Every year, *Elements* publishes six thematic issues on subjects related to the general disciplines of mineralogy, geochemistry, and petrology. The editorial team looks for topics that:

- are broadly related to mineralogy, geochemistry, and petrology
- are interdisciplinary
- represent established but progressing fields
- would be of interest to a broad cross section of readers
- have not been adequately represented by *Elements* before or have advanced considerably since the topic was previously covered

Each proposal is carefully evaluated by our editorial team for thematic scope, content, and authorship. Feedback is then provided to the proposers.

Once a proposal is accepted and included in the *Elements* lineup, the fun really begins! Over the subsequent 15–20 months, timelines and deadlines are set, authors are invited by the guest editors to write articles, and articles go through several stages of review (by external reviewers, by the guest and principal editors, and by the *Elements* editorial team). At the end of this process, the issue goes to press and is shipped to our over 16,000 readers.

The journey from an idea to a published magazine involves many steps. The goal? A lineup of well-written thematic issues that readily conveys the exciting aspects of mineralogy, petrology, and geochemistry to specialists and non-specialists alike.

**Call for Thematic Proposals**

Would you like to read about a certain topic in *Elements*? Do you think your research area would make a great thematic issue? Submit a thematic proposal!

The next submission deadline is **February 25, 2024**.

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We look forward to receiving your proposal!
Geometallurgy

Guest Editors: Max Frenzel, Raimon Tolosana-Delgado, and Jens Gutzmer

Geometallurgy: Present and Future
Max Frenzel, Regina Baumgartner, Raimon Tolosana-Delgado, and Jens Gutzmer

Characterisation of Ore Properties for Geometallurgy
Alan R. Butcher, Quentin Dehaine, Andrew H. Menzies, and Simon P. Michaux

All About Particles: Modelling Ore Behaviour in Mineral Processing
Lucas Pereira, Edgar Schach, Raimon Tolosana-Delgado, and Max Frenzel

Fire and Water: Geometallurgy and Extractive Metallurgy
Deshenthree Chetty, Glen T. Nwaila, and Buhle Xakalashe

Action Versus Reaction: How Geometallurgy Can Improve Mine Waste Management Across the Life-Of-Mine
Anita Parbhakar-Fox and Regina Baumgartner

Uncertainty and Value: Optimising Geometallurgical Performance Along the Mining Value Chain
Julian M. Ortiz, Sebastian Avalos, Alvaro I. Riquelme, Oy Leuangthong, Nasser Madani, and Max Frenzel

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The Clays Mineralogical Association of Canada was incorporated in 1955 to promote the advancement of the knowledge and related disciplines of clay minerals, clay science, and clay technology. The Association focuses on the study of clays and clay science and technology. The CMS holds annual meetings, workshops, and field trips, and publishes Clays and Clay Minerals and the CMS Workshop Lecture Series. Membership benefits include reduced registration fees at CMS meetings, reduced registration fees for short courses, and a subscription to the Clay Minerals Volcanic Ash Association, which serves as a forum for discussion and collaboration in the field of volcanic ash science. The VAA produces a newsletter and organizes workshops and field trips. Membership is open to individuals and institutions interested in volcanic ash science. The VAA is an affiliate of the International Association of Volcanology and Chemistry of Volcanic Eruptions (IAVCEI) and participates in international conferences and workshops. Affiliates may be granted associate, regular, or honorary membership, depending on their level of activity and contribution to the field. The VAA serves as a platform for the exchange of ideas and information, fostering collaboration and advancing the science of volcanic ash.
Verbatim conversation with one of my French post-docs (which took place before 2023) blockbuster movie “Oppenheimer”) as they prepared to embark on their next research position in Chicago.

Me: “So you absolutely must go see the landmark Henry Moore monument.”

Post-doc: [blank stare]

Me: “You know, the bronze sculpture (‘Nuclear Energy’) that commemorates the site of the first human-made, self-sustained, controlled nuclear chain reaction by Fermi (on December 2, 1942)?”

Post-doc: [blank stare]

Me: “Well, you know—the early days of the Manhattan Project?”

Post-doc: “The what…?”

Me: “The Manhattan Project. You don’t know the Manhattan Project??”

Me: “Wondering if I had run into yet another language problem with French, because I clearly was not making myself understood—and what other explanation could there be?!”

Me: “Perhaps it’s called something else in French?”

Post-doc: [confused]: “I have no idea—but I’m going to Chicago, not Manhattan.”

Me: [shocked]: “How can you not know about the Manhattan Project?! At 30-something?! Have you never read Richard Rhodes’ classic books “The Making of the Atomic Bomb” and “Black Sun”? Which, by the way, are complete page-turners!”

Post-doc: [blank stare]

My personal shock aside, this kind of conversation—it is not unique, nor a recent phenomenon. It is one of the reasons why the European Association of Geochemistry, now over a decade ago, came up with the thematic series Geochemical Perspectives, now over a decade ago, came up with the Geochemical Perspectives booklet series, written on invitation-only by the more senior scientists of our geochemistry community (so admittedly, but by definition, not DEI compliant), to ensure that we commit the history, players, and evolution of our field to paper while still in living memory so as to pass on the foundation of our discipline to our students and early-career scientists—many of whom today do not seem to realize that the field of isotope geochemistry is rooted in the WWII Manhattan Project.

Elements, of course, is another great vehicle for conveying the history of science, as you will see when you read this issue’s captivating Triple Point (page 403) concerning two peculiar pages of “The Making of the Atomic Bomb” and “Black Sun”?

Me: “Oppenheimer” as they prepared to embark on their next research position in Chicago.
that inevitably emanate from complex mining operations, with the ultimate goal (yet to be achieved) of converting all mine waste into resources. The questions of how to make decisions about mine waste disposal and how to quantify resource ingredients in mine waste piles for possible resource recovery to fully utilize the primary materials we mine, while simultaneously protecting the environment, are fast becoming first priorities to the mining industry and society at large. Hence, the present issue of *Elements* is as timely as it gets.

The players in the theater of WWII went all in—finding all possible resources (intellectual, physical, logistical, financial) to do what seemed practically impossible, but theoretically possible—to succeed with the hugely ambitious, Herculean, never-before-done Manhattan Project, because life as it was known at the time, and freedom above all, was at stake. Will the players in today’s theater of attempting to combat climate change have the same drive, sense of urgency, and fear of impending catastrophe to act similarly? One can safely say that, by comparison, everything is again at stake, even if not exactly in the same way or for the same reason as during WWII, but that seems rather irrelevant as the overall outcome of losing the current battle against climate change will be pretty much the same as having failed the Manhattan Project, even if resulting in very different end scenarios.

To loop back to my favorite books with a bit of speculation: in the distant future, when humanity looks back on history at our time right now when Earth’s population just passed the 8-billion mark and is projected to continue its growth unabatedly to ~10 billion by 2050, and Earth itself is on its way, if not already there, to hit the tipping point of +1.5 °C despite the world’s commitment to the Paris Agreement in 2015—will there be a book to read one day entitled “The Making of a Sustainable Planet” in the same way we today, 80 years after the fact, read about “The Making of the Atomic Bomb”? Maybe, but only if we succeed in building a sustainable future. Otherwise, there will be neither books nor readers.

So now: full disclosure. None of the above was written without me realizing full well that the use of the Manhattan Project analogy is a highly sensitive and delicate matter because of its many-faceted layers, with the technological breakthroughs it spawned being only one of them—and even that aspect is not entirely positive. So let me frame my Editorial in that spirit. By drawing the analogy of a “Manhattan Project on climate change”, I was thinking only on the strong motivation and extraordinary dedication involved in solving a vital existential emergency, there will inevitably be social upheaval at the same scale as a world war, this time brought about, not by a tyrant, but by climate change—induced crop failures, droughts, water shortages, floods, wildfires, famines, population migrations, epidemics/pandemics, etc.

Another controversial aspect is that the Manhattan Project is associated not only with having given us a potential source of energy, but also with terrible destruction of a kind and at a scale (potentially the entire planet) never seen before, which in the decades following WWII went on to cause much political maneuvering and anxiety… and still does to this day (I shall leave out “who” comes to mind). It is, however, no use thinking that any of this could have been avoided: with the state of knowledge in the late 1930s, the exploration and development of nuclear weapons—culminating in the horror the Bomb unleashed on the world—and the acquisition of nuclear energy by countries with the necessary technological, industrial, and economic capacity and knowledge were bound to happen sooner or later, but happened much faster because of the war. Wouldn’t it be great if the same could happen today with climate-change solutions? Perhaps the recent catastrophic weather events (e.g., horrific heatwaves, forest wildfires, foul air, extreme precipitation events, flooding, rising ocean temperatures, record low sea ice) that the entire world has been experiencing for some years now—not to mention that as I am writing this Editorial in July 2023, this month saw the hottest day in recorded climate history, while the month of July itself is on track to become the hottest month on record—will make humankind understand, like really understand, that the problem will not go away by itself and, consequently, open our collective minds (and thus governments, corps, politicians, and scientists) to the extreme urgency of the situation. As a whole, our society has so far barely lifted a pinky finger to truly address the climate problem, despite us being aware of it for decades.

To nonetheless finish on a positive note despite the fast-approaching threat of climate change, the present situation does provide for a lot of new opportunities, call them silver linings, whether this be bio-, geo-, or chemical engineering, recycling, or geometallurgy, to name just a few of those disciplines for which basic and applied research must now come together and be more creative and innovative than ever before to save the world2. Still, a word of caution: bio-, geo-, and chemical engineering solutions should not be used as an excuse to continue the status quo and absolve us from facing the more direct first-order need to make serious long-lasting lifestyle changes and use less energy. So to our young *Elements* readers: it is your knowledge, efforts, initiative, diligence, and leadership that will be key to mitigating the climate-change problem with its imminent horrors. It is the resourcefulness, intelligence, and empathy that I see in your generations that give us all hope. This, in turn, is what keeps inspiring the older generations (like myself) to continue to find purpose and meaning in teaching a new class of geoscience students every year. This issue of *Elements* is part of that effort.

Janne Blichert-Toft
Principal Editor

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2 ...by which, I mean “save ourselves”—a slightly less noble goal than saving the planet—as the Earth undoubtedly will be fine without us and spring right back into shape after we have committed collective suicide. After all, the Earth spent most of its existence without humankind.
ABOUT THIS ISSUE

Initial discussions on the need to reduce global CO2 emissions focused mostly on the transition from fossil fuels to renewable energy sources. However, it has now become clear that large additional supplies of mineral resources—like copper, nickel, and lithium—will be required to build the energy systems of the future. Valid concerns have been raised about the sustainability of increasing production from a natural resource base marked by ever-decreasing metal contents and increasingly challenging environments. One major conclusion from this discussion is that the efficiency of raw material production must improve rapidly. We simply cannot afford to waste energy and resources in the face of quickly rising demand. This is where geometallurgy comes in—the topic of this Elements issue.

Geometallurgy is an interdisciplinary research field concerned with the planning, monitoring, and optimization of mineral resource extraction and processing. For this, geometallurgy integrates geological, mineralogical, and geochemical data on mineral deposits with expertise on mining and beneficiation, geostatistics, economics, and a range of other closely related fields. This Elements issue explores the fundamental concepts of the field, and reviews how geometallurgical research is opening up exciting new opportunities for geoscientists in both industry and interdisciplinary research.

YEAR IN REFLECTION

Elements is thrilled to wrap up the fascinating 2023 publication cycle with this issue’s eloquent primer on the fundamental science, techniques, and modern challenges of geometallurgy. Each Elements issue covers a carefully curated collection of review papers on a topic of broad interest in the geosciences, particularly mineralogy, geochemistry, and petrology. This year, Elements published six well-rounded thematic issues, guest edited by top researchers in the field, on the following topics: “Alkaline Lakes” (February 2023), “Into the Rift: The Geology of Human Origins in Eastern Africa” (April 2023), “Olivine” (June 2023), “Biomagnetism” (August 2023), “Large Igneous Provinces: Versatile Drivers of Global Change” (October 2023), and now “Geometallurgy” (December 2023). We thank you for reading and sharing Elements magazines with your geoscience-oriented students and colleagues, both in print and online. Please enjoy a sneak peek of the Elements 2024 lineup on the subsequent two pages.

We would particularly like to recognize the following society volunteers for their extraordinary efforts this year. Each society can contribute a Society News page for each issue, covering current events including activities, awards, anecdotes, opportunities, and much more. News entries are fully coordinated by the Society News Editor of each society and involve extended hours of content creation and proofing. Subscriber lists for the print mailing and online access of each issue are carefully maintained by the Database Manager of each society. This year, our Database Managers put in extra hours and provided helpful feedback to support our team rebuild the Elements’ database platform.

These 32 individuals have been a pleasure to work with along each step of the Elements path. We are grateful for their kindness, careful eye for detail, and the growing camaraderie we have all enjoyed with laughter and story-telling at a few informal Elements Coffee Hour virtual chats. We sincerely thank them for their hard work, patience, and creativity to help Elements achieve its best form.

We extend our gratitude and warmest wishes for a happy and healthy new year to the full Elements community: the Society News Editors, Database Managers, Guest Editors, authors, Principal Editors, Executive Committee, graphics team, IT support team, print press and distribution associates, proofreaders, calendar coordinator, advertisers, and, of course, all of our cherished readers. May 2024 be a year of positive change and inspiration!

