complex relationship with lithium and the digital technologies it enables, while inspiring a less-Eurocentric approach to envisioning a sustainable future.

Silicon

Chris Chafe

After oxygen, silicon is the second most abundant element on Earth. The Planet's crust is rich in silicate minerals, like quartz, which contain atoms of silicon and oxygen bonded together in crystals. By comparison, the pure elemental form of silicon is much rarer in nature. The super-flat, shiny and exceedingly pure silicon wafers used for electronic components are only a recent human invention. They are produced by refining silica sand into pure blocks of silicon, which are sliced into sheets about the thickness of a human fingernail. Over the past half century, these thin silicon wafers and their embedded circuits have provided a literal backbone for the growth of digital technologies around the globe.

The semi-conducting properties of silicon have made it an essential building block for ever denser electronic circuits, which switch current on and off at extremely high speeds. The three-year-old laptop on which I composed the silicon movement of the *Heavy Metal Suite* contains several billion transistors. Today, a processor chip in a new laptop has twenty billion or more transistors, approaching the number of neurons in the human brain (about one hundred billion). Although a transistor isn't a neuron, the scale of the circuitry that can be built with silicon is nonetheless remarkable. Equally

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remarkable is silicon's ability to harvest energy from the Sun; silicon wafer technology is used in 95% of the solar panels in the United States, and solar power currently provides as much commercial electricity as the country's entire hydroelectric supply.

My home, near the San Francisco Bay in northern California, is in Silicon Valley, one of the world's great research and development hubs for digital technologies. Despite the name, no silicon is actually mined or processed there. It is a place for mining of a different sort, known worldwide for its deposits of cash (not sand) and synonymous with techno-investment. The history of this region has been shaped, time and time again, by change and upheaval; from earthquakes, mountain building and sea-level rise, to colonialism, climate change and globalization. All of these forces, whether slow-paced or cataclysmic, natural or human, have made the place what it is today; an area with stories that need to be told. On the surface, it is a resplendent, affluent place. Without reflection, you wouldn't know that its ancient trees had been completely clear cut, its animals wiped out and the first inhabitants horrifically ill-treated.

Before computers, Silicon Valley was the home of Indigenous populations who, for millennia, used silicon in its natural mineral forms for tools and other purposes. Spain's colonization of Alta California caused abrupt, extreme upheaval, initiating several centuries of subjugation and displacement of Indigenous peoples, and wanton resource and labor extraction.[1] The story of this colonialism has been largely silenced in the dominant historical narrative. But that is now slowly changing, as descendants of the early inhabitants are driving a new awareness of the dynamics of exploitation and consumption, global political economies and the limits of nature's resources and resilience.

The silicon movement of the *Heavy Metal Suite* was inspired by the properties of two substances; sand and pure silicon. As a starting point, I created three-dimensional software models representing the chaotic distribution of sand grains, as compared to the regular lattices of silicon atoms in their pure crystalline form.

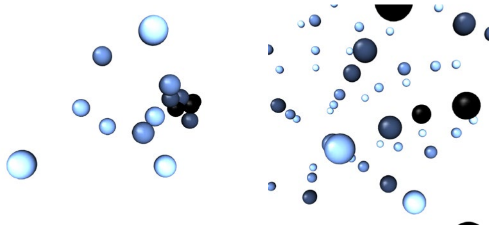

Fig. 4a–b Three-dimensional software models representing the chaotic distribution of sand grains (left) and the regular lattices of silicon atoms in their pure crystalline form (right). Images created by Chris Chafe (2024), CC BY-NC.

To represent these graphical designs in a musical form, each point in the diagrams was translated into features in the score for each member of the brass quintet. The models are allowed to change over time as their particles move through space. This movement is then mapped musically into dynamic melodies, rhythms and articulations, with interlocking ensemble textures following the changing geometries of the grains and atoms. For example, a blue sphere in the graphic above represents an event assigned to the horn part. As time advances, its position changes, providing new spatial coordinates that produce new musical information. One spatial coordinate might be mapped to loudness, as a compositional choice that depends on where we are in the unfolding music. Further along, the same blue sphere might instead produce an element of a rhythmic motif. The movement's overall form is a contrasting sequence of motifs derived from the sand and lattice models, and tied together by the fundamental property of silicon—its (semi)conductivity, following the motif written by Augusta Read Thomas.

If Silicon Valley itself has a form to draw upon, it should include stark juxtapositions in a turbulent history. Unlike the smooth shiny surface of a highly-refined silicon wafer, or a real estate depiction of a picture-perfect neighborhood, the truth underneath is bumpy and wrinkled, filled with interesting textures of an Indigenous world that has largely been undone and glossed over. The silicon theme, and the software models used in this movement, are my musical carriers for the Valley's millennia, its turbulent recent centuries, its high-speed present, and even some whispers of its possible future.

The ambiguity of interpretations from music back to an intended subject is one essence of the art form. The same music can mean different things to different ears, and even to the same listener at different times. Sometimes, music can even convey different messages at the same time. Listen to the *Silicon* movement for reflections of the Valley, how its living and natural resources have been eroded or blended, or perhaps forgotten altogether. The change of form and shape is a fundamental property of the natural world, and of human civilizations; how stones become sand, and eventually how the sand becomes the silicon wafers that have shaped our world.

Endnotes

1 Gustavo Adolfo Flores Santis, 'Native American Response and Resistance to Spanish Conquest in the San Francisco Bay Area, 1769–1846' (MA Thesis, San José State University, 2014), https://scholarworks.sjsu.edu/etd_theses/4462/

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.

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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Metal and Water

Nadja Kunz

The Atacama Desert stretches over more than 100,000 square kilometers of northern Chile and southern Peru and Bolivia. It is one of the driest places on Earth, with an average rainfall of just fifteen millimeters per year, and less than two millimeters in many places. The desert soil is so barren that National Aeronautics and Space Administration (NASA) scientists use it to examine the feasibility of finding life on Mars.[1] This sparsely populated region is home to Indigenous Atacameños, whose culture can be traced back more than a thousand years. Today, most of the desert's population is spread between the small coastal cities of Arica, Iquique and Antofagasta. About one hundred kilometers from Antofagasta, at an altitude of 2,400 meters above sea level, the small commune of San Pedro de Atacama is a destination for tourists from around the world, who congregate there to see an otherworldly landscape, known as El Valle de la Luna (the 'Valley of the Moon').

Though largely inhospitable to life, the Atacama Desert is exceedingly rich in mineral deposits, including copper and lithium, two elements essential for society's transition to a low-carbon economy. For the past several decades, these desert rocks have allowed Chile to dominate global production of copper; the country currently supplies more than twice as much as its closest competitor and northern neighbor, Peru. Chile is also the world's second largest producer of lithium (after Australia). According

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to the United States Geological Survey, the country produced 5.6 million metric tons of copper, and 26,000 metric tons of lithium in 2021.[2] Altogether, the mining sector contributes almost 14% of Chile's gross domestic product (GDP) and nearly 60% of total exports.[3] As valuable as these minerals are to the Chilean (and global) economy, their production poses a growing threat to an even more precious resource; water. And, increasingly, resistance to mining in Chile has focused specifically on the industry's impact on the country's water resources.