Becky Lange, Janne Blichert-Toft, Sumit Chakraborty, Tom Sisson, and Esther Posner
EXTRATERRESTRIAL ORGANIC MATTER

Guest Editors: Mehmet Yesiltas (Kirkareli University, Turkey) and Yoko Kebukawa (Tokyo Institute of Technology, Japan)

Extraterrestrial organic matter is found in various extraterrestrial environments and in various forms. It forms in a variety of locations through different mechanisms in space. As such, its nature, distribution, formation mechanisms and locations are of particular interest. Some organic molecules are even considered as key players for the emergence of life on Earth and possibly beyond. Therefore, their detection and characterization can contribute to the understanding of the early solar system evolution as well as the origin of life. Despite decades of work and research, there are still many questions and unknowns on this topic. The aim of this issue of Elements is to offer an overview of the concept of extraterrestrial organic matter as well as the latest scientific findings.

• Extraterrestrial Organic Matter: An Introduction  Mehmet Yesiltas (Kirkareli University, Turkey) and Yoko Kebukawa (Tokyo Institute of Technology, Japan)
• Formation and Evolution Mechanisms of Organic Matter in Space  Hikaru Yabuta (Hiroshima University, Japan), Hideko Nomura (National Astronomical Observatory of Japan, Japan), and Queenie H.S. Chan (Royal Holloway University of London, UK)
• Delivery of Organic Matter to Early Earth  Zita Martins (Universidade de Lisboa, Portugal) and Matthew A. Pasek (University of South Florida, USA)
• Diversity of Complex Organic Matter in Carbonaceous Chondrites, IDPs, and UCAMMs  Bradley T. De Gregorio (US Naval Research Laboratory, USA) and Cécile Engrand (Université Paris-Saclay, France)
• Asteroideal Organics from the Sample Return Mission Hayabusa2 and their Implication for Understanding our Origins  Shogo Tachibana (University of Tokyo, Japan) and Nami Sakai (RIKEN Cluster for Pioneering Research, Japan)
• Analytical Techniques for Identification and Characterization of Extraterrestrial Organic Matter  Yoko Kebukawa (Tokyo Institute of Technology, Japan), Mehmet Yesiltas (Kirkareli University, Turkey), and Timothy D. Glotch (Stony Brook University, USA)

PAIRED METAMORPHIC BELTS OF SW JAPAN: METAMORPHIC RECORDS OF A SUBDUCTION SYSTEM

Guest Editors: S. R. Wallis (University of Tokyo, Japan), K. Miyazaki (Geological Survey of Japan, AIST, Japan), and U. Knittel (RWTH Aachen University, Germany)

Subduction, where one plate dives beneath another, controls long-term whole-Earth cycling of rocks, fluids and energy. Plates subduct faster than they heat up, making them the coldest parts of the Earth’s interior. Fluids released from these cold plates rise into hotter overlying rocks forming magma that feeds surface volcanism. Cold deep conditions associated with subduction complemented by hot shallow conditions under volcanic arcs are reflected in the presence of pairs of metamorphic belts representing sites of ancient subduction—the Cretaceous Sanbagawa-Ryoke metamorphic pair of Japan is a premier example. Estimates of pressure, temperature, the age and duration of metamorphism, and the tectonic framework in which metamorphism took place help us develop quantitative models both for the evolution of SW Japan and subduction systems in general.

• Paired Metamorphism in SW Japan  S. R. Wallis (University of Tokyo, Japan), K. Miyazaki (Geological Survey of Japan, AIST, Japan), T. Okuda (Osaka Metropolitan University, Japan)
• Sanbagawa Subduction: What Went In, How Deep, and How Hot Did It Get  S. Endo (Shimane University, Japan), Y. Kouketu (Nagoya University, Japan), M. Aoy (Tokushima University, Japan)
• Mantle Wedge of the Sanbagawa Subduction Zone  A. Okamoto (Tohoku University, Japan), S. Endo (Shimane University, Japan), and T. Nagaya (University of Tokyo, Japan)
• Geochronology of the Sanbagawa Belt: Younger and Faster Than Ever Before  U. Knittel (RWTH Aachen University, Germany), T. Tokiwa (Shinshu University, Japan), Y. Tsutsumi (National Museum of Nature and Science, Japan), S. Endo (Shimane University, Japan), and S. R. Wallis (University of Tokyo, Japan)
• Metamorphism beneath the Ryoke Volcanic Arc: Timing and P–T conditions  T. Okudaira (Osaka Metropolitan University, Japan), T. Kawakami (Kyoto University, Japan), T. Ikeda (University of Kyushu, Japan), and E. Skrypek (University of Graz, Austria)
• Cretaceous Plate Movements in the Eastern Pacific Domain and the Geology of Japan  Jonny Wu (University of Houston, USA), Sung-Jui Wu (University of Houston, USA), and Ken Yamaoka (Geological Survey of Japan, AIST, Japan)
• Thermal Models of the Ryoke and Sanbagawa Metamorphic Domains  K. Miyazaki (Geological Survey of Japan, AIST, Japan), K. Ishii (Osaka Metropolitan University, Japan), S. R. Wallis (University of Tokyo, Japan), and C. Annen (Institute of Geophysics Czech Academy of Science, Czech Republic)

CRATONS RECEIVE THE HIGHEST GRADES

Guest Editors: Paul Mueller (University of Florida, USA) and Carol Frost (University of Wyoming, USA)

Archean continental crust is present on every continent, but does not constitute a dominant part of any continent’s surficial exposures. Nevertheless, Archean cratons are the longest-lived coherent physical structures on earth. Viewed holistically they comprise a welded combination of continental crust and a sub-continental lithospheric mantle keel. They are survivors of what may, or may not, have been a more numerous and varied population of protocontinents. Many of these crustal blocks have origins in the Hadean and have survived for billions of years through many supercontinent cycles. Consequently, these craton-keel structures have influenced the physical and chemical evolution of the silicate earth. This issue of Elements provides an overview of Archean cratons and the information they retain about the early development of Earth’s continental crust.

• In the Beginning There Were Cratons  Paul Mueller (University of Florida, USA) and Carol Frost (University of Wyoming, USA)
• Earth’s Earliest Crust  Jonathan O’Neill (University of Ottawa, Canada), Hanika Rizo (Carleton University, Canada), Jesse Reimink (Pennsylvania State University, USA), Marion Garçon (Université Clermont-Auvergne, France), and Richard W. Carlson (Carnegie Institution for Science, USA)
• At the Dawn of Continents: The Archean Tonalite-Trondhjemite-Granodiorite Suite  Oscar Laurent (CNRS, Géosciences Environnement Toulouse, France), Martin Guiraud (Université Clermont-Auvergne, France), Emilie Bruand (Université Clermont-Auvergne, France), and Jean-François Moyen (CNRS, Geo-Ocean, Brest, France)
• Structural Evidence for Plate Tectonics in Archean Cratons  Brian Windley (University of Leicester, UK)
• Decoding the Surface of Archean Cratons  Patrice Rey (University of Wollongong, Australia), Nicolas Coltice (École Normale Supérieure, Paris, France), and Nicolas Flament (University of Sydney, Australia)
• Embracing the Complexity at Depth: Exploring the Heterogeneity within Cratonic Lithosphere  Catherine Cooper (Washington State University, USA) and Meghan Miller (Australian National University, Australia)
THE INVISIBLE OCEAN: HYDROGEN IN THE DEEP EARTH

GUEST EDITORS: Sylvie Demouchy (Univ. Clermont Auvergne, France), Hélène Bureau (Sorbonne University, France), and Hans Keppler (Univ. Bayreuth, Germany)

Hydrogen is the most abundant element in the universe and its distribution, transfer, and speciation in the deep Earth remain a fascinating topic of ongoing research. We review the most notable discoveries constraining the H cycle in the deep Earth. This includes new methods for detecting hydrogen, insights into the size of deep reservoirs, and new constraints from inclusions in ultradepth diamonds. Advances in seismic and magneto-telluric imaging provide unique data on the storage and mobility of water in Earth's interior. Models of the early Earth and of its habitability critically depend on the behavior of hydrogen in a magma ocean–atmosphere system. Later in Earth history, water may have been essential for establishing plate tectonics, a phenomenon making Earth a unique planet.

• Hydrogen in the Depth Earth Jed Mosenfelder (Univ. Minnesota, USA), Anthony C. Wilbers (Univ. Bayreuth, Germany), and Hélène Bureau (Sorbonne University, France)

• Fuel for Plate Tectonics: The Burial of Hydrogen During Subduction Hans Keppler (Univ. Bayreuth, Germany), Eiji Ohtani (Tohoku University, Japan), and Xiaozhi Yang (Univ. Nanjing, China)

• Deep Hydrogen Reservoirs and Longevity Davide Novella (Univ. Padova, Italy), Sylvie Demouchy (Univ. Clermont Auvergne, France), and Nathalie Boltan-Casanova (Univ. Clermont Auvergne, France)

• Hydrous Melting and its Seismic Signature Stéphanie Durand (Univ. Lyon, France), Marija Putak Juricek (Univ. Göttingen, Germany), and Karen Fischer (Brown University, USA)

• Probing Deep Hydrogen using Electrical Conductivity Takashi Yoshino (Okayama University, Japan), Geeth Manthilake (Univ. Clermont Auvergne, France), Anne Pommier (Carnegie Inst. for Science, USA)

• Hydrogen in the Early Earth and through Geologic Time Fabrice Gaillard (University of Orléans, France) and Lars Rüpe (GEOMAR, Germany)

HIMALAYAN LEUCOGRANITES

GUEST EDITORS: Fang-Zhen Teng (University of Washington, Seattle, USA) and Fu-Yuan Wu (Institute of Geology and Geophysics, Chinese Academy of Sciences, China)

Himalayan leucogranites crop out intermittently over 2000 km along the Himalayan crest in the Himalayan–Tibetan plateau. They constitute some of the most well-studied granites in the world. They are considered to be purely crustal-derived melts and indicators of collisional orogenesis, and have greatly improved our general understanding of crustal anatexis, differentiation of felsic magmas, and tectonic evolution of the Himalayan–Tibetan Orogen. They provide a rare opportunity to explore the feedback relationships among geodynamics, tectonics, and magmatism in a classic continental collisional context. In this issue, we will describe our current understanding of the petrogenesis and significance of the Himalayan leucogranites by focusing on their tectonic and geodynamic background, source rocks, petrology, geochemistry, and links to orogenesis and economic resources. This issue will not only summarize the state-of-the-art research on leucogranites but also present an example of how a multidisciplinary approach can be used to constrain the petrogenesis of granites and the associated mineralization and orogenic evolution.

• Himalayan Leucogranites: Petrogenesis and significance Fang-Zhen Teng (University of Washington, Seattle, USA) and Fu-Yuan Wu (Institute of Geology and Geophysics, Chinese Academy of Sciences, China)

• Himalayan Leucogranites: Tectonics and geodynamics Mike Searle (University of Oxford, UK) and John Cottle (University of California, Santa Barbara, USA)

• Himalayan Leucogranites: Orogenesis and crustal flow Matt Kohn (Boise State University, USA), Sean Long (Washington State University, USA), and Mark Harrison (University of California, Los Angeles, USA)

• Himalayan Leucogranites: A petrological perspective Bruno Scaillet (Orleans University, France) and Michel Pichavant (Orleans University, France)

• Himalayan Leucogranites: A geochemical perspective Ze-Zhou Wang (University of Washington, Seattle, USA), Fang-Zhen Teng (University of Washington, Seattle, USA), LingSen Zeng (Institute of Geology, Chinese Academy of Geological Sciences, China), and Zhi-Chao Liu (Sun Yat-sen University, China)

• Himalayan Leucogranites: Rare-metal resources Fu-Yuan Wu (Institute of Geology and Geophysics, Chinese Academy of Sciences, China), Xiao-Chi Liu (Institute of Geology and Geophysics, Chinese Academy of Sciences, China), Fang-Yang Hu (Institute of Geology and Geophysics, Chinese Academy of Sciences, China), Lei Xie (Nanjing University, China), and Ru-Cheng Wang (Nanjing University, China)
Regina Baumgartner is a section leader of the Applied Mineralogy and Geoscience Group at Teck’s Technical Services in Trail, Canada. She obtained her PhD from University of Geneva in Switzerland. Regina has gained expertise in geometallurgy over the last 18 years working on a number of advanced projects and mine operations, as well as focusing on tailings and waste rock characterization. She is currently working on various internal projects focusing on the geometallurgy of ore, tailings, and waste rock characterization to support more informed mine planning and waste management. The additional economic potential through re-processing and re-purposing is one key focus of her projects at operating and legacy sites. Regina has been involved in several characterization projects worldwide.

Alan R. Butcher is currently a professor of geosciences and applied mineralogy at the Geological Survey of Finland (GTK). His main interests are in the imaging and analysis of rocks and commercial significance, where he is developing multi-dimensional, multi-modal, and multi-scale workflows that can be used in geometallurgy applications. Previously, Alan was involved in developing automated mineralogy technologies for a range of applications, from ores, coal, oil, and gas to soil and criminal forensics, quantitative petrology, and even extra-terrestrial materials (1998–2017). He began his career mapping the Rum layered intrusion whilst studying for a PhD at Manchester University, UK, and afterwards the Bushveld Complex, during research fellowships held at Pretoria University (Australia), CSIR (India), and Rhodes University (USA) (1980–91). This experience led to his appointments as lecturer in igneous petrology, and director of the MSc in mining geology, both at the Camborne School of Mines, UK (1991–98).

Deshentthree Chetty heads the Mineral Science Group in the Mineralogy Division at Mintek, South Africa, where she has spent the past 25 years working on process mineralogy of various commodities with respect to comminution, physical separation, flotation, hydrometallurgy, biometallurgy, and pyrometallurgy, particularly for flowsheet development. Her PhD at the University of Johannesburg (South Africa) focused on the northern Kalahari Manganese Deposit in South Africa, with respect to ore genesis and smelting properties. Her interests lie in analytical techniques to measure mineral properties relevant for process behaviour, mineralogical impacts on ore behaviour under given process conditions, and relating these to spatial distribution of ore types.

Quentin Dehaine is a senior researcher at the Geological Survey of Finland (GTK) interested in ore geology, geometallurgy, mineral processing, and traceability of battery minerals (cobalt, lithium) and critical raw materials (CRMs). After completing his PhD at the University of Lorraine (France) in 2016, he worked as a postdoc researcher at the Camborne School of Mines (UK), working on the geometallurgy of cobalt from the Democratic Republic of Congo (DRC). In 2019, Quentin joined the GTK with the objective of developing innovative integrated approaches to support mine value chain optimization through geometallurgy. Quentin is the officer for Scandinavia within the International Union of Geological Sciences Initiative on Forensic Geology (IUGS-IFG).

Max Frenzel currently leads the Geometallurgy and Economic Geology Group at the Helmholtz-Institute Freiberg for Resource Technology in Germany. His research focuses on different aspects of the geology, mineralogy, geochemistry, and texture of base-metal ores, and how these affect mineral processing operations. In addition, he is interested in the modelling of metal supply chains to better understand potential future availability issues. Max obtained his MSc in geological sciences from the University of Cambridge (UK) in 2012, followed by a PhD in economic geology from TU Bergakademie Freiberg in 2016. After a postdoc at the University of Adelaide, Australia, he returned to Freiberg in 2018.

Jens Gutzmer is an economic geologist fascinated by the question of how to translate mineral system models into concepts for sustainable resource discovery and utilization. He obtained his PhD in geosciences at the Rand Afrikaans University in South Africa in 1996 and was awarded a South African Research Chair in Geometallurgy at the University of Johannesburg, South Africa, in 2008—a global first in this new field of research. In 2011, he was employed as scientific director of the Helmholtz Institute Freiberg for Resource Technology—a position he still holds. More recently, he was appointed as professor in economic geology and geometallurgy at the Technische Universität Bergakademie Freiberg in Germany.

Oy Leuangthong is a corporate consultant (geostatistics) at SRK Consulting Canada. Oy has over 20 years of experience with geostatistics and 3D modelling of mineral and petroleum resources. Oy has been involved with estimation and simulation studies in multiple commodities worldwide. She has authored and co-authored 20 journal papers, and more than 30 conference articles on geostatistics for resource characterization. Prior to joining SRK in 2010, she was an assistant professor in Mining Engineering at the University of Alberta in Edmonton, Canada. Oy has given numerous presentations at national and international conferences. In 2018, she was voted one of the 100 Global Inspirational Women in Mining.

Nasser Madani is an associate professor at Nazarbayev University in Kazakhstan, where he teaches and conducts research on geostatistics and mineral resource estimation. He has consulted to mining companies and research projects in geostatistical modeling in Kazakhstan and worldwide. Nasser is especially interested in developing and accelerating the geostatistical algorithms via programming in mathematical scripting languages such as MATLAB.

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Anita Parbhakar-Fox is a mine waste geoscientist and associate professor of environmental geoscience at the Sustainable Minerals Institute of The University of Queensland (Australia) and is the inaugural group leader of MIWATCH. She received her PhD in 2012 from The University of Tasmania (CODES), Australia. Her current research focuses on the secondary prospectivity of mine waste, and she is leading an Australian-wide campaign sampling these environments to explore the relationships between ore deposit type and mine waste signature and to find new metallurgical pathways for critical metal recovery. Her research agenda is focused on better integrating mineralogy in mine waste assessments across the life-of-mine, which also includes exploring new methods to extract environmental indices from drill-core scanning technologies.
The clean energy transition is essentially a shift from fossil fuels, including coal, natural gas, and petroleum, to nonfuel mineral commodities, such as tellurium, lithium, and rare earths. That is because clean energy technologies like solar panels, wind turbines, electric vehicles, and electric grid energy storage systems require significant quantities of these and other nonfuel mineral commodities—but it is, of course, much more than that. The clean energy transition is about trade and supply chains; manufacturing and jobs; resource nationalism and great power competition. It is also about the environment and community relations; economic development and the circular economy; emerging technologies and intellectual property. As we race toward the middle of the 21st century, one would be hard pressed to identify a topic that is at the nexus of more consequential issues than this one.

Consider that climate change—arguably the “biggest threat modern humans have ever faced” (United Nations Security Council 2023)—and mineral commodity supply chains are linked in at least three distinct ways. First, mineral commodities are essential to clean energy generation, transmission, and storage technologies. Second, the production of mineral commodities requires notable quantities of energy during mining, beneficiation, smelting, and refining operations, currently resulting in greenhouse gas (GHG) emissions that cause climate change. Third, the effects of climate change can impact mineral commodity supply chains by disrupting mining and processing infrastructure and operations, affecting water availability and weather patterns that may be essential to certain operations and regional watersheds, changing access to supply chains and disrupting trade routes, impacting worker health and safety, affecting ecosystems, and increasing conflict with local communities. Although distinct, the linkages between climate change and mineral commodity supply chains are also interdependent. For example, increasing demand for clean energy technologies (to offset the demand for fossil fuels that cause climate change) will result in increased demand for mineral commodities, the production of which may release additional GHG emissions that would increase the impacts of climate change and may, in turn, limit access to the necessary mineral resources. This Perspective article explores these linkages, discusses some of their interconnections, and highlights the importance of geometallurgy (the practice of combining geology or geostatistics with extractive metallurgy to design a spatially or geologically based predictive model for mineral processing plants) and systems thinking to tackle the potential positive feedback loops that could jeopardize the technological changes necessary to counter climate change.

As demand for clean energy technologies increases so, too, will demand for mineral commodities. For example, in addition to requiring cobalt, graphite, lithium, nickel, and manganese for certain lithium-ion batteries, electric vehicles (EVs) also require more copper and rare earth permanent magnets than their internal combustion engine (ICE) counterparts (International Energy Agency 2022). While demand for EVs and other clean energy technologies is expected to increase markedly in the coming decades, the specific technology or technologies that will become dominant is highly uncertain. There are, for example, several different lithium-ion battery cathode compositions including lithium nickel–manganese–cobalt oxide (NMC, at different proportions of nickel to manganese to cobalt), lithium nickel–cobalt–aluminum (NCA), lithium manganese oxide (LMO), and lithium iron phosphate (LFP). The different lithium-ion battery chemistries have different strengths and weaknesses regarding important aspects of functionality including lifespan, power and energy densities, safety, and cost. This uncertainty in technological choices and adoption rates translates into uncertainty for mineral commodity demand, as different technologies require different quantities and varieties of mineral commodities.

Certain lithium-ion battery cathode chemistries require relatively large quantities of cobalt (e.g., NCM 111, with equal proportions of nickel, cobalt, and manganese), some require considerably less cobalt but more nickel (e.g., NMC 811), while others do not require cobalt or nickel at all (e.g., LFP and LMO). Similarly, different solar PV technologies require different byproduct mineral commodities (e.g., silver for crystalline silicon versus cadmium and tellurium for cadmium telluride solar photovoltaics). Demand for mineral commodities will thus depend on not only the growth in the demand for solar PV, but also on the individual technologies that are adopted and their material intensities (Nassar et al. 2016). Mineral commodities will also be increasingly needed in various applications that may be less obviously identified as “clean” energy technologies, but will be needed for the reduction of energy use and related GHG emissions nonetheless. For example, the continuing trend toward the light-weighting of vehicles and aircraft may require the use of lightweight nonferrous alloys (e.g., aluminum–lithium alloys) and high-strength, low-alloy steels that require elements like niobium and vanadium. Conversely, the shift to clean energy technologies may decrease demand for some mineral commodities. Approximately 41% of platinum, 83% of palladium, and 89% of rhodium gross global demand in 2022 were in automotive catalytic converters for the reduction of tailpipe emissions of ICE vehicles (Bloxham et al. 2022)—demand that will not be needed for EVs. Additionally, some platinum-group metal demand is for catalysts used in petroleum refining, which may also diminish with the reduced demand for gasoline and diesel. This shift may “free up” some platinum-group metal supplies to be used in other applications, such as the production of “green” hydrogen via proton exchange membrane fuel cells and electrolyzer technology (Moreira et al. 2022).

As demand for certain mineral commodities increases, it is not clear that supply from primary or secondary (i.e., end-of-life or post-use recycling) sources can keep pace. Some analyses in the literature suggest that there is significant potential to increase the recovery of some byproduct mineral commodities, such as gallium, germanium, indium, and tellurium, which have historically not been recovered at high rates (Licht et al. 2015; Frenzel et al. 2016a, 2016b, 2017; Nassar et al. 2022a). There is an obvious need for the geosciences, and particularly geometallurgy, to help increase the knowledge necessary to determine if these potentials can actually be realized.

Most analyses in the literature (e.g., Elshkaki and Graedel 2013; Nassar et al. 2016; Moreira et al. 2022; International Energy Agency 2022), however, focus on developing demand forecasts or scenarios, with few examining demand and supply concurrently. The resultant picture is often one in which demand projections greatly surpass those of current supply (or current supply plus any additional supply from announced projects). In reality, without sufficient supply from primary and secondary sources, demand will not be fulfilled as projected, and prices will increase, leaving some to find substitute materials or other means of fulfilling that need. In anticipation of difficulties in securing cobalt supplies, some vehicle manufacturers have already begun shifting away from high-cobalt to low-cobalt and cobalt-free battery cathode chemistries (e.g., LFP) (Blois 2023). Higher-level (e.g., systems-level) substitution may also occur (or be encouraged via various policies) to offset some of the demand. Increased mass transit and designing urban areas for alternative and more efficient modes of mobility can, for example, offset some of the demand for new personal vehicles (Riofrancos et al. 2023).

Pressure to increase supply, as signaled through higher market prices, will likely result in mineral projects coming online that would have previously been considered uneconomic. Some of the previously uneconomic projects may have simply had relatively low ore grades. This has important implications as mining and processing ores with previously been considered uneconomic projects may have simply had relatively low ore grades. Some of the previously uneconomic projects may have simply had relatively low ore grades. This has important implications as mining and processing ores with relatively low grades generally translates to greater volumes of waste (Nassar et al. 2022b), greater energy usage, and more GHG emissions (Norgate et al. 2010; Calvo et al. 2016). While it is recognized that large amounts of energy and GHG emissions are associated with major metals such as iron...
and steel (International Energy Agency 2020), relatively little information is available for many other mineral commodities. Some life cycle energy and GHG emissions data are available and updated regularly by mineral industry associations (e.g., International Aluminium Institute 2023). Most of the data in the life cycle inventory and related literature (e.g., Nuss and Eckelman 2014) are, however, not regularly updated and commonly cover only one or two “typical” operations. The degree of variability in energy usage and GHG emissions between operations is thus generally not known. Similarly, while there have been detailed asset- or process-based analyses for specific mineral commodities (see recent work on lithium-ion battery materials by Benchmark Minerals Intelligence (2023) and the assessment of several commodities by Skarn Associates (2022)), such efforts are typically limited in scope and commodity coverage. Having comprehensive asset-level information that is updated regularly can help in not only understanding the variability in the data, but also provides a strong foundation for understanding the key drivers of that variability between operations. This would thus provide essential information to understanding the energy use and GHG emissions of current mineral commodity supplies and the factors that may affect them in the future, thereby allowing companies and governments to make more informed decisions and policies.

Reducing GHG emissions of mining and processing operations will likely involve increasing the share of clean energy technologies that supply their electricity (which will increase demand for certain mineral commodities), as well as other efforts that seek to reduce or eliminate GHG emissions from the processes themselves. An example of the latter is the joint venture formed between Alcoa and Rio Tinto, Elysis, which in 2018, announced the development of a novel aluminum smelting process that does not directly release GHG emissions (Elysis 2023). Again, geometallurgy can play a key role in understanding what might be possible with respect to reducing the amount of energy and GHG emissions in other mining and mineral processing operations. End-of-life recycling can also help reduce GHG emissions by utilizing less energy and emitting less GHGs than the processes used for new materials, and by offsetting the demand for additional material that would otherwise be required. There are, of course, technical, logistical, and economic challenges to recycling of mineral commodities (Reuter et al. 2013). However, end-of-life recycling’s contribution to the reduction of energy use and associated GHG emissions (and to reducing demand for new materials) will be comparatively small (at least to start) simply because it cannot keep pace with the rapidly growing demand for clean energy technologies. That is not to say that it will not be important or should not be encouraged; it is simply to state that recycling alone cannot be a solution if demand continues to grow.