Half a world away from the Atacama Desert, in northwestern British Columbia, Canada, mining activity is also expanding rapidly in an area known to miners as the Golden Triangle. This land, rich in gold, copper, silver and other metals, sits on the traditional and unceded territory of the Tahltan, Gitanyow and Nisga'a First Nations who have used Earth's minerals for millennia. Since the arrival of colonial prospectors in the late nineteenth century, more than one hundred and fifty mines have operated in the region. Here, the problem is not a scarcity of water, but rather the associated impacts of mining activities on pristine water bodies. To First Nations, the Golden Triangle is known as the 'Sacred Headwaters'; the shared birthplace of the Stikine, Nass and Skeena Rivers, with countless other lakes and streams that provide critical habitat and food for a wide variety of species, including salmon, bears, moose, caribou, elk and others. The expansion of mining activities in this region has the potential to cause devastating downstream ecological and cultural impacts.[4] This was most vividly demonstrated by the 2014 collapse of a tailings pond at the Mount Polley Mine in south-central British Columbia, which released more than twenty billion liters of mine waste and contaminated water into Quesnel Lake, Polley Lake and the Cariboo River, a major salmon spawning habitat. It was one of the largest mining disasters in Canadian history, prompting the Tahltan Nation to demand an independent review of the tailings dam for the Red Chris Mine located in their territory and owned at the time by the same company that operated Mount Polley.[5]

The contrasting examples of Chile and British Columbia highlight a fundamental characteristic of mining; regardless of where mines are located, they require and interact with enormous quantities of water. On a global scale, it is estimated that mining withdraws between six to eight trillion liters of water each year.[6] For perspective, this rate of water use could supply the basic needs of about 12% of Earth's human population and would drain the entire volume of Switzerland's Lake Geneva in about ten years. Water is a common currency that cuts across all forms of metal extraction and processing, from the concentration of lithium in brine pools, to the flotation of metal ores and the panning of gold from streams in small-scale artisanal mining operations. But not all aspects of mining and mineral processing have equal impacts on local water supplies, and these differences have important environmental and social implications. For example, artisanal gold mining, which employs millions of people worldwide, has also been identified as the main source of global mercury pollution.[7] On the other hand, larger-scale and technologically advanced mining and mineral processing pose their own diverse potential impacts on water.

In large-scale mining operations, the greatest use of water is during mineral flotation, which is the most common method used to separate valuable minerals from uneconomic waste. Flotation is a fascinating process, in which ground-up minerals are introduced into a chemical solution tank filled with rising bubbles. The valuable minerals attach to the bubbles and rise to the surface, while the uneconomic materials (the tailings) sink to the bottom to form a slurry. If the water contained in the waste slurry is not recycled or reused, it ends up in tailings storage facilities, where it evaporates or becomes locked up in the remaining liquid suspension. Once water is stored in a tailings dam, it is not trivial to reuse and recycle—imagine trying to squeeze water out of wet sand! Other uses of water in mining and minerals processing include slurry transport, fire control, equipment washing and cooling, and dust suppression, which alone can account for around 20% of water losses from arid mining sites.

In recent years, there has been increased attention on the risks posed by tailings storage facilities, especially following several high-profile tailings dam failures in Canada and Brazil, which led to significant environmental damage and (in Brazil) hundreds of human fatalities.[8] These disasters led to heightened investor, community and regulatory scrutiny on tailings storage facilities at a global scale, with increased pressure on the industry to mitigate the associated legacies.[9] Given the close relationship between water and tailings, many of the solutions to the tailings problem require innovations in mine water management. This is especially true for sites located in wet regions, where water accumulation in tailings storage facilities creates a potential trigger for infrastructure collapse.

From a technical perspective, there are two broad approaches that can reduce the amount of water needed in a mining operation. Technologies at the 'back-end' of the minerals processing chain, such as thickeners, filter presses and dry-stack tailings can be used to reduce the volume of water retained in tailings, while 'front-end' technologies, such as coarse particle flotation, can improve metal recovery and lower the overall water consumption and volume of tailings generated per metric ton of metal extracted. Water losses from a mine can also be reduced by installing covers to reduce evaporation from water storage facilities, or by minimizing the use of water for dust suppression and equipment washing. There are also approaches that can minimize the legacy effects of mining on water—for example, the selective handling of waste during rock excavation to separate potentially acid-generating material from more benign wastes. This segregation of wastes leaves a smaller volume of hazardous material to be treated and stored. As novel technical approaches are developed and refined, new regulatory frameworks require improved practices to manage tailings, with the goal of minimizing water use and pollution.

Beyond the technical innovation needed to better manage water use in mining operations, companies must also engage with potentially impacted communities and rights-holders who are increasingly concerned about the mining-related water impacts in both arid and wet regions. Between 2000 and 2017, water-related issues were implicated in nearly 60% of mining-related complaints filed with the Compliance Officer Ombudsman (CAO), an independent accountability mechanism for projects supported by some units within the World Bank Group.[10] Community concerns about water and mining can vary widely, ranging from fears of local drinking water depletion, to concerns about the long-term contamination of surface and groundwater systems.

In the bone-dry Atacama Desert, mining-impacted communities worry about their access to scarce groundwater resources, and the potential effects of seawater use on artisanal fishing communities (the desalination process leads to warming, increased salt content and turbidity in coastal seawater).[11] Meanwhile, communities in the Yukon territory of Canada wonder if the economic benefits that accrued over the twenty-year operating life of the Faro lead-zinc mine, were sufficient to justify the perpetual rehabilitation and cleanup costs. These cumulative costs—from the mine's closure in 1998 and in perpetuity—are estimated to be upwards of two billion dollars for the treatment of seventy million metric tons of abandoned tailings and 320 million metric tons of waste rock.[12] Such long-term legacy effects have led many to question whether they should support the expansion of new mining projects in the future.

To earn the trust of communities and broader societal support for continued operations, there is no doubt that the mining industry of tomorrow must manage water issues much more proactively than they have done in the past. Recognizing this, many major mining companies and industry organizations have begun adopting the concept of 'water stewardship', which encourages improved management of water systems beyond the mine lease boundary and seeks to build enhanced relationships with communities and regulators around water governance issues. This differs from the more inward-looking 'water management' approach that companies adopted in the past, which focused more narrowly on preventing water discharge from mine sites and optimizing water reuse to meet production needs.