Without significant abatement, climate change will likely impact the availability of (and/or accessibility to) mineral commodities in several ways including disruption of operations and related infrastructure due to increases in the frequency of severe weather events, changes in weather and precipitation patterns, and sea level rise; disruption of supply chains and trading routes; and impacts to community relations and worker health and safety (Nelson and Schuchard 2011). Consider lithium minerals, which will be required in lithium-ion batteries regardless of cathode composition. Lithium minerals are recovered from both hard rock (e.g., spodumene), as well as brine operations. Brine operations rely on solar irradiation and wind to concentrate the lithium. This evaporitic process is thus strongly dependent on climatic and weather conditions, in particular solar irradiation, rain levels, and wind strength (Flexer et al. 2018). There are other ways in which climate change may impact mineral supply chains. For example, hotter and drier conditions may lead to increased wildfires that may threaten facility operability; heavy rains may increase erosion that may cause slope instability at open cast mines; and reduced water availability may curtail operations and exacerbate strains with nearby communities, especially in water stressed areas (Nelson and Schuchard 2011; Northery et al. 2017; Delevingne et al. 2020). At the very least, supply chain disruptions will increase costs of materials or cause delays, which will likely translate into higher prices for consumers that, without intervention, would reduce demand for the clean energy technologies. Many of these and other effects and feedback mechanisms that climate change may have on mineral supply chains need to be examined systematically, especially when considering the fact that the production of most mineral commodities is highly concentrated (geopolitically and spatially) (Schnebele et al. 2019; Nassar et al. 2020) and that most mineral commodities are co-produced (Nassar et al. 2015).

It likely comes as no surprise that our decisions and collective actions over the coming years and decades regarding how we produce and store our energy, transport ourselves and our goods, grow our food, and build our cities will have profound implications for both human and Earth systems. What might be surprising to some is that nonfuel mineral resources and their supply chains might be at the center of it all. Will the transition to clean energy simply shift our dependency from fuel minerals to nonfuel minerals and recast the familiar problems and pitfalls of the past century? Or, will we avoid these problems, break the undesirable feedback loops, and usher in a genuinely new era of sustainable energy? The answer will depend, at least in part, on our ability to provide and successfully communicate the best and most timely science that we have available.

ABOUT THE AUTHOR

As chief of the Minerals Intelligence Research Section at the U.S. Geological Survey, Dr. Nedal Nassar and his research team quantify the global stocks and flows of nonfuel mineral commodities at each stage of their life cycle, analyze trends and examine concerns regarding foreign mineral dependencies, develop supply and demand scenarios, and assess the mineral commodity supply risk to the U.S. economy and national security. Dr. Nassar received his PhD from Yale University (USA) where he worked on the development and application of a methodology for assessing critical minerals. He has continued that work as a leading member of the U.S. National Science and Technology Council’s Critical Minerals Subcommittee. He also serves as co-chair of the Council of Senior Science Advisors at the U.S. Geological Survey and has been on the advisory board of various international research projects. In 2019, he was awarded the Presidential Early Career Award for Scientists and Engineers—the highest honor bestowed by the U.S. Government to outstanding scientists and engineers who are beginning their independent research careers. His research has been published in high-profile journals and highlighted in major media outlets. He has also been called upon to testify before committees of the U.S. Senate and House of Representatives, brief senior government officials, and invited to give keynote addresses and present his research at significant venues including The National Academies, the European Commission, and the World Bank. Previously, Dr. Nassar worked as a consultant and as a process development engineer in the semiconductors and data storage industries where he was the recipient of three trade secrets. He also holds a bachelor’s degree in chemical engineering from the University of Minnesota (USA), an MBA in sustainable global enterprise from Cornell University (USA), as well as two master’s degrees from Yale University.
Geometallurgy: Present and Future

INTRODUCTION

Geometallurgy is an interdisciplinary research field concerned with the planning, monitoring, and optimisation of mineral resource extraction and beneficiation. Geometallurgy relies on a quantitative understanding of primary resource characteristics such as mineralogical composition and texture, the spatial distribution and variability of these characteristics, and how they interact with mining and beneficiation processes. Thus, geometallurgy requires accurate analytical data for resource characterisation and detailed models of orebody geology, mining and processing technologies, mineral economics, and the often-complex interactions between them. Here, we introduce the fundamental concepts relevant to the field, with particular emphasis on the current state-of-the-art and some notes on potential future developments.

KEYWORDS: raw materials; sustainability; value chains; resource efficiency

Mining and the production of minerals and metals have been crucial for the development of human civilisation. They are set to retain this role for the foreseeable future. This is mostly due to continuing global population growth and economic development, as well as the increasing shift towards renewable energy production and electromobility, technologies that are much more raw-material intensive than fossil fuels or nuclear energy (Vidal et al. 2013). Technological developments are expected to drive up the global demand for minerals and metals over the coming decades. Unfortunately, recycling alone cannot cover this added demand. Mining will have to fill the gap (International Energy Agency 2022).

Meeting this rapidly increasing demand poses a significant challenge for the global minerals industry. Not only has the quality of various types of mineral deposits available for extraction decreased over the past 100 years (e.g., Mudd et al. 2013, 2017), but it has also become increasingly difficult to find new commercially viable deposits. This has important economic and environmental implications, because lower-quality ores, which typically contain less metal in more complex mineral associations, require more energy for metal extraction and result in the production of larger volumes of waste. Counteracting the detrimental effects of these developments requires substantial increases in the energy and resource efficiency of mining and processing operations.

Geometallurgy is an interdisciplinary research field that addresses this important problem. Its major goal is to maximise the efficiency and environmental sustainability of mining and processing operations through a detailed understanding of ore characteristics, ore variability, and their influence on operational performance. This article introduces the main concepts relevant to the field, including a glossary of the key terms used in this issue (Box 1), and briefly describes the status of academic research and industrial application. The subsequent articles in this issue then explore the most important aspects in more detail.

HISTORICAL PERSPECTIVE

The concept to use the geological and mineralogical understanding of mineral resources for the planning of mining and mineral processing operations is not new. Its origins can be traced at least as far back as the writings of Georgius Agricola (Agricola 1556), but it is probably much older.

Simple quantitative approaches to this problem started to appear in the mineral processing literature of the late 19th and early 20th centuries, clearly recognising the importance of mineralogy and texture for the process responses of ores (e.g., Gaudin 1939). However, the term geometallurgy as a crossover between geology and metallurgy was only coined in 1968 by McQuiston and Bechaud (1968), recognising the necessity for close collaboration between geoscientists and engineers in mining operations.

Over the past 20–30 years, such collaboration has greatly benefited from rapid improvements in quantitative analytical techniques, which have also enabled the more widespread implementation of modern geometallurgical workflows. Relevant analytical techniques include scanning electron microscope (SEM)-based image analysis (also called automated mineralogy; Fandrich et al. 2007), multi-element geochemical analyses, quantitative X-ray powder diffraction, laser ablation-inductively coupled
plasma mass spectrometry (LA-ICP-MS), and various forms of drill-core scanning as described in more detail by Butcher et al. (2023 this issue).

**WHAT IS AN ORE AND HOW DOES IT BEHAVE?**

Perhaps the most central concept in geometallurgy (and mining in general) is that of an ore, a geological material, usually a rock, from which a mineral or metal can be extracted at a profit (Robb 2020). Ores generally consist of a variable mixture of ore minerals, i.e., those of commercial interest, and gangue minerals, i.e., the waste. To produce a marketable product, the ore and gangue minerals must be separated (Wills and Finch 2015), usually by physical, physicochemical, or chemical means. If a metal or other pure substance is the final product, additional chemical processing steps may be necessary (Dunne 2019). In a few rare cases, only chemical processes are needed, e.g., for the in-situ leaching of uranium ores (Haque and Norgate 2014), or if the ores are not rocks at all, such as in lithium-rich brine deposits (Kesler et al. 2012).

**Figure 1** schematically illustrates the most common process chain from ore to metal. A volume of ore (in mining terms, a block) is first drilled and blasted to allow removal from the ground. The ore is then transported (= hauled) to a mineral processing plant, where it passes through the primary crusher, is stockpiled, and subsequently blended with ore from other blocks. Next, the ore blend is crushed further and milled to reduce it to small fragments, called particles. This fragmentation process, called comminution, has the goal to free up as many of the grains of the ore mineral(s) as possible to produce separate particles (Wills and Finch 2015). The degree to which this is achieved is described as mineral liberation. Different mineral separation
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<th><strong>GLOSSARY OF GEOMETALLURGY TERMS</strong></th>
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<td><strong>Definitions are provided here strictly as used in this issue. Other common usages are highlighted where relevant.</strong></td>
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**Association** (of minerals) – The degree of intergrowth of one mineral with another, generally measured as the proportion of the total grain surface area of the first mineral in contact with grains of the second.

**Beneficiation** – General term for the upgrading of a raw material to a more valuable product; typically including both mineral processing and extractive metallurgy.

**Block** (of ore) – A volume of ore in a deposit; often corresponds to the smallest volume that can be mined separately.

**Block model** – A geospatial model of an ore deposit in which the characteristics of each ore block are inferred from data collected on drill-core and mine faces.

**CAPEX** – Capital expenditure; the investment costs required to find, build, and open a mine.

**Classification** – The process of separating a crushed or ground material into different size fractions.

**Comminution** – The process of size reduction: blasting, crushing, and grinding.

**Concentrate** – An enriched product consisting mostly of ore minerals, produced by a mineral processing plant (comminution and mineral separation).

**CRM (= critical raw material)** – A raw material deemed economically essential, with simultaneously high supply risk.

**Crushing** – The process of size reduction at particle sizes above ~3 mm; often done using cone or jaw crushers.

**Deporment** (of an element) – The quantitative allocation of an element to different minerals in an ore sample, e.g., the percentage of the total gold content present in pyrite and as free gold in a gold ore; an important parameter for process design.

**Extractive metallurgy** – The operation of extracting metals from their ores through a series of chemical transformations; subdivided into hydrometallurgy and pyrometallurgy according to the chief medium of extraction.

**Feed** (ore) – The material delivered to a mineral processing plant.

**Gangue** (minerals) – The non-valuable minerals in an ore.

**Geostatistics** – The branch of statistics concerned with the description and modelling of the spatial (or spatiotemporal) distribution of variables.

**Grade** (of a metal) – The concentration of a metal in an ore.

**Grain** – Generally, a crystal of a single mineral in a rock or particle, separated from other grains by grain boundaries.

**Grinding** – Also called milling; the process of size reduction at particle sizes below ~3 mm, for example in ball mills or semi-autogenous grinding (SAG) mills.

**Hardness** – Generally, a measure of the energy required to crush or grind a given mass of material to a specific size.

**Hydrometallurgy** – An extractive metallurgical process where chemical transformations in aqueous solutions are used to extract the metal(s) from an ore or mineral concentrate, e.g., heap leaching.

**Liberation** (of a mineral) – The degree to which grains of a mineral in a milled ore occur in separate particles, generally expressed as the mass fraction (volume liberation) or surface area fraction (surface liberation) of a particle, which consist of that mineral.

**Metallurgy** – The science of extracting metals from their ores, generally subdivided into mineral processing and extractive metallurgy, respectively, referring to physical and chemical separation processes. In more general usage, the term metallurgy can also be used to refer to the branch of materials science dealing with the further manufacture of metal products and alloys.

**Mineral processing** – Sometimes also minerals processing; the operation of crushing, grinding, and separating an ore into one or several concentrates of the ore minerals and tailings.

**Mineral separation** – The operation of separating minerals from milled ore through physical (e.g., density separation) or physico-chemical (e.g., froth flotation) processes.

**Model** – An informative representation of an object or system; in geometallurgy, generally a mathematical description of a geological body or industrial process.

**Net present value (NPV)** – The current value of a mining project, calculated by subtracting CAPEX from the sum of all expected future cashflows (revenue minus OPEX), discounted back to the present.

**OPEX** – Operating expenditure; the annual cost of operating a mine.

**Optimisation** – The selection of the best scenario for something (mine plan, processing plant design, etc.) with regard to some quantitative criterion; usually done by maximising or minimising a specific mathematical function.

**Ore** – A geological material, generally a rock, from which a metal or mineral can be extracted at a profit.

**Particle** (of ore) – A generally small (<3 mm) rock fragment consisting of one or several mineral grains.

**Penalty element** – A deleterious, often toxic, element present in a mineral concentrate, which negatively affects downstream extractive metallurgy processes, and for which a penalty must therefore be paid by a mine, e.g., As in Cu ores.

**Primary (ore) characteristics** – The inherent properties of a rock or ore, including its geochemical or mineralogical composition, texture, density, porosity, etc.

**Pyrometallurgy** – An extractive metallurgical process where high temperatures are used to induce chemical transformations in a mineral concentrate and extract the metal(s), e.g., in a blast furnace.

**Recovery** (of minerals/metals) – The relative amount of a mineral or metal recovered in a concentrate stream, expressed as a fraction of the mass of the minerals/metals contained in the feed material.

**Reserve** (of a commodity) – The economically extractable amount of a commodity within a resource, accounting for the dilution and losses which occur during mining and processing.

**Resource** (of a commodity) – The total amount of a commodity which has been shown to be present within an ore deposit by drilling, at a maximum degree of uncertainty. Different categories (measured, inferred, indicated) exist according to the estimated level of uncertainty.

**Secondary (ore) characteristics** – The behaviour of a rock or ore in a specific process, e.g., its grinding hardness, leachability, flotation behaviour, etc.

**Texture** (of an ore) – The overall 3D structure of an ore resulting from the combination of sizes, shapes, orientations, and intergrowth relationships of individual mineral grains, voids, and fractures.

**Tailings** – The fine-grained waste material remaining after crushing and grinding of an ore, and separation of the valuable minerals.

**Throughput** – The amount of feed processed by a mineral processing or extractive metallurgy plant in a given unit of time, typically stated in tonnes/day.

**Waste rock** – The non-ore rock material extracted to access ore.
processes are then applied to the particles, acting on the specific physical or physico-chemical properties of the minerals within them to separate ore mineral(s) from gangue minerals. The result is one or more mineral concentrates containing the desired ore mineral(s), as well as one or more streams of fine-grained waste material or tailings. Tailings, as well as coarser, uncrushed, rock material removed to access the ore (= waste rock), are deposited in piles and dams near the mine site. The ore mineral concentrates are dewatered and transported to pyrometallurgy or hydrometallurgy plants where they undergo the necessary chemical transformations to produce pure metals or other substances suitable for use by downstream industries, a process known as extractive metallurgy. This transformation results in the formation of further residues, e.g., slags, dusts, and slimes, typically deposited near the smelter or hydrometallurgy plant.

An alternative processing route is the direct leaching of the crushed and milled ore using reagents and/or bacteria in an aqueous medium, followed by chemical extraction of the metals from the resulting solution. This is typically done at the mine site, with the leached ore remaining as the main residue.

The success of the various extraction processes is generally measured in terms of how much material is being mined and processed within a given unit of time (= throughput), what proportion of the ore minerals or metals contained in the ore are extracted into products (= recovery), and how much energy, chemicals, tools, and labour are expended to do so (= operational expenditure (OPEX)) (cf. Dominy et al. 2018; Olson-Hoal and Frenzel 2022). Other aspects include the overall sales value of the products, environmental impacts of the mine, the amount and nature of the generated waste materials, and the requirements for their storage, disposal, and/or remediation after mine-closure, as well as the original investment costs (= capital expenditure (CAPEX)).

The inherent geological characteristics of an ore enact a strong influence on all these aspects, as follows:

- **Ore hardness**, or its resistance to fragmentation, is a direct function of modal mineralogy (e.g., the content of hard minerals like quartz or topaz) and the scale of mineral intergrowths, i.e., ore texture. Thus, these properties exert a major control on throughput and energy consumption.

- **Ore texture**, in particular grain size, controls the final particle size that must be achieved by comminution. This, in turn, controls the ultimate recoverability of the minerals and metals. More finely intergrown ores must be milled to finer particle sizes to achieve mineral liberation, causing higher energy consumption and OPEX, and produce chemically more reactive tailings. Figure 2 shows some ore particles with varying degrees of liberation resulting from comminution.

- The nature of the ore and gangue minerals dictates which types of separation processes are appropriate for a given ore. For instance, magnetic separation is only sensible when ferro- or strongly paramagnetic minerals are present.

- The spatial associations of the different minerals, resulting in their co-occurrence or separation in different ore particles, control recovery options and product quality. For instance, if two minerals co-occur as extremely fine intergrowths, then they may have to be recovered into a single product and separated during metallurgical treatment. Alternatively, substantial losses of valuable material may occur if these intergrowths are discarded.

- **Ore grade**, or the concentration of the valuable components in the ore, strongly controls the total sales value of the final product(s), with total revenues mostly related to grade × throughput × recovery × price.

**Figure 2** Back-scattered electron (BSE) images and corresponding false-colour mineral maps from SEM-based image analysis showing good, bad, and ugly ore particles resulting from the comminution of an Indonesian Pb-Zn skarn ore: (A) and (B) Fully liberated, easily recoverable, sphalerite particles; (C) and (D) particles with good surface liberation of sphalerite, but containing locked gangue mineral grains which may carry impurities into the zinc concentrate; (E) and (F) particles containing non-liberated (locked) sphalerite grains within gangue minerals, which may cause loss of sphalerite/zinc to the tailings. Illustration from S. Faizy (HZDR).
In waste rocks and tailings, the balance between minerals prone to acid generation when exposed to air (e.g., pyrite) and those with acid-neutralising properties (e.g., calcite) directly controls the potential for acid mine drainage generation (Parbhakar-Fox and Baumgartner 2023 this issue). This, in turn, controls waste storage and disposal options, as well as remediation costs.

**VARIABILITY AND UNCERTAINTY**

The previous section provided some insights into how different ore characteristics influence the way in which ores are processed. However, it did not discuss the influence of the inherent spatial variability of these characteristics within a deposit. Ore deposits are geological bodies of unusual composition and are often the product of a complex sequence of geological events with spatially varying characteristics. Many ore-forming systems, be they magmatic, hydrothermal, or sedimentary, comprise strong thermal and/or chemical gradients, resulting in corresponding gradients in the mineralogical composition and texture of the ores. The resultant deposits may later be overprinted and partially remobilised by metamorphic events, again resulting in spatially varying changes to ore textures and mineralogy. Exhumation and weathering may cause further changes. Figure 3A shows an example cross section through a copper deposit, illustrating the spatial variability in Cu grade.

Because we cannot exhaustively characterise an ore deposit before mining, but only have access to about 1/10,000th to 1/1,000,000th of the total volume through drill-core, this inherent geological variability causes considerable uncertainties with respect to the true in-situ characteristics of the ores and their spatial distribution, which will be encountered during mining and beneficiation (cf. Dominy et al. 2018). Figure 3B and 3C illustrate this for the example in Figure 3A, showing several potential distributions of Cu recovery compatible with the observed data. The poor correlation between Cu grade and Cu recovery should be noted. This is due to Cu recovery being chiefly controlled by ore properties unrelated to Cu grade, such as texture and gangue mineralogy.

This uncertainty causes problems during the mining and processing of the ore. Current mineral processing plants are optimised to operate under relatively static conditions (hence, the stockpiling and blending of different ore blocks in the plant feed; Fig. 1). Therefore, unpredictable variations in feed characteristics will cause suboptimal processing performance. Unfortunately, the true extent of ore variability and its effects on downstream process outcomes are not well characterised in many operations. This is the principal reason why more than half of all new mining operations fail to reach projected performance targets (Carlson 2019). Thus, a major aspect of all geometallurgical studies is the quantification of uncertainties, and if possible, their reduction. Ortiz et al. (2023 this issue) provide a more detailed account of ore variability, uncertainties, and how they can be dealt with.

**CURRENT GEOMETALLURGY WORKFLOWS**

What exactly does geometallurgy do to achieve its goals? Geometallurgical studies often consist of a general series of steps. These are schematically illustrated in Figure 4. This general sequence is independent of the specific goals of a study. However, adjustments are generally made in the design and execution of the individual steps to fit specific cases.

First, a sampling scheme is designed to collect relevant, representative samples for the problem at hand. If the problem is an initial geometallurgical assessment of an ore deposit during the exploration stage, this will cover ore samples representing the range of geological variability present within the deposit as recognised by the site geologists. If, on the other hand, the goal is to solve a problem within an existing operation, sampling may focus on the mineral processing plant. Sampling schemes generally consider as much of the available information as possible to yield an effective selection of typically tens to hundreds of samples.

Second, the samples are characterised for relevant ore properties. This generally includes primary ore characteristics such as mineralogy, texture, and geochemical composition (Butcher et al. 2023 this issue), as well as process responses, commonly referred to as secondary characteristics (Pereira et al. 2023 this issue). These responses may...
be observed directly by tracking specific volumes of ore through a running processing plant, or they may be approximated by standardised laboratory tests.

Third, the characterisation data are integrated to yield quantitative predictive models that relate the secondary ore characteristics to primary ones. These models must generally be extrapolatable to the entire ore deposit. Because the samples with detailed mineralogical, textual, and metallurgical test data generally cover only a small part of the available drill-core material, this is currently achieved by directly correlating specific secondary ore characteristics with multi-element geochemistry and geological drill-core logs. Such data are usually available with good spatial coverage. Image data from various drill-core scanning methods (optical, hyperspectral, XRF, etc.) are becoming another important input for this purpose.

Fourth, the extrapolated predictive outputs from the models covering the entire deposit are used for optimisation. The optimisation process may include the mining methods, mine schedule, processing plant design, and waste disposal methods, depending on the scope of the geometallurgical study. A commonly optimised function in current operations is the net present value (NPV) of the ore deposit. This is calculated by subtracting CAPEX from the sum of all expected future cashflows (Revenue minus OPEX), discounted back to the present day via an average discount rate, or

\[
NPV = \sum_{i=1}^{LOM} \frac{(Revenue_i - OPEX_i)}{(1 + d)^i} - CAPEX \quad (EQUATION \ 1)
\]

where \( i \) is the year, \( d \) is the discount rate, and \( LOM \) is the total life-of-mine, expressed in years. Other measures that can be optimised include metal or mineral recoveries (= resource efficiency), greenhouse gas emissions (e.g., Pell et al. 2019), and other environmental impacts. Finally, true operational outcomes are used to validate the predictions from the geometallurgical modelling and adjust relevant models where these fail to provide accurate predictions. This process is known as reconciliation.

As the circular shape of Figure 4 suggests, geometallurgy programs are not linear processes, but rather proceed as a series of iterations throughout the lifetime of a mine.

**EXAMPLE**

To conclude the description of the current state of geometallurgy, the following case from the literature provides an example of the application and benefits of state-of-the-art geometallurgical workflows. The results of mineralogical and geochemical analyses, combined with variability testing, estimations, and simulations are integrated into the ore deposit model to provide reliable process performance predictors and reduce uncertainty and associated technical risks. Iterative reconciliations of this geometallurgical model with actual performance have provided higher confidence and, thus, better operational results.

**Case Study: Olympic Dam, Australia**

Olympic Dam is a large, breccia-hosted, Fe-oxide Cu–U–Au–Ag deposit in Australia. Due to the complexity of the ore with over 100 minerals present (Ehrig 2021), the beneficiation strategy is complex and involves multiple processing steps to make the overall recovery economic and the resulting products saleable. Each mineral has its own unique response to each part of the mineral processing plant (Ehrig 2021). Therefore, the type of minerals present in an ore block is one of the most important drivers of overall process performance. For these reasons, a geometallurgical approach was adopted to plan and monitor the operation. It consists of a routine mineralogical and geochemical characterisation of ore and waste. Over 30 elements are analysed, and the abundances of the more than 100 minerals are quantified via SEM-based image analysis from holes drilled ahead of production. The most impactful elements and minerals are directly included in the deposit model via interpolation, only possible due to the high data density. These are subsequently used in mathematical models to estimate each metallurgical parameter for which direct information is not available, enabling an assessment of expected metallurgical behaviour for each ore block contained in the model (Ehrig 2013; Liebezeit et al. 2016). The deposit model containing all this block-specific data then serves as the major input for the optimisation of the mine plan.

Over the years, the geometallurgical model at Olympic Dam has permitted a reduction of the technical risks of current and future operations by identifying areas of positive- and negative-impact materials, increasing the confidence of predictions, and providing the data necessary to comply with regulatory mining codes (Ehrig 2013; Liebezeit et al. 2016).

**OUTLOOK**

Despite their obviously positive impact on operations, current geometallurgy workflows are still not widely applied by the minerals industry. Furthermore, current workflows are mostly limited to the mine site, i.e., from excavation to mineral separation, and do not consider the impact of mineral concentrate composition on the performance of extractive metallurgy (Chetty et al. 2023 this issue). Similarly, predictions of environmental performance are often omitted (Parbhakar-Fox and Baumgartner 2023 this issue). Finally, there is still room for substantial...
future improvements in predictive power and thus mining outcomes. For instance, the prevalent use of multi-element geochemical data to extend predictions of process outcomes across a deposit has limited power where ore textures are a chief control on the variation of these outcomes (Pereira et al. this issue). The optical or SEM-based methods currently used to quantify ore textures in 2D introduce stereological bias into assessments of particle sizes and mineral liberation, causing losses in predictive power because ore particles are 3D objects (Butcher et al. 2023 this issue). Last but not least, mineral processing plants still operate under relatively static process conditions resulting in avoidable inefficiencies due to feed variability (Ortiz et al. 2023 this issue). Current developments in analytical technology, stochastic geometry, and computational power are rapidly opening new avenues of research to address these efficiency potentials. The most important of these are discussed in more detail in the subsequent articles of this issue.

FURTHER READING

Readers wishing to delve more deeply into the general subjects covered in this issue may find it useful to acquire the following introductory texts on different areas relevant to geometallurgy: Robb (2020) gives a general introduction to ore deposits and their geology; Wills and Finch (2015) and Dunne (2019), respectively, provide up-to-date introductions to mineral processing and extractive metallurgy; Rossi and Deutsch (2014) give an overview of resource estimation; and Lottermoser (2007) provides an introduction to mine wastes and associated issues. Finally, Dominy et al. (2018), van den Boogaart and Tolosa-Delgado (2018), and Olson-Hoal and Frenzel (2022) provide more detailed perspectives on geometallurgy and include more comprehensive reference lists than possible in the present short review.