The adoption of a more holistic water stewardship paradigm requires a deeper understanding of inherent cost-benefit trade-offs associated with different water management approaches. In Chile, for example, regulators have encouraged companies to use seawater as an alternative to scarce groundwater resources. Chile's state copper commission, Cochilco, estimates that 68% of the water used by the industry will be sourced from seawater by 2032, and the national government's mining policy seeks to increase this to more than 95% by 2040.[13] While some mining companies laud the increased use of seawater as a sustainable approach to meet mining-related water needs, this overlooks the negative effects of desalination on coastal ocean ecology and artisanal fishing, as well as the potential socio-environmental effects of infrastructure expansion. A further challenge is the eye-watering costs and energy needs required to transport seawater to mines in the high Atacama Desert, hundreds of kilometers inland and thousands of meters above sea level. These trade-offs are a stark reminder that there is no 'free lunch' when it comes to improving mine water management, and that diverse perspectives are essential to understand the implications of alternative technological choices.

Going forward, improved water management and stewardship by the mining industry will require increased collaboration across disciplines, and between individuals and organizations involved in various aspects of a mine's life cycle, from mineral exploration to site closure. Abandoned mining projects, such as Faro in the Yukon, with their long-term environmental impacts and astronomical rehabilitation and closure costs, should warn us of the dangers of deprioritizing environmental legacies such as water. Yet, there are decisions that can be made much earlier in the mine life cycle to prevent such impacts. A current challenge to such upstream decision-making is the rigid organizational structure of many mining companies, which impedes collaborative problem solving among disciplines and sub-groups.[14] Additionally, different worldviews and competing priorities across departments and management levels within large organizations can prevent decisions that are more desirable from a systems perspective. As an example, the economic case for investing in new technologies is rarely quantified by technical staff, even though this is a key driver of decision-making by upper management.

The policy and regulatory environments are also crucial for driving positive change by mining companies. Currently, miners pay considerably less for water than they do for other operating expenses, and this low cost can hinder the economic case for water efficiency. Yet, when the industry is pushed to change, it can do so quickly. For example, on the cusp of a major drought in the Gladstone Region of Queensland in the late 1990 and early 2000s, alumina refineries were able to quickly and dramatically reduce their water use following legislated water restrictions.[15] It is also essential that the remediation costs of mining-related environmental pollution are adequately quantified within the financial planning for mine closure. Currently, these costs are woefully underestimated in many mining jurisdictions. For example, the closure costs for the Faro Mine in the Yukon, estimated at five hundred million dollars in 2017, increased to over two billion dollars just five years later.[16] Inadequate quantification of mine closure costs reduces the economic incentives for companies to invest in technologies that could reduce their environmental legacies. This can lead to sub-optimal decisions, from both a financial and socio-environmental perspective.

Beyond economics, there is also a need for miners to recognize the important cultural and spiritual value of water for many community members and Indigenous rights-holders within mining-impacted regions. Many have argued that these values cannot be adequately captured in economic terms, requiring that miners employ decision-making processes that consider economics alongside more qualitative measures and criteria.

While the mining industry has made great strides towards recognizing water as a key business risk, a changing operating environment will continue to demand innovation. One such external pressure relates to the increased variability in global climate, which will intensify existing water management challenges for some sites and create new problems for others. For example, mines in northern Canada will face greater environmental risks, as tailings dams and other critical infrastructure become destabilized on thawing permafrost. For other sites, changes in the timing and intensity of peak snow melt and river discharge will require increased attention to the dynamics of mine water balances across seasons. Similarly, changes in the water cycle may directly impact the reliability of energy supplies for mines that rely on hydropower. In many water-scarce mining regions, such as Australia, anticipated warming and increased drought are expected to present both negative and positive effects. Operating mines in a drier climate will exacerbate water scarcity challenges, while also reducing the risks of water overflow from abandoned mining pits.

The changing nature of accessible mineral deposits will also create new water-related risks. As the availability of high-grade ore deposits dwindles, companies will shift to lower-grade ore deposits that will demand more water and energy unless disruptive innovations are embraced. Additionally, the increasing depth and geological complexity of mines,[17] creates new hydrogeological challenges as operations increasingly interact with the groundwater table. Indonesia's Grasberg copper mine, for example, receives up to five meters of rainfall per year, necessitating a complex web of dewatering systems to prevent the collapse of its block caving operations.[18] New automated technologies can help mitigate the associated safety risks, by removing the need to place people in potentially hazardous environments.

Other technologies, including data science and remote sensing also offer exciting opportunities to advance mine water management and governance. These technologies can help improve the reliability of water balance models by filling data gaps, which are common due to the remote locations of many mines and the associated high costs of monitoring equipment. For regulators and community groups, the increased availability of high-quality data may enhance the real-time control of mine sites and prediction of their associated impacts on water systems. These new approaches, along with fundamental shifts in how water is valued and prioritized, will hopefully ensure that future mines are more environmentally responsible, from exploration through to closure, across diverse operating contexts in all corners of the world.

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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

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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 'over-burden' 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

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Microbial Mining

Gordon Southam

The earliest forms of biotechnology can be traced back to the beginning of human civilization, with the domestication of plants and animals, and the discovery of fermentation. These early innovations sought to harness naturally occurring biological processes to provide useful products, such as food and wine. In the context of mining, biotechnology has also been used, though indirectly, for over a thousand years. The Romans used the 'colors of earths', in particular the intense red staining of iron oxide, to discover nearly all of the world-class metal ore bodies present across the Iberian Pyrite Belt in present-day Spain and Portugal. More than a millennium later, the German scholar Georgius Agricola published his 1556 book *On the Nature of Metals*, the fifth part of which discusses how various minerals and colors of earths can be used to give indications of the presence of metal ores.[1] Both Agricola, and the ancient Romans before him, had unwittingly discovered the signature of bacteria associated with metal-sulfide deposits. But it is only over the past few decades that we have come to better understand the potential for these microbes to identify significant mineral deposits and liberate metals from their host rocks.

Today, as we face the enormous challenge of provisioning massive quantities of minerals for the green energy transition, there is significant focus on innovation in the mining sector, including the application of biotechnology. With the advent of

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the molecular biology revolution, we can map the diversity and metabolic potential of microbes across the entire Earth system, from the deepest ocean trenches to the highest mountain glaciers. Microorganisms are ubiquitous in surface and subsurface environments, where they exhibit tremendous molecular and metabolic diversity, and exploit a wide range of chemical reactions to support their metabolism. By harnessing these microbial metabolic pathways, new biotechnology tools could eventually transform the mining industry, from the recovery and extraction of metals to the downstream treatment of wastes.

The first step in mining begins with the identification and characterization of an economically significant accumulation of metal(s) in an ore deposit. Historical mineral exploration focused on easily accessible ore body deposits contained in exposed rock outcrops on Earth's surface. As these 'easy' deposits have become scarcer, contemporary mineral exploration programs have increasingly employed geophysical surveys to target ever deeper subsurface geological materials. Once a potential exploration target is identified, surface geological measurements are used to improve confidence in the presence of subsurface metals. In many cases, these measurements are complicated by the presence of significant groundcover, including ancient marine sediments and glacial debris, which can mask underlying signatures of metal deposits. As a last step in exploration, drilling programs are used to extract rock samples for the analysis of chemical and mineralogical properties of potential ore deposits, and to identify potential harmful elements, such as arsenic, which could diminish the viability of a mining project. Coring (and the associated downstream laboratory analysis) is extremely expensive and time-consuming, accounting for a significant fraction of the total costs and personnel time associated with mineral exploration.