ACKNOWLEDGMENTS

We would like to thank Kathryn Goodenough and Kurt Aasly for their reviews of this article, which helped us to improve it significantly. Helmholtz-Zentrum Dresden-Rossendorf is thanked for funding open access to this article.

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Characterisation of Ore Properties for Geometallurgy

Alan R. Butcher¹, Quentin Dehaine¹, Andrew H. Menzies², and Simon P. Michaux¹

INTRODUCTION

Before the invention and implementation of the geometallurgical approach, the exploration and mining industry had relied largely on a traditional element-based methodology to evaluate commercially important mineral deposits. This involved a simple but cost-effective approach whereby samples were submitted for chemical assays (e.g., XRF, ICP-OES, ICP-MS, see Table 1 for abbreviations) for the elements of interest. For example, in a gold exploration program, key elements such as Au, Ag, and As would be of main concern, while Pb, Zn, Fe, Ag, and As would be important for a Pb–Zn deposit. Only the most essential elemental assays were commissioned, largely to save time and money. Whilst this was considered practical at the time, and often worked to some degree for most ore bodies, ore characterisation is best served by more than just chemical assays. This is because, at the fundamental level, we mine minerals and not elements; in addition, we process complex particles and not pure mineral grains. This leads to the inevitable conclusion that, to fully understand, predict, and improve the performance of an ore during its life cycle from extraction to marketable products and waste, the geology, mineralogy, texture, elemental deportment, and breakage characteristics must be known and their effects on processing well understood.

A cursory look at geometallurgy may suggest that it is simply what was previously called ‘ore characterisation’, but it is far more than that today. Technology has developed in the last ~20 years such that ores can now be imaged and analysed in 2D and 3D, at high resolution, and in practical time frames, providing all the key parameters to optimise mineral processing and extraction. There are many types of samples that can be investigated with modern analysis and imaging methods for geometallurgical purposes. Mobile or hand-held devices can be used in the field for in-situ material (e.g., outcrop, mine-face). Once removed from their geological and physical context and transported to a mineral processing plant or analytical laboratory, ex-situ samples can be examined online, in-line, and in 3D- and 2D-sections (Dehaine and Esbensen 2022).

MINERAL AND ORE GEOMETALLURGICAL PROPERTIES

We often make the distinction between primary ore properties (intrinsic to the ore), as opposed to secondary properties (describing ore behaviour during processing; Frenzel et al. 2023 this issue). The current paper focuses on primary ore properties as measured by geochemical and mineralogical analysis, while secondary ore properties, which are quantified as the response to a geometallurgical test and are used to predict the performance of the mineral processing and metallurgical operations, are described in Pereira et al. (2023 this issue). Both primary and secondary properties of ores are directly linked to the minerals making up the ore and their respective mineral properties. While minerals are characterised by numerous different properties, only a few are relevant for mineral processing and metallurgy: hardness, density, magnetic susceptibility, electrical conductivity, hydrophobicity, and chemistry (cf. Pereira et al. 2023 this issue; Chetty et al. 2023 this issue; Fig. 1).

Key ore properties, which need quantification before processing, include elemental assay, modal mineralogy, grain size, grain shape, mineral associations, elemental deportment, and the presence of deleterious minerals (e.g., clays, asbestiform minerals, or minerals containing elements that cause contamination or harm to the environment (so-called penalty elements)). The same parameters

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Keywords: mineralogy; texture; elemental deportment; liberation; ore characterisation

References

Chetty et al. 2023 this issue
Frenzel et al. 2023 this issue
Pereira et al. 2023 this issue
can be established for ore particles generated by comminution, along with particle shape and size, and degree of liberation of key phases (by surface area or volume). Finally, materials that have been subjected to further downstream physical and chemical processes can be scrutinised in detail for purity, losses, and potentially harmful minerals or elements (cf. Parbhakar-Fox and Baumgartner 2023 this issue).

**MINERALOGICAL CHARACTERISATION**

**Methods of Mineral Characterisation**

An overwhelming number of modern geoanalytical techniques are available for the imaging and analysis of Earth materials, including ore (Table 1). To evaluate them, it is often useful to consider the type of energy source on which they are based, as this determines their practicality, capabilities, and applications. For convenience, we consider the following types of sources (Fig. 2): visible and

**Figure 1** Illustration of the variability of some key mineralogical properties for a gold-cobalt ore deposit (target minerals/metals highlighted in bold) and their impact on relevant process technology. Modified after Dehaine et al. (2021).

MINERALOGICAL CHARACTERISATION

**Table 1**

<table>
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**Figure 2** Multi-scale, multi-modal, and multi-dimensional characterisation methods used in geometallurgy. (1) Mega is at a scale of 100s of km as observed using space and airborne techniques. (2) Macro operates at km to metre scales and is reserved for field-based observations. (3) Meso, (4) Micro, and (5) Nano are all laboratory-scale observations. Modified after Butcher (2019).
<table>
<thead>
<tr>
<th>Type</th>
<th>Method</th>
<th>Type1</th>
<th>Scale2</th>
<th>Minimum Resolution3</th>
<th>Typical LOD4</th>
<th>Cost/ Sample (US$)5</th>
<th>Properties characterised6</th>
<th>Reference or example study</th>
</tr>
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<tbody>
<tr>
<td><strong>Geochemical</strong></td>
<td>X-ray fluorescence (XRF)(^p)</td>
<td>B</td>
<td>–</td>
<td>–</td>
<td>0.01%(^e)</td>
<td>30</td>
<td>Major and minor element abundances</td>
<td>Dietrich LeVier (2019)</td>
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<td></td>
<td>Atomic absorption spectroscopy (AAS)</td>
<td>B</td>
<td>–</td>
<td>–</td>
<td>1–10 ppm(^e)</td>
<td>15</td>
<td>Major and minor element abundances</td>
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<td>Inductively coupled plasma-atomic emission spectrometry (ICP-AES)</td>
<td>B</td>
<td>–</td>
<td>–</td>
<td>0.01–1 ppm(^e)</td>
<td>40</td>
<td>Major, minor, and trace element abundances</td>
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<td></td>
<td>Inductively coupled plasma-optical emission spectrometry (ICP-OES)</td>
<td>B</td>
<td>–</td>
<td>–</td>
<td>0.1%–1%(^e)</td>
<td>20</td>
<td>Major and minor element abundances</td>
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<td>Inductively coupled plasma-mass spectrometry (ICP-MS)</td>
<td>B</td>
<td>–</td>
<td>–</td>
<td>1 ppb–0.01 ppm(^e)</td>
<td>40–60</td>
<td>Minor and trace element abundances</td>
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<td></td>
<td>Instrumental neutron activation analysis (INAA)</td>
<td>B</td>
<td>–</td>
<td>–</td>
<td>1 ppb–0.01 ppm(^e)</td>
<td>20–50</td>
<td>Major, minor, and trace element abundances</td>
<td></td>
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<tr>
<td><strong>Mineralogical</strong></td>
<td>X-ray diffraction (XRD)(^p)</td>
<td>B</td>
<td>–</td>
<td>–</td>
<td>0.1–5 wt.%(^m)</td>
<td>100–300</td>
<td>Mineral identification, mineral abundances (major, semi-quantitative), crystal structure, amorphous content</td>
<td>Parian et al. (2015)</td>
</tr>
<tr>
<td><strong>Mineralogy and texture</strong></td>
<td>Hyperspectral imaging (HSI)(^p)</td>
<td>S</td>
<td>Meso to micro 25 µm</td>
<td>–</td>
<td>10–50 / m</td>
<td>Imaging, textures, mineral abundances (major)</td>
<td>Johnson et al. (2019)</td>
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<tr>
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<td>Fourier transform infrared spectroscopy (FTIR)(^p)</td>
<td>S</td>
<td>Meso 10–20 µm</td>
<td>1–5 wt.%(^m)</td>
<td>15–50</td>
<td>Imaging, mineral identification, mineral abundances (major)</td>
<td>Dehaine et al. (2022)</td>
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<tr>
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<td>Micro X-ray fluorescence (µ-XRF)</td>
<td>S</td>
<td>Meso to micro 4–20 µm</td>
<td>10–100 ppm(^e)</td>
<td>100–500</td>
<td>Imaging, 2D textures, element and mineral abundances, grain size, associations, and liberation</td>
<td>Haschke (2014)</td>
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<td></td>
<td>Optical microscopy (OM)</td>
<td>S</td>
<td>Micro 0.1–10 µm</td>
<td>–</td>
<td>100–500</td>
<td>Imaging, mineral identification, textures</td>
<td>Pirard et al. (2007)</td>
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<td>Scanning electron microscopy (SEM)</td>
<td>S</td>
<td>Micro 0.5–4 nm</td>
<td>0.5%–1%(^e)</td>
<td>200–600</td>
<td>Imaging, mineral identification, textures, mineral chemistry (semi-quantitative)</td>
<td>Hartner et al. (2011)</td>
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<tr>
<td></td>
<td>Raman microscopy/Micro-Raman (µ-Raman)(^p)</td>
<td>S</td>
<td>Micro 1 µm</td>
<td>1–5 wt.%(^e)</td>
<td>20–50</td>
<td>Imaging, mineral identification, textures</td>
<td>El Mendilli et al. (2019)</td>
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<td></td>
<td>Automated Mineralogy (AM)</td>
<td>S</td>
<td>Micro 5–10 µm</td>
<td>0.01–1 wt.%(^m)</td>
<td>200–600</td>
<td>Imaging, 2D textures, mineral abundances, grain size, associations, and liberation</td>
<td>Goodall et al. (2005)</td>
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<td>X-ray computed tomography (XCT)</td>
<td>3D</td>
<td>Meso to micro 1 nm to 100 µm</td>
<td>–</td>
<td>300–700</td>
<td>Imaging, 3D textures, porosity, mineral abundances (estimate)</td>
<td>Bam et al. (2016)</td>
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<td><strong>Mineralogical</strong></td>
<td>Electron probe microanalysis (EPMA)</td>
<td>M</td>
<td>Micro 0.5–10 µm</td>
<td>50–300 ppm(^e)</td>
<td>100–500</td>
<td>Major and minor elements in minerals</td>
<td>Frenzel et al. (2019)</td>
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<td><strong>Mineral chemistry</strong></td>
<td>Laser ablation ICP-MS (LA-ICP-MS)</td>
<td>M</td>
<td>Micro 5–200 µm</td>
<td>1 ppb–10 ppm(^e)</td>
<td>50–100</td>
<td>Minor and trace elements in minerals</td>
<td>Aylmore et al. (2018)</td>
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<td></td>
<td>Laser-Induced Breakdown Spectroscopy (LIBS)(^p)</td>
<td>M</td>
<td>Micro 20–100 µm</td>
<td>1–5 ppm(^e)</td>
<td>50–100</td>
<td>Major and minor elements in minerals, grain size, imaging</td>
<td>Fabre (2020)</td>
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<td><strong>Petrophysical</strong></td>
<td>Equotip(^p)</td>
<td>S</td>
<td>Meso 3 mm</td>
<td>–</td>
<td>NA</td>
<td>Surface hardness</td>
<td>Keeney and Nguyen (2014)</td>
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<td>Gamma-ray attenuation density (GAM)</td>
<td>B</td>
<td>Meso –</td>
<td>0.01 g</td>
<td>–50</td>
<td>Bulk density</td>
<td>Ross and Bourke (2017)</td>
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<td>Galvanic resistivity (MAFRIP)</td>
<td>B</td>
<td>Meso –</td>
<td>1 × 10^-6 Ωm</td>
<td>–50</td>
<td>Resistivity/conductivity</td>
<td>Vatandoost et al. (2008)</td>
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<td></td>
<td>Magnetic susceptibility(^p)</td>
<td>B</td>
<td>Meso –</td>
<td>&lt;2 × 10^-6 SI</td>
<td>–50</td>
<td>Volume magnetic susceptibility</td>
<td>Ross and Bourke (2017)</td>
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<td>Ultrasonic pulse velocity (UPV/p-wave)(^p)</td>
<td>B</td>
<td>Meso –</td>
<td>10 m/s</td>
<td>NA</td>
<td>Compressional (P) and shear (S) wave velocity</td>
<td>Vatandoost et al. (2008)</td>
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</table>

1 3D: 3-dimensional analysis, B: bulk analysis, M: micro-analysis, S: surface analysis.
2 See Figure 1.
3 Technical minimum resolution; minimum resolution used in practice would be higher.
4 Indicative Limit of Detection (LOD). LOD varies depending on the analyte (element or mineral), sample preparation (e.g., digestion methods, pellets versus fused beads), the material analysed (matrix effect), and operational parameters (including resolution).
5 Indicative cost, when available, based on laboratory testing company brochures and authors’ experience. Price may decrease for higher sample numbers and increase if there is a need for an experienced operator.
6 Major, minor, and trace refer to element (or mineral) concentrations in the range of 0.5%–100%, 0.01%–0.5%, and 2–100 ppm, respectively.
7 Technology for which equivalent handheld or portable technologies exist.
Optical systems have been around since the invention of the petrographic microscope by Henry Clifton Sorby in 1848 and continue to provide a sound basis for mineral identification and textural descriptions. Many commercially important minerals can be readily identified optically. The big drawback to the technique is its dependence on the skills and output of the microscopist, and as with most single-exertion activities, the difficulty to upscale the output. There are also limitations to what the human eye can discriminate and record, which are not consistent between different individuals. It was on this basis that new microscopes were developed that offered operator-independent analysis with higher-magnification imaging capabilities, and higher productivity, such as the modern scanning electron microscope (SEM) developed in the 1930s.