In many ways, the search for mineral deposits is like looking for needles in haystacks. But the search is guided by an underlying understanding of the geological processes that lead to metal enrichment in Earth's crust, and the 'footprint' these processes leave behind. Metal-rich materials are emplaced and concentrated in diverse geologic settings via high temperature, magmatic, hydrothermal, sedimentary and metamorphic processes.[2] Once emplaced and cooled, metal deposits can be subjected to chemical reactions, which spread out their subsurface and surface signatures. These anomalous geochemical signatures reflect the dispersion of metals from an ore body during weathering, and the enrichment of metals in near surface environments. Traditionally, these footprints have been mapped by measuring the concentration and isotopic composition of various elements across a defined sampling volume. With rocks in hand, geologists can measure the chemistry, mineralogy and geologic structures, targeting samples in three dimensions around the suspected location of an ore body. In practice, funding and time-constraints often limit the amount of sampling and chemical analysis that can be performed, and geologists typically use only a limited snapshot of data to point towards an ore body. At present, much less than 1% of mineral exploration projects lead to the development of a mine. Given this low probability of success, innovative approaches are needed to improve efficiency and reduce the costs of exploration.

Over the past decade, increasing focus has been placed on the potential use of bacteria to identify mineral deposits. This approach is based on the genetic information coded within bacterial cells, which provides clues about the concentration of metals in the rocks, soils and groundwaters that surround these tiny organisms. Soils typically contain thousands of different bacteria, each possessing hundreds to thousands of metal-specific metabolic pathways with distinctive molecular signatures. These molecular signatures, coded in genes and proteins, have been shaped by the evolutionary and ecological history of bacteria (i.e., exposure to metals over geologic time), and they can provide an integrated picture of metal availability in modern environments.

Many of the economically important metals, such as copper and zinc, are biologically toxic at the high concentrations found in ore systems. Exposure of microorganisms to these metals will select for metal-resistant microbes, which can persist down to several kilometers below Earth's surface. Some bacteria, for example, have pumps embedded into their plasma membranes that act to transport metals out of the cell. Other bacteria release metal-binding compounds (chelators) to reduce metal toxicity outside of the cell. Both these processes of metal detoxification are associated with genes that can be identified in natural samples. These metal-sensing genes 'respond' to many elements across the periodic table, providing a potential biological signature of high concentration metal deposits. The sum of all genes present in a bacterial population (the 'meta-genome') is thus akin to a genetic library, describing the collective metabolic pathways of all bacterial groups present in a sample. The more complex the bacterial population, the greater the genetic capacity of the 'library' that can be accessed through biotechnology. With up to hundreds of millions of bacteria per gram of soil, microbial metagenomes present a massive archive of metal-specific genetic elements that can be targeted for mineral exploration, providing information about the chemical environment surrounding the cells. Over geological time, the exposure of bacteria to weathered ore bodies has undoubtedly produced thousands of currently unknown biotechnological targets (such as chelators) that are waiting to be discovered.

Beyond the initial exploration phase, bacteria can also play a significant role in downstream aspects of the mining process. Once a mineral deposit has been identified, metals of interest must be economically extracted from the host rock in a way that minimizes energy consumption and the release of harmful wastes. At present, the mining industry is extremely energy and fossil fuel intensive, accounting for approximately 5% of global CO_2 emissions. Most of the energy used in mining is directed towards rock crushing and grinding, which is the typical first step in the extraction of metals. Over the past several decades, the industry has worked to improve energy efficiency and transition to renewable energy. These efforts have focused on improving conventional techniques; however, radically novel approaches, inspired by bacteria, could potentially offer even better results.

Naturally occurring bacteria play a significant role in the formation of certain mineral deposits, and could, in the future, be used to 'super-charge' these formation processes. So-called 'supergene' deposits provide a case in point. These metal enrichments form when bacterial metabolism helps break down minerals, allowing extracted metals to percolate down from upper rock horizons into an enriched subsurface 'blanket'. Targeting this enriched layer during mining can significantly reduce the amount of rock that needs to be crushed and ground, improving the efficiency of metal extraction. It is conceivable that bacteria could be used to 'grow' a supergene ore body, by introducing percolating fluids and nutrients to stimulate bacterial metabolism and speed up the dissolution of metal-containing minerals.

Even better than targeting metal-rich layers of host rock, what if metals could be extracted from ore without crushing any rocks? Such a process of in situ leaching occurs naturally when bacterial populations metabolize host minerals, releasing dissolved metals into the surrounding fluids. If such microbially mediated reactions could be controlled and scaled up, significant supplies of metals could be liberated into pore fluids, which could be accessed without the need to extract rock. This 'bioleaching' would massively decrease the energy requirements of metal extraction, leaving all the waste rock in the ground. It would also make it easier to selectively remove potential harmful metals from a solution. The underlying processes of bacterially mediated mineral weathering and dissolution are the same ones that account for the mineral-associated colors of Rio Tinto originally observed by the Romans thousands of years ago.

In recent years, bioleaching has come to play an increasingly important role in mining operations. As an example, approximately 15% of the world's copper is currently recovered using biohydrometallurgy, a process catalyzed by iron and sulfur-oxidizing bacteria that accelerates the extraction metals from rock. By artificially stimulating bacterial iron oxidation in an ore sample, the rate of bioleaching can be increased 100,000-fold. In addition, the same bacteria used to extract copper can help access gold from sulfide minerals, exposing interior mineral surfaces for more efficient chemical leaching. This greater efficiency significantly reduces the amount of cyanide needed for the chemical reaction, minimizing the production of hazardous waste.

The examples above serve to illustrate how bacteria could be used to target a range of metals from ore deposits. At present, most current mining operations are directed at the recovery of a primary metal (for example, copper), and perhaps a secondary target (for example, gold) that is amenable to economic extraction. There are no current mines that recover all the metals in a deposit, whether for potential economic benefit or to avoid environmental contamination. These abandoned metals often include low-grade deposits of critical minerals, such as cobalt, nickel and rare-earth elements (REEs), which are essential for our technologically advanced society. The recovery of abandoned metals in left-over mined rocks provides an opportunity to transform wastes into resources, with the goal of eventually accessing all the metals in a deposit.

With thousands of metal-specific metabolic pathways and metal-binding compounds, bacteria have an enormous potential to selectively remove metals from ore deposits. For example, the identification and use of metal-specific chelators holds significant promise to increase the recovery of a wide suite of metals from complex ore bodies. This would lead to improved economic benefits, in terms of valuable metals, while minimizing environmental impacts from harmful elements, such as arsenic, which remain behind in mine wastes. Such a biotechnology approach could effectively 're-mine' the waste from the ore, greatly improving the overall efficiency of metal extraction, and reducing the potential environmental impacts of waste storage.[3]

As noted elsewhere in this volume,[4] mining is essentially a waste management business. Massive quantities of metal-containing rocks and tailings are left behind after metal extraction, and these wastes pose the most significant environmental threat from mining activities. At present, it is estimated that there are currently thousands of major waste sites around the world. Of particular concern is the problem of acid mine drainage (AMD), which currently affects thousands of kilometers of rivers globally. AMD occurs when bacteria oxidize sulfide containing minerals to form sulfuric acid, which, in turn, releases a range of potentially toxic metals from an ore body and its host rock. The presence of AMD is often indicated by bright orange and red wastewaters, reflecting high concentrations of dissolved iron released from pyrite (an iron sulfide-containing mineral). If left untreated, metal precipitation from AMD can occur at significant distances (more than tens of kilometers) downstream from an acid-generating mine site. It can continue for hundreds or even thousands of years, well beyond the timescales of mine closure planning. The red-orange colors of Spain's Rio Tinto provide a particularly vivid example of this.

Current approaches to treating AMD focus on chemical methods aimed at preventing or limiting long-range impacts. These include the use of acid-neutralizing reagents such as calcium carbonate or caustic soda (sodium hydroxide), both of which have their own negative impacts. The use of calcium carbonate leads to significant CO_2 release (increasing the greenhouse gas emissions of mining), while the high pH of caustic soda can cause negative ecosystem impacts. Importantly, neither of these treatments address the underlying process that generates AMD. Rather, they produce treated mine waste reservoirs that are similar in size to the original mine waste site. Concentrations of metals in these reservoirs may be significantly lower than in untreated sites, but they often still exceed health and safety limits, affecting tens of thousands of kilometers of streams globally.

Biotechnology can offer some alternatives to address AMD. First, bacteria can be used to reverse the production of AMD. In the absence of oxygen, sulfate-reducing bacteria have the capability to convert sulfate ions into reduced sulfur (sulfide), which reacts with a wide range of metals to form highly insoluble metal sulfides. These minerals form a precipitate and sink out of solution, allowing them to be recovered and concentrated. This approach addresses the issue of environmental toxicity and provides a value-added economic benefit from metal recovery.

In addition to catalyzing reactions that cause metals to precipitate out of solution, bacteria can accumulate high concentrations of metals on their outer cell surfaces. Under normal conditions, negatively charged molecules on the bacterial membrane bind to a variety of positively charged ions, including calcium and magnesium, helping to stabilize the membrane. At high concentrations, positively charged metals, such as copper and zinc, can displace calcium and magnesium from the membrane binding sites, leading to the formation of mineral precipitates on the cell surface. The small size of bacteria makes them particularly efficient at stripping metals out of solution through cellular adsorption (as the size of a particle decreases, its relative surface area increases). A population of bacteria can thus present an extremely high effective surface area available to adsorb metals out of solution. Such 'bio-mineralization' holds significant promise as a means of metal recovery from mining waste materials, with both environmental and economic benefits.

Microbes have existed on Earth for billions of years and have evolved a wide variety of useful, biotechnological metabolic functions. These tiny organisms are partially responsible for the oxygen that we breathe and the food we eat. They also play a critical role in the natural cycling of elements, but it is only recently that we have begun to better understand their potential use in mining-related applications. Current biotechnological methods can offer a diverse range of approaches that could one day revolutionize the entire mining life cycle, from the discovery and extraction of economically important minerals, to the downstream recovery of metals from mine waste. In the face of diminishing ore grades, improved metal extraction efficiency is essential to our future material needs. As we look to the future, we may need to look also to the ancient past; it may be that the solution to our metal supply problems lies with some of the most ancient organisms on our planet.

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A New Life for Old Metals

Maria Holuszko

In ancient human civilizations, metal objects were venerated in religious ceremonies, passed down across generations and traded as prized commodities. Today, thousands of years later, the situation is vastly different. As metals have become increasingly critical for the advancement of human societies—from cars and wind turbines to computers, smart phones and health care equipment—we have become increasingly disconnected from these vital elements. These days, you would be hard-pressed to name even a small fraction of the metals contained in your favorite electronic device. The average smartphone, for example, contains gold, silver, copper, lithium, platinum and a wide range of rare-earth elements (REEs) that most people have never even heard of—yttrium, lanthanum, terbium, neodymium, gadolinium and praseodymium, among others. We use these objects every day, often without much thought or intention, and we likewise dispose of them, sight unseen, without understanding where they go when they leave our hands, homes, schools and businesses. Many of these devices are produced with built-in obsolescence, designed to be used for just a short while, until something shinier and better comes along.

As global demand for critical metals grows rapidly with the expansion of renewable energy and digital economies, many difficult questions are being asked about how and from where projected mineral demands will be met. Some have called this a new 'gold

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rush', as countries around the world seek to secure strategically important mineral supplies for their future economic development.[1] But this time around, we will need much more than gold.

How are we to supply all these metals to support our future needs? In some cases, we have found substitutes for metals, most notably through the increasing use of plastics and other synthetic materials. But in many applications, such as electrical wiring, the unique properties of metals cannot (yet) be replicated by these materials, and the alternatives are not always cheaper or more environmentally friendly over the long term. Increased mining will be needed to supply growing metal demands, but this faces several significant challenges. For one thing, the decreasing metal grades of ore deposits are making it harder to extract economically viable quantities of metal from host rocks, while also increasing the amount of waste material that must be stored and treated, often for decades or longer.[2] At the same time, the potential negative social and environmental impacts of mining have created significant community opposition (and court challenges) to many new projects. And even for those mining projects that are conducted responsibly, with due attention to environmental, social and governance (ESG) issues, the extraction of minerals from Earth can never be sustainable in the true sense of the word. Once minerals are extracted from the ground, they can never be put back.

If we cannot replace the metals in our devices, homes and businesses, or mine our way out of the problem, the long-term solution will have to rest with the transition to a circular economy, where products (and their embedded metals) are recycled or 'upcycled' back into the industrial supply chain. The goal of this approach is to maintain mineral resources in circulation for as long as possible, while minimizing the need for primary resource extraction. To achieve this goal, we must be able to recover and reuse the materials found in our manufactured goods.

All metals, including copper, zinc, gold and the others, are chemical elements—the basic building blocks of matter. For the most part (ignoring radioactive decay and a few other processes), metals are neither destroyed or created on Earth; they can combine with other elements to form various compounds, but the chemical properties of the pure elements remain constant. This means that most of the metals that exist on Earth today have been here, unchanged, since the earliest days of our planet, continuously recycled across different geological reservoirs for more than four billion years. And at some distant point in the future, long after we are gone, all the metals on our planet (minus whatever we send into outer space) will continue to exist on Earth. Seen in this light, the problem of metal supply is not about the total quantity of metals on the planet, but rather about how they can be kept circulating in useful and accessible forms.