In more recent times (1980s onwards), this has led to a new field known as automated mineralogy, which utilises both the imaging capabilities of the SEM along with the possibility of conducting micro-chemical analyses along pre-defined lines, grids, or points (electron-based mineral identification, or SEM-EDS), allowing automated data capture on polished surfaces of solid samples or particulates at the micrometre-scale, and at a rate and quantity that is not humanly possible.

The further advantage of the SEM-based approach is that hundreds, thousands, and in some cases even millions of EDS spectra can be digitally processed both online and off-line using dedicated analytical software to provide quantitative mineralogical and petrographic data for use in geometallurgy. The main outputs are digital images of the sample under investigation (Fig. 3), where the composition of each pixel is known, as well as its associations with neighbouring pixels. Thus, modal mineralogy, as well as textual and chemical attributes, can be determined on a pixel-by-pixel basis. Surface mineral maps can be created for polished thin-sections or polished sample blocks up to decimetre-size, providing mineralogy within a textural context. Particle-by-particle analysis is also possible for particle mounts of crushed and processed samples (Fig. 4). Given the high level of measurement automation, statistically valid measurements can be undertaken, which

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**Figure 3** Textural variability in ores captured at different scales:

(A) Mineral map of a polished thin section of a gold-bearing ore illustrating the degree of detail obtainable from SEM-EDS–based automated mineralogy technology. This digital information yields information on gold grain size and association, as well as the presence of other minerals of economic interest (chalcopyrite, sphalerite), and penalty minerals (arsenopyrite). Estimates of optimum grind size to liberate the gold can be obtained. Resolution: 1 µm/pixel.

(B) Mineral map of a half drill core obtained with scanning micro-XRF, typical of a cobalt-bearing ore type, displaying a metamorphic foliation that controls the distribution of the mineralisation. Two types of cobalt-bearing minerals, cobaltite and linnaeite, can be distinguished based on their mineral chemistry. Resolution: 10 µm/pixel.
provide quantitative estimates of mineral mode, particle-grain sizes and shapes, liberation, association, elemental deportment, and calculated assay.

If upscaling of textural and mineralogical characteristics from the micrometre- to the metre-scale is of interest, hyperspectral methods are now also available and widely used, e.g., visible-near infrared (VNIR) and shortwave infrared (SWIR), and can be deployed in combination with other technologies. Specifically, scanning micro-XRF is now available with mineralogical and elemental capabilities such that drill cores, for example, can be evaluated at micrometre scales over centimetre to metre distances, either directly on the curved surface, or on a 2D cut surface. Thus, a core pulled straight from the ground (and ideally orientated appropriately) can be used to generate first estimates of mineralogy and potential liberation behaviour of the commercially important minerals in an ore before further (usually destructive) testing is performed.

Stereological Bias in 2D Measurements

Most of the above-mentioned techniques rely on 2D image analysis, which is the current industry standard. However, when measuring 3D objects via 2D sections, a stereological bias inevitably occurs (Gottlieb et al. 2000). This phenomenon mostly concerns the estimation of apparent grain size and apparent liberation (Fig. 5). The sectioning of grains in a polished mount always results in a 2D sectional view where the apparent grain size is less than or equal to the true size of the grains (Fig. 5A; Sutherland 2007). Similarly, the measured apparent liberation in 2D measurements overestimates true 3D liberation (Spencer and Sutherland 2000). Indeed, a liberated grain always appears liberated in sectional views, whereas locked grains can appear to be liberated or locked in sectional views depending on where the section cuts the particle in which they are locked (Fig. 5B).

The magnitude of the stereological bias for liberation estimates will vary with particle size, texture, and actual liberation. The bias will be important for particles with a simple texture (e.g., binary or ternary particles, as in Fig. 5B), but virtually negligible for fully liberated grains (e.g., Fig. 5A). The effects of stereological bias can be controlled by careful sample preparation, including sizing of the samples and mounting of the size fractions in distinct polished mounts for liberation analysis (Spencer and Sutherland 2000). While some authors have suggested that the effects of stereological bias are minimal in most real cases (e.g., Petruk 2000), it is not trivial to assess how strong its effect will be in any specific case. Therefore, some authors have developed correction methods to account for the effects of stereological biases (Gay and Morrison 2006).

However, only 3D techniques such as X-ray computed tomography (XCT) may ultimately overcome the effects of stereological bias. Indeed, XCT has the ability, if the density contrast between minerals is suitable, to directly measure the 3D liberation of grains. The method does, however, have some limitations in terms of spatial and phase resolution (Table 1), and the liberation of small grains in a complex particle may be difficult to resolve.

Sampling

The granular nature of geological and processing samples may introduce significant sampling errors. If not controlled for, these may be orders of magnitude higher than the typical analytical errors of the analytical techniques described above. Obtaining a representative sample is therefore of paramount importance in ore characterisation, as no amount of measurement, even with many different techniques, can compensate for inadequate sampling. While we do not have space to delve into this topic more deeply here, the Theory of Sampling (TOS) developed by Pierre Gy (1998) provides a comprehensive introduction to this issue, including protocols for the sampling and preparation of geological materials to ensure representative results.
DATA INTEGRATION OVER DIFFERENT LENGTH SCALES AND MODALITIES

It is common practice in other disciplines of science and engineering, where complex imaging and analysis are required, to create what are known as workflows. This is a concept where samples are examined in a particular order using a variety of techniques, providing multi-scale, multi-modal, multi-dimensional, and multi-disciplinary information. Geometallurgy is ideally suited to adopt this approach given that rock textures and ore types are developed at different scales of observation. We might, for example, need to know information at the grain boundary-scale (for liberation or processing behaviour), as well as at the ore deposit-scale (for resource modelling). It is only by using the workflow approach that we can bridge these important scales of observation.

The order in which the different technologies and methods are applied usually follows the scale, from macro to micro, and from in-situ non-destructive methods to bulk or destructive methods. The choice of techniques depends on the type of information needed. Some workflows may include, for instance, two distinct methods that may seem redundant, like two (semi-) quantitative mineralogical analytical methods, e.g., XRD with Rietveld refinement (QXRD) and automated mineralogy. But each method has its advantages and limitations. XRD is often better at phase identification than automated mineralogy and further can differentiate polymorphs like pyrite and marcasite. Typically, XRD cannot quantify amorphous phases (unless an internal crystalline standard is used), or minor and trace minerals below 1–3 wt.% abundance (Table 1). However, XRD phase quantification includes crystallites down to the nanometre scale, while SEM-based automated mineralogy systems typically only cover mineral grains down to 2 µm. Thus, both methods are complementary and should be used together.

It is also necessary to ensure in multi-method analysis that the methods are cross-validated and calibrated. This is achieved by taking a sample and analysing the same representative aliquot by more than one method and checking for the consistency of results, e.g., XRF, QXRD, Raman, and ICP-MS in the case of powders; or optical microscopy, SEM-EDS, micro-XRF, and EPMA, combined with image registration software, in the case of the 2D surface of a thin section or polished block.

In addition, the modal mineralogy data obtained by automated mineralogy can be combined with mineral chemistry data obtained by EPMA to back-calculate the bulk chemistry of each sample based on its mineralogical composition. This can then be compared to the measured bulk chemistry of the sample obtained by bulk chemical analyses (e.g., XRF and ICP-OES/MS) to cross-validate the results, and to refine modal mineralogy data, the accuracy of which is often an order of magnitude below those of chemical analytical methods.

The result of such an integrated multi-scale approach is to have full visibility of all minerals present over any relevant scale and, thus, knowledge of how they occur (Figs. 1 and 2).

NEW TECHNOLOGIES AND FUTURE DEVELOPMENTS

Going forwards, geometallurgy will depend more (not less) on geological-, mining-, and minerals engineering–related data being made available. This will require continued development in the improvement of analytical techniques, the speed of data acquisition and processing, as well as data handling, archiving, and retrieval architectures for geologists, mineralogists, miners, and processors. The faster, cheaper, and more efficient collection of information will also enable better interdisciplinary collaboration along the processing chain.
Whole core scanners are already available that can produce a 3D archive of drill cores in practicable time frames. Hyperspectral scanning has also advanced in recent years, and now offers the possibility of near real-time analysis. Scanning micro-XRF has the potential to make mineral and texture maps of entire drill core trays and provide mineral and liberation information at, or near, the drill-site. Nevertheless, we still lack the ability to contemporaneously scan drill cores and process the acquired data at a rate that keeps up with drilling and allows for immediate access to the processed and interpreted data for decision makers. Indeed, this is a field where active developments are occurring at the time of writing, and great improvements are expected over the next few years.

Based on these increasing rates of data acquisition for primary ore properties, and increasing diversity of available data types, geometallurgy will likely continue to contribute to the design of ever more sophisticated mineral processing plants. Ideally, geometallurgical campaigns should efficiently establish the mineralogical and textural signatures, including their variability, for the main ore types, each with different processing performances, along with secondary properties (cf. Pereira et al. 2023 this issue), which together can be used to estimate overall process performance.

In a mineral processing plant, the different ore types, or even specific ore properties, will then ideally be characterised with characteristic spectral measurements. For example, a combination of XRF, FTIR, and Raman spectrometry may be measured by an instrument cluster positioned over the mill feed belt that could estimate the proportions of the different ore types entering the mill. An automation system would then influence the speed and fill rate of the mill.

The ultimate outcome of all these measurements, monitoring, and associated optimisation routines, will be the highly efficient recovery of minerals of commercial interest. However, to fully achieve this potential, geometry must take full advantage of developments in artificial intelligence to process the big data sets generated in modern mines. This is starting to occur at the time of writing, and we anticipate new breakthroughs in the upcoming years.

ACKNOWLEDGMENTS

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REFERENCES


All About Particles: Modelling Ore Behaviour in Mineral Processing

Lucas Pereira¹, Edgar Schach², Raimon Tolosana-Delgado¹, and Max Frenzel¹

Mineral processing encompasses the series of operations used to first liberate the valuable minerals in an ore by comminution, and then separate the resulting particles by means of their geometric, compositional, and physical properties. From a geometallurgical perspective, it is fundamental to understand how ore textures influence the generation of ore particles and their properties. This contribution outlines the processes used to generate and concentrate ore particles, and how these are commonly modelled. A case study illustrates the main ideas. Finally, a brief outlook on the most important research challenges remaining in this branch of geometallurgy is presented.

Keywords: raw materials; mineral processing; particle technology; resource efficiency

INTRODUCTION

In their general introduction to geometallurgy, Frenzel et al. (2023 this issue) provide a broad overview of the two key processes occurring in most mineral processing plants, comminution and mineral separation, as well as their respective goals. In addition, Butcher et al. (2023 this issue) outline the different analytical techniques available for the quantitative characterisation of ores, intermediate materials, products, and wastes. This article delves more deeply into the processes occurring within comminution and mineral separation devices, how they are influenced by primary ore properties, and how this can be understood and forecast quantitatively. This is an essential part of geometallurgical modelling, as mineral processing operations form the link between the orebody, the downstream extractive metallurgical processes, and tailings. Optimisation of the entire value chain is only possible if reliable, quantitative forecasts can be made for the performance of mineral processing operations.

Before proceeding with the detailed descriptions of comminution and mineral separation, it is helpful to emphasise two general features of mineral processing operations. First, the output of comminution devices generally consists of polymetallic, not monometallic, ore particles. Consequently, sorting devices do not act on pure mineral properties, but on particle properties, and ore particles are therefore the fundamental entities to be considered in the modelling of mineral processing operations (cf. Lamberg and Vianna 2007). This is analogous to atoms, molecules, and ions being the fundamental entities for the description of thermodynamic processes.

Second, while the specific physical processes affecting each particle (e.g., breakage after a collision event in a comminution device, or movement in a magnetic field) are, in principle, deterministic, one can never obtain sufficiently complete information on the initial states of all particles to completely describe their behaviour in a process. That is, the exact positions and momenta of all individual particles when they enter a device are unknown, as are their sizes, shapes, mineralogical and surface compositions, and internal textures. For this reason, the processes within a mineral processing plant are best modelled stochastically: one needs to describe, for each particle or particle type, the various potential process outcomes and their probability of occurrence (cf. Pereira et al. 2021a). An analogy can again be made with thermodynamics, where the macroscopic behaviour of a system is generally explained in terms of the movements and interactions of its microscopic constituents (atoms, ions, or molecules), which cannot all be described precisely, but are instead characterised by probability distributions.

COMMINUTION AND MINERAL LIBERATION

Comminution is the process of reducing the particle size of an ore to liberate the ore minerals from the gangue minerals. Thus, comminution strongly controls the overall efficiency of a mineral processing operation. Even though blasting as the first step of extracting an ore from the ground is also a form of comminution, the focus here is on the processes occurring in comminution devices: crushing, which reduces large rock lumps to millimetre-sized fragments, and milling, which subsequently produces micrometre-sized particles.