Before the Industrial Revolution, it would have been unthinkable to discard metallic objects, which were made by hand, often by skilled artisans. These objects were used for as long as possible, and then re-purposed into other items; swords were converted into ploughs, spears into hooks.[3] Since the time of the ancient Romans, when bronze coins were melted to produce raw material for statues and military equipment, metal recycling has increased at various points in history, particularly during times of scarcity and war. Following the Declaration of Independence, in 1776, American patriots in New York toppled a metal statue of Britain's King George III, melting it down to make musket balls for the Continental Army. About a century later, during the American Civil War, southerners facing a blockade of their ports began melting church bells and steeples, pots, pans and farm equipment to fuel their war effort. As they struggled against Abraham Lincoln's well-equipped northern armies, confederate soldiers collected spent ammunition from battlefields to replenish their metal supplies.

During the early twentieth century, metal recycling expanded rapidly with growing industrialization. The first aluminum recycling factories appeared in the United States by the early 1900s, shortly before the outbreak of World War I, when the US government initiated a nationwide metal recycling campaign. All citizens were encouraged to collect metal items, particularly tin, aluminum, copper and steel, which could be used to increase the production of tanks, ships and other weapons needed for mechanized warfare. About twenty years later, as the world found itself in another global conflict, recycling became critically important once again. At the beginning of World War II, there were more than one million tons of scrap metal scattered across farms in the US, enough to construct more than one hundred warships, thousands of tanks and airplanes, and countless bullets.

In the post-World War II years, the economic imperative for metal recycling diminished as military demands decreased, and plastics began to substitute metals in many products. But at the same time, a growing environmental consciousness emerged in the 1960s, focusing more attention on the contamination of land, water and air with various industrial wastes, including large amounts of abandoned metals. At the time of the first Earth Day, on 22 April 1970, only about half of the copper and 20% of the aluminum used in the US was recycled, adding to a growing problem of waste accumulation across the country. Today, half a century later, recycling has more firmly entered the public consciousness, but significant challenges remain. While Europe and South America now recycle more than 70% of their metals, this value is only about 45% in North America and Africa, leaving large amounts of potentially valuable material in waste streams.[4] In 2018, for example, US landfills received 10.5 million metric tons of steel, amounting to about 70%, by weight, of all material in municipal solid wastes. Clearly, we still have a long way to go to achieve a circular economy.

A significant part of our metal recycling challenges results from the growing complexity of metal-containing products. In the early twentieth century when recycling began at an industrial scale, metals were recovered in bulk forms from simple alloys—steel cars and tin cans, for example. Today, the nature of metal-containing products has changed significantly. Each year, millions of new electronic devices are introduced into the market to assist an increasingly digital lifestyle for consumers worldwide. These devices have increased productivity and access to information and entertainment, and they allowed us to stay connected during the global COVID-19 pandemic. The downside, however, is an accumulating mountain of waste scattered across our planet.

Electronic waste (e-waste) is now the fastest growing form of garbage on Earth, with over fifty million metric tons generated in 2020 alone, 7.3 kilograms of e-waste per person. This waste, equivalent to the mass of 5,000 Eiffel Towers, consists of a wide range of metal-containing products, from appliances, screens and monitors, lamps, and various IT and tele-communications equipment. The amount of e-waste generated correlates strongly with per capita gross domestic product (GDP), ranging from twelve to fifteen kilograms per person in North America, Europe and Australia, to four kilograms per person in Asia and two in Africa. And as the world grows richer (on average), more e-waste is being produced every year. Between 2014 to 2019, the global quantity of e-waste increased by 9.2 million metric tons, and by 2030, it is expected to reach about seventy-five metric tons, representing a doubling in less than two decades.[5]

The massive increase in the production of e-waste is far outpacing recycling rates. Currently, only about 15–20% of global e-waste is formally collected and appropriately recycled. The rest, more than 80% (about forty million metric tons in 2020), is either incinerated with other wastes, or dumped in landfills. As with e-waste production, recycling rates vary significant across the world; Europe has the highest rates at around 42%, followed by Asia, America and Australia (about 9–12%) and Africa, at less than 1%. Although infrastructure for e-waste recycling continues to improve in developed countries, a significant amount of e-waste is still illegally exported to developing nations, where recycling is mostly done informally, often using manual labor and methods that pose human health and environmental risks. Of particular concern is the presence of toxic metals in e-waste, such mercury, lead and cadmium, alongside potentially carcinogenic organic compounds used as flame retardants in various electronic devices.

Where some see a growing e-waste environmental catastrophe, others see significant economic opportunity. For one thing, e-waste is highly enriched in valuable metals, with concentrations that can be many times higher than the rocks from which they were initially extracted. Take gold for example; a rich geological deposit contains about five to ten grams of gold for every metric ton of rock excavated, as compared to about three hundred grams of gold in a metric ton of printed circuit boards (PCBs).[6] It is estimated that PCBs account for about 40% of the total monetary value of e-waste and could represent more than seven hundred million US dollars' worth of gold in Europe alone by 2025. Globally, the value of metals in all e-waste types (gold, silver, platinum, copper and others) was estimated to be more than fifty billion US dollars in 2019. For this reason, e-waste recycling could turn millions of metric tons of waste into billions of dollars of new wealth, while also addressing future metal supply gaps. And there are also a significant number of jobs that could be created in e-waste recycling. The Electronics TakeBack Coalition estimates that hundreds of thousands of people are currently employed in informal e-waste recycling, with over 500,000 jobs in the US alone, and possibly millions of additional jobs worldwide. Other important benefits from e-waste recycling relate to the lower environmental footprint of recycled metals, which require less energy and carbon dioxide (CO_2) emissions than an equivalent amount of metal obtained through primary extraction.

Given the potentially large economic and environmental benefits, why has more effort not gone into recovering important metals from our global e-waste scrap heap? As with many things, the devil is in the details. The process of recycling metals involves a series of distinct steps, which are often undertaken by different people, in locations spread out around the globe. An efficient recycling system requires that metal-containing scrap materials, including e-waste, are collected and separated from other waste streams, something that happens with varying degrees of efficiency around the world, and even within different regions of a single country. Collected e-waste must then be disassembled to remove potentially hazardous components and separate out different bulk materials (metal, plastic, glass). The sorted material is typically shredded, using various methods to separate metals, including magnets (for iron, steel and REEs) or gravity (copper, gold and silver). In recent years, new infrared and other optical sensors have also been used to selectively remove glass and plastics from metals, but these technologies can have high up-front costs, and are not well suited to smaller, informal operations, such as those that dominate recycling in developing countries.

A key challenge in e-waste recycling is the extent to which metals are increasingly embedded within composite materials containing ceramic, glass and various plastic polymers. Some of the materials within these composites are blended on a molecular scale, making the individual components invisible to the naked eye, and difficult to physically separate.[7] For such complex mixtures, other approaches are needed to recover metals, including pyrometallurgy, where materials are melted in a high-temperature furnace, and hydrometallurgy where wastes are treated with chemical solutions to extract dissolved metals. Both these approaches can be effective, but they each have drawbacks. Pyrometallurgy can extract significant amounts of metals from waste, but it has extremely high energy costs, and can release harmful compounds, such as dioxins, when plastics are burned. On the other hand, hydrometallurgy can be a rather slow and time-consuming process, and it requires aggressive 'leaching solutions'—including nitric, sulfuric and hydrochloric acids—that can pose significant environmental risks. Such risks must be factored into any cost-benefit analysis.

In recent years, there has been an increased emphasis on developing novel approaches to metal recovery from e-waste. One approach, inspired by nature, uses particular groups of microbes to extract metals from complex wastes.[8] This 'bioleaching' method holds significant promise as a more benign alternative to pyro- and hydrometallurgy, but it remains in its infancy, and has yet to be deployed at scale. Other high-tech approaches are also being developed. The tech giant, Apple, has built a robot named Daisy that can dismantle the company's iPhones and recover many of the valuable metals. A typical phone takes less than thirty seconds to process, and each robot can disassemble more than one million phones per year. That number is impressive, but it represents less than 1% of the new phones produced annually. A significant expansion of these technologies is thus needed, and other companies including Dell, Microsoft and Google have followed Apple's lead. They have come together to form the Circular Electronics Partnership, with the goal of significantly increasing recovery of metals and other valuable products from e-waste.

There is no doubt that technical innovation is needed. But that will not be enough. Innovative technologies will require appropriate regulatory and economic frameworks, with sufficient financing to operate at scale. The collection of e-waste needs to be significantly improved to provide an adequate 'feed stock' for new recycling methods. This could be achieved, for example, by building distributed networks bringing together informal e-waste collection and licensed recycling facilities, with appropriate financial incentives to attract experienced recyclers into the market. An increasing numbers of countries have legislation regulating the production and fate of e-wastes, but enforcement is poor in many cases, and existing policies do not sufficiently incentivize proper collection and management. Clear and enforceable regulations for e-waste collection and recycling are needed, with explicit responsibilities for the industry, consumers, municipalities and other levels of government.

Everyone has a role to play. Researchers must continue to develop more efficient, lower-cost and environmentally friendly technologies for e-waste recycling, seizing a significant opportunity to recover valuable materials from metal-rich 'urban mines'. Consumers should educate themselves on the full environmental and social impacts of their electronic products, demanding tighter oversight on e-waste disposal, and a licensing system to track the content of recycled materials (the electronic equivalent of fair-trade coffee, for example). The tech industry must take greater responsibility for its products, working to extend the lifetimes of our electronic gadgets, while also designing them for easier repair, upgrade and refurbishment. Both durability and ease of recycling should be built into the upstream design of all electronics, and manufacturers should also be actively involved in the downstream recovery process. Governments can help raise broad awareness about the importance of recycling, while also holding tech companies accountable, through both financial carrots and regulatory sticks. Governments at all levels, municipal, regional and national, should also work to standardize and streamline collection and recycling practices across different jurisdictions. In British Columbia, Canada, for example, recyclers only conduct the first steps of dismantling electronics before sending them by truck across the country to Quebec or Ontario for further processing. This represents a significant cost of both money and greenhouse gases, and a missed opportunity for local economic development and employment.

Looking ahead, we must work towards a global system that can recycle all metals currently in circulation, decoupling future economic growth from the large-scale extraction of primary resources. In this herculean task, we must focus on maximizing the use of our products over an extended lifetime, while also planning for their end-of-life recovery. Any future recycling systems will need to be practically feasible, cost effective and environmentally benign. They will also require appropriate financial incentives and enforceable regulatory frameworks. In the future, recycling of e-wastes will become increasingly attractive, as the cost of materials and waste disposal increases, and as the consumers become more aware of the true environmental footprint of their electronic devices. As we seek to live sustainably on a finite planet, we must come to once again appreciate the true value of the metals that support our daily lives.

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The End of Endlessness

Naomi Klein

Back in 2015, I attended a meeting in Toronto, along with sixty organizers and theorists from across the country, representing a cross section of movements: labor, climate, faith, Indigenous, migrant, women, anti-poverty, anti-incarceration, food justice, housing rights, transit and green tech. The catalyst for the gathering was a sudden drop in the price of oil, which had sent shock waves through an economy that relied on revenues from the export of high-priced oil. The focus of our meeting was how we could harness that economic shock, which vividly showed the danger of hanging your fortunes on volatile raw resources, to kick-start a rapid shift to a renewables-based economy. For a long time, we had been told that we had to choose between a healthy environment and a strong economy; when the price of oil collapsed, we ended up with neither. It seemed like a good moment to propose a radically different model.

At the time that we met, a federal election campaign was just gearing up in Canada, and it was already clear that none of the major parties was going to run on a platform of a rapid shift to a post-carbon economy. Both the Liberals and the New Democratic Party (NDP), then vying to unseat the governing Conservatives, were following the playbook that you needed to signal your 'seriousness' and pragmatism by picking at least one major new oil pipeline and cheering for it. There were vague promises being offered on climate action, but nothing guided by science, and nothing that presented

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a transition to a green economy as a chance to create hundreds of thousands of good jobs for the people who needed them most.

So, we decided to intervene in the debate and write a kind of people's platform, the sort of thing we wished we could vote for but that wasn't yet on offer. And as we sat in a circle for two days and looked each other in the eye, we realized that this was new territory for contemporary social movements. We had all, or most of us, been part of broad coalitions before, opposing a particularly unpopular politician's austerity agenda, or coming together to fight against an unwanted trade deal or an illegal war.

But those were 'no' coalitions, and we wanted to try something different: a 'yes' coalition. And that meant we needed to create a space to do something we never do, which is dream together about the world that we actually want. What we came up with was the Leap Manifesto.

I am sometimes described as the author of the Manifesto, but that's not true. My role was to listen and notice the common themes. One of the clearest themes was the need to move away from the national narrative that many of us had grown up with; one that was based on a supposedly divine right to endlessly extract from the natural world as if there were no limit and no such thing as a breaking point. What we needed to do, it seemed to us, was set that story aside and tell a different one based on a duty to care: to care for the land, water, air—and to care for one another.

When we first launched the Leap Manifesto, we hit up against a narrative that runs extremely deep; one that predates the founding of young countries like Canada.[1] It begins with the arrival of European explorers, at a time when their home nations had slammed into hard ecological limits: great forests gone, big game hunted to extinction. It was in this context that the so-called New World was imagined as a sort of spare continent, to use for parts. (They didn't call it NewFrance and New England by accident.)

And what parts! Here seemed to be a bottomless treasure trove—of fish, fowl, fur, giant trees and, later, metals and fossil fuels. In North America and then in Australia, these riches covered territories so vast that it was impossible to fathom their boundaries. These were places of endlessness—and whenever we began to run low, our governments just moved the frontier west.

The very existence of these lands appeared to come as a divine sign: forget ecological boundaries. Thanks to this body-double continent, there seemed to be no way to exhaust nature's bounty. Looking back at early European accounts of what would become Canada, it becomes clear that explorers and early settlers truly believed that their scarcity fears were gone for good. The waters off the coast of Newfoundland were so full of fish that they 'stayed the passage' of John Cabot's ships. For Quebec's Father François-Xavier de Charlevoix in 1720, 'The number of [cod] seems equal to that of the grains of sand that cover the bank'.[2] And then there were the great auks. The feathers of the penguin-like bird were coveted for mattresses, and on rocky islands, particularly off Newfoundland, they were found in huge numbers. As Jacques Cartier put it in 1534, there were islands 'as full of birds as a field of grass'.[3]

Again and again, the words inexhaustible and infinite were used to describe the Eastern forests of great pines, the giant cedars of the Pacific Northwest, all manner of fish. There was so much that there was a glorious freedom to be careless. Thomas Huxley (the English biologist known as 'Darwin's bulldog') told the 1883 International Fisheries Exhibition that 'the cod fishery are inexhaustible; that is to say nothing we do seriously affects the number of fish. Any attempt to regulate these fisheries seems consequently [...] to be useless'.[4]

That's a lot of famous last words, given what we now know. Given that by 1800 the great auks were completely wiped out. Given that beaver stocks began to crash in Eastern Canada soon after. Given that Newfoundland's supposedly inexhaustible cod was declared 'commercially extinct' in 1992. As for our inexhaustible old-growth forests: virtually wiped out in Southern Ontario. More than 91% of the biggest and best stands on Vancouver Island, gone.

Our economic niche was always voraciously devouring wilderness—both animals and plants. Canada was an extractive company, the Hudson's Bay fur trading company, before it was a country. And that has shaped us in ways we have yet to begin to confront. But it does go some way toward explaining why it caused such an uproar when a group of us got together and said: actually, we have hit the hard limits of what the Earth can take; we have to leave resources in the ground, even when they are still profitable. The time for a new story, and a new economic model, is now.

Because such enormous fortunes have been built in North America purely on the extraction of wild animals, intact forest, interred metals and fossil fuels, our economic elites have grown accustomed to seeing the natural world as their God-given larder. What we discovered with the Leap is that when someone or something (like climate science) comes along and challenges that claim, it doesn't feel like a difficult truth. It feels, as we learned, like an existential attack.

The economic historian Harold Innis warned of this almost a century ago. Canada's extreme dependence on exporting raw natural resources, he argued, stunted our country's development at 'the staples phase'. This is true for large parts of the US economy as well—Louisiana and Texas for oil, West Virginia for coal. This reliance on raw resources makes economies intensely vulnerable to monopolies and to outside economic shocks. It's why the term banana republic is not considered a compliment.

Though Canada doesn't think of itself like that, and some regions have diversified, our economic history tells another story. Over the centuries, we have careened from bonanzas to busts. In the late 1800s, the beaver trade collapsed when European elites suddenly lost their taste for top hats made of pelts and moved on to smoother silk. In 2015, the economy of Alberta went into free fall because of a sudden drop in the price of oil.

The trouble isn't just the commodity roller coaster. It's that the stakes grow larger with each boom-bust cycle. The frenzy for cod crashed a species; the frenzy for tar sands oil and fracked gas is helping to crash the planet.

And yet despite these enormous stakes, we can't seem to stop. The dependence on commodities continues to shape the body politic of settler-colonial states like Canada, the United States and Australia. And in all three countries, it will continue to confound attempts to heal relations with First Nations. That's because the basic power dynamic—our countries relying on the wealth embedded in their land—remains unchanged. For instance, when the fur trade was the backbone of wealth production in the northern parts of this continent, Indigenous culture and relationships to the land became a profound threat to extraction. (Never mind that there would have been no trade without Indigenous hunting and trapping skills.) Which is why attempts to sever those relationships to the land were so systematic. Residential schools were one part of that system. So were the missionaries who traveled with fur traders, preaching a religion that cast Indigenous cosmologies as sinful forms of animism—never mind, once again, that the worldviews they attempted to exterminate have a huge amount to teach us about how to regenerate the natural world, rather than endlessly deplete it.

Today in Canada, we have federal and provincial governments that talk a lot about 'truth and reconciliation' for those crimes. But this will remain a cruel joke if nonindigenous Canadians do not confront the 'why' behind those human rights abuses. And the why, as the official Truth and Reconciliation Commission report states, is simple enough: 'The Canadian government pursued this policy of cultural genocide because it wished to divest itself of its legal and financial obligations to Aboriginal people and gain control over their land and resources'.[5]

The goal, in other words, was always to remove all barriers to unrestrained resource extraction. This is not ancient history. Across the country, Indigenous land rights remain the single greatest barrier to planet-destabilizing resource extraction, from pipelines to clear-cut logging. We're still trying to get the land, and what's underneath. We see it south of the border as well, in the Standing Rock Sioux's pitched struggle against the Dakota Access Pipeline. This was true two hundred years ago, and it is true today. When governments talk of truth and reconciliation, and then push unwanted infrastructure projects, we must remember this: there can be no truth unless we admit to the 'why' behind centuries of abuse and land theft. And there can be no reconciliation when the crime is still in progress.

Only when we have the courage to tell the truth about our old stories will the new stories arrive to guide us. Stories that recognize that the natural world and all its inhabitants have limits. Stories that teach us how to care for each other and regenerate life within those limits. Stories that put an end to the myth of endlessness once and for all.

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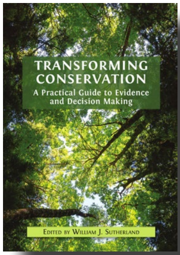
William J. Sutherland

https://doi.org/10.11647/OBP.0321



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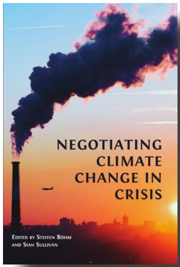

HEAVY METAL

EARTH'S MINERALS AND THE FUTURE OF SUSTAINABLE SOCIETIES

EDITED BY PHILIPPE TORTELL

Heavy Metal brings together world-leading experts from across the globe to reimagine the future of mineral exploration and mining in a post-fossil fuel world. Minerals and metals – for batteries, circuit boards, wiring and other components – are essential to a digital, carbon-neutral economy. But how can we grapple with the environmental, social and geopolitical challenges caused by the extraction and use of these critical resources?

Concise, accessible, and engaging, the essays in this timely collection intertwine a broad spectrum of disciplines to help us understand and reimagine our relationship with minerals. Exploring a wide range of themes, from the colonial history of mining and Indigenous resistance, to new frontiers in exploration geology, waste management and recycling, this book draws on experts from fields as diverse as geology, mining engineering, law, economics and public policy. The book also explores mineral resources through an artistic lens, with a collection of stunning images from the Canadian photographer Edward Burtynsky, and excerpts of a new musical work, the *Heavy Metal Suite*.

This thought-provoking and ultimately hopeful book guides us towards a more responsible, ethical and sustainable use of metals and minerals. It is essential reading for anyone interested in how we supply the resources needed for a carbon-neutral economic future.

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