The several types of crushers and mills available (Wills and Finch 2015) mainly differ by the stress mechanisms and energy intensity they apply to ore particles, as summarised in Table 1. The most important stress mechanisms are shear and compression (Fig. 1A). Shear mostly leads to breakage by abrasion, which produces many small fragments but only slowly reduces the size of the feed particles. Thus, shear seldom contributes to liberation, but generates large amounts of finer particles that can be...

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Table 1: Stress mechanisms and energy intensity in mineral processing devices

<table>
<thead>
<tr>
<th>Process</th>
<th>Stress Mechanism</th>
<th>Energy Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushing</td>
<td>Shear</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Compression</td>
<td>High</td>
</tr>
<tr>
<td>Milling</td>
<td>Shear</td>
<td>Medium</td>
</tr>
</tbody>
</table>

False-colour image of a monazite-bearing carbonatite rock, constructed over a back scattered electron image.
detrimental to downstream separation processes. In some cases, abrasion is useful, e.g., when particle surfaces must be cleaned before processing. On the other hand, compression can lead to particles breaking into several fragments of mostly similar size, plus some much finer particles. Compared with shear, breakage by compression leads to a more significant reduction of average particle sizes and better contributes to liberation. In practice, comminution devices are designed to mostly apply compression stresses to particles, but shear ultimately happens as a corollary effect, especially if the energy available for breakage is low. Parapari et al. (2020) provide more details on the interplay between stress mechanisms, energy intensities, and breakage types.

In addition to the stress mechanism, the actual breakage events undergone by individual ore particles depend on particle properties such as size, shape, mineralogy, and texture. For instance, the largest and smallest particles in a tumbling mill generally break at lower rates than intermediate-size particles because they are less likely to experience high stress intensities due to collisions with the grinding media. Particles primarily consisting of hard minerals, such as quartz, are typically less likely to break than those consisting of softer minerals like calcite or galena. In addition, minerals with prominent cleavages, such as galena, are also more likely to break. In addition, the internal texture of the ore particles, i.e., the arrangements, sizes, shapes, and cleavages of the mineral grains within them, play a vital role in controlling breakage and mineral liberation.

To better understand the influence of particle texture, the distinction between random and non-random breakage must be introduced (Mariano et al. 2016). Random breakage occurs when particles of the same shape and size break

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### Table 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Applicable size range (in mm)</th>
<th>Stress mechanism</th>
<th>Reduction ratio</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaw Crusher</td>
<td>–</td>
<td>$10^3$</td>
<td>Compression</td>
<td>5–9</td>
<td>Primary crushing; robust design</td>
</tr>
<tr>
<td>Gyratory Crusher</td>
<td>With steep cone</td>
<td>$10^1$</td>
<td>Compression</td>
<td>7–10</td>
<td>Primary crushing</td>
</tr>
<tr>
<td></td>
<td>With flat cone</td>
<td>$10^2$</td>
<td>Compression</td>
<td>7–18</td>
<td>Post-primary crushing; produces a well-defined size distribution</td>
</tr>
<tr>
<td>Roll Crusher</td>
<td>Smooth</td>
<td>$10^2$</td>
<td>Compression</td>
<td>3–4</td>
<td>Used for material with hard mineral inclusions; stacked devices produce higher reduction ratios</td>
</tr>
<tr>
<td></td>
<td>Profiled</td>
<td>$10^2$</td>
<td>Compression</td>
<td>3–12</td>
<td>Comminution of soft to intermediate materials; profiles allow high reduction ratios</td>
</tr>
<tr>
<td>Rod Mill</td>
<td></td>
<td>$5 \times 10^1$</td>
<td>Shear &amp; Compression</td>
<td>20</td>
<td>Coarse milling down to 0.3–0.5 mm</td>
</tr>
<tr>
<td>Tumbling Mill</td>
<td>Autogenous Mill</td>
<td>$10^2$ ($10^0$)*</td>
<td>Shear &amp; Compression</td>
<td>up to 100</td>
<td>Coarser particles act as grinding media, allowing high reduction ratios and high throughput</td>
</tr>
<tr>
<td></td>
<td>Ball Mill</td>
<td>$10^2$ ($10^0$)*</td>
<td>Shear &amp; Compression</td>
<td>60</td>
<td>Final milling step to reach the target particle size for flotation</td>
</tr>
<tr>
<td>Stirred Media Mill</td>
<td></td>
<td>$10^{-1}$</td>
<td>Shear &amp; Compression</td>
<td>100</td>
<td>Ceramic beads (~5–10 mm), steel balls, or silica sand is added as grinding media. Pins, discs, or spiral screws transfer the energy into the mill. Energy input can lead to fluidisation of the grinding media, suitable to mill fine feed materials effectively</td>
</tr>
<tr>
<td>Vertical Mill</td>
<td>–</td>
<td>$10^2$</td>
<td>Compression</td>
<td>20</td>
<td>Pressure applied vertically by rollers</td>
</tr>
</tbody>
</table>

* Marks values based on the authors' experience in the mineral processing sector.

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**A** Stress mechanisms

- Compression
- Shear

**B** Non-random breakage types

- Feed particles
- Boundary-region fracture
- Selective breakage
- Liberation by detachment

**Figure 1** (A) Simplified illustration of the direction of forces acting on monomineralic particles in compression and shear, as well as the expected breakage types. (B) Example of non-random breakage types for a hypothetical quartz-galena ore.
in the same way under the same stress, irrespective of their internal structure. In non-random breakage, on the other hand, the particle texture determines the outcome of the breakage event. The most important non-random breakage mechanisms are illustrated in Figure 1B for a hypothetical example of quartz-galena particles. In selective breakage, one mineral breaks more easily than others due to its cleavage, low hardness, or pre-existing fractures. This is likely to occur for quartz-galena particles due to the prominent cleavages and low hardness of galena, resulting in many fine and well-liberated galena particles. Liberation by detachment happens when fractures propagate better along phase boundaries than within mineral grains. This is less likely in the present example, but would result in perfect liberation of galena and quartz. Finally, boundary-region fracture occurs when stress is concentrated in one of the minerals next to a phase boundary due to a significant contrast in the elastic properties of the two minerals. This is possible in the galena-quartz example. Interestingly, it results in particles generated from the boundary region showing worse liberation than the feed particles, reversing the typically positive correlation between particle size and liberation. King and Schneider (1998) provide more detailed descriptions of breakage types, whilst Hesse et al. (2017) document how non-random breakage can be used to design energy-efficient comminution routes.

It should be noted that the different stress mechanisms, energy levels, and breakage types co-occur in all comminution devices. The rate at which they affect individual particles depends on the type of device, the operating conditions (material throughput, energy input), and the geometallurgical properties of the feed particles. Hence, for any given particle, each possible breakage event may occur with a certain probability, arising from the complex interplay between the comminution device and the particle properties. It is thus fundamental to understand and model these probabilities to fully model comminution processes at the particle level. This is also the key to the success of any integrated geometallurgical framework, where textures observed in the orebody are to be converted to quantitative estimates of metal recovery. However, the variable and complex interactions between comminution devices, operating conditions, and 3D particle geometry, particularly where non-random breakage is essential, still pose considerable difficulties to the practical implementation of such a modelling approach.

Due to this complexity, most comminution models currently only predict how particle size distributions change from input to output streams (King et al. 2012), even though comminution is about mineral liberation. Overall, the approaches to model particle breakage and mineral liberation in comminution can be subdivided into three main groups that roughly reflect the chronological order of their development:

- **Empirical approaches** are based on the results obtained from dedicated test work, e.g., the relationship between the energy input into the system and measures of the particle sizes of the feed and output streams (Bond 1952; Morrell 2004). Some more modern empirical models attempt to predict mineral liberation and size reduction (Gay 2004; Gunctoro et al. 2021); however, these models are currently strictly limited in the number of minerals they can consider given computational limitations.

- **Population-balance approaches** combine particles into a small number of types or groups according to the hypothetical distribution of some of their properties (e.g., particle size, mineral composition). They then model how often the particles in each type experience a breakage event, the likely types resulting from such events, and the discharge rate of the various particle types out of the device. This approach can account for some non-random breakage modes (King and Schneider 1998). While population-balance models use physics-based equations to quantify each process, the parameters of the governing equations are estimated from experimental work (Powell and Morrison 2007; King et al. 2012). The major limitation of these models is the small number of properties considered in the definition of the particle types. For instance, only two ‘minerals’, i.e., ore and gangue, are often considered, ignoring the different properties and distinct behaviour that different ore and gangue minerals may exhibit. For example, chalcopyrite and galena can be found together in some deposits, and their breakage behaviour (as a function of hardness, cleavage, etc.) is very different.

- **Fundamental approaches** attempt to mechanistically model the interactions of individual particles within the comminution device to determine their breakage behaviour, e.g., quantifying the movement of particles and grinding media, the forces resulting from their interactions, and the breakage events occurring (Weerasekara et al. 2013). The high level of detail concerning particle interactions makes these models a powerful tool for designing new machinery. However, their usage in geometallurgy is limited: only a few minerals and simple particle shapes (e.g., spheres) can be modelled, which represent gross oversimplifications for capturing the true textural variability of actual ore particles.

The transition from empirical to fundamental models has mostly been linked to improvements in process understanding, available computational power, and the development of characterisation techniques focused on textures (Butcher et al. 2023 this issue). A major research challenge for the future is the full inclusion of the vast amounts of textural data produced by modern analytical techniques into comminution models. This is a complex problem in stochastic geometry and will likely require some time to be fully resolved. Regardless, this challenge is key to the successful implementation of geometallurgical programs because the particle data to be used in mineral separation models should ideally be provided by comminution models based on direct observations of in-situ ore textures. As covered in the next section, mineral separation modelling requires knowledge of many textural properties of the ore particles.

**MINERAL SEPARATION**

Once comminution has produced sufficiently well-liberated particles, the next task is the separation of those particles carrying ore minerals. This step is necessary to increase the efficiency of downstream metal extraction processes (Chetty et al. 2023 this issue), and is generally done in several stages. The basic idea is to subject the particles to an external field or force, which causes each particle to move along a different trajectory, usually because of its specific mineralogical composition, size, and shape. Different trajectories then result for particles with different compositions reporting to different output streams, as illustrated in Figure 2 for the case of magnetic separation.

**FIGURE 3** provides an overview of important mineral separation methods, indicating the properties they exploit and the particle size range over which they are applied. The most frequently exploited properties are density, electric susceptibility, magnetic susceptibility, and surface chemistry (Wills and Finch 2015), depending on the specific property contrasts between ore and gangue minerals. For example, magnetite is typically concentrated by magnetic separation because of its high magnetic susceptibility, while chromite can be separated from silicates with gravity separation due to its higher density. Additionally, depending on the
mineral associations present in the ore, different combinations of methods in a different order may be necessary for an efficient concentration of the value minerals: an example is described in Pereira et al. (2019) for a carbonatitic niobium ore.

Particle size is also critical for choosing an appropriate separation device (Fig. 3), the main reason being the stronger influence of particle–particle interactions in finer particle systems, which are often larger than the forces acting in favour of selective separation. A possible solution is to reduce particle–particle interactions by, for instance, using wet instead of dry separation processes (cf. wet and dry magnetic separation in Fig. 3). This is because particles are better dispersed in a slurry (a wet environment). When choosing between wet and dry processes, though, one must consider the resulting ancillary costs (e.g., water treatment, dewatering) and the overall availability of water (Aitken et al. 2016).

When modelling separation processes, the main difference to comminution is that ore particles are largely preserved intact during mineral separation, whereas they are strongly modified or destroyed during comminution. This makes mineral separation much easier to model, as it does not involve the solution of the complex geometrical problems associated with particle breakage.

As mentioned, the trajectories followed by individual particles inside separation devices depend on their specific properties and corresponding interactions with the device. From an outside perspective, these trajectories are, again, uncertain. Thus, they are best modelled by a set of probabilities for each particle to report to each of the several output streams of the device, with the probabilities depending directly on the particle properties and process conditions. This way of modelling mineral separation is illustrated for a simple example in FIGURE 4, showing what would happen to galena-quartz particles from the hypothetical ore of FIGURE 1 inside a dense media separator. In this device, particles are suspended in a liquid with an intermediate density between the ore and gangue minerals. This suspension travels along the device, allowing individual particles to float or sink. In the output, particles denser than the medium are collected in the underflow, while lighter particles are collected in the overflow. The probability of a particle going to a specific stream largely depends on its density, hence on the relative content of galena and quartz, as indicated in Figure 4B. Besides particle density, turbulence, particle–particle interactions, and particle size and shape further modify these probabilities. For instance, light particles may be trapped within a few dense particles causing them to report to the underflow stream. These unwanted effects affect the aforementioned probabilities, so the observed probability function (or partition curve) as a function of particle density is less sharp than the ideal separation curve (Fig. 4B).

The modelling of mineral separation processes revolves around assigning appropriate probabilities to individual particles or particle classes to report to the different output streams. Different approaches are used in the literature, just as in comminution modelling:

- **Empirical approaches** are based entirely on test-work or direct process characterisation in a plant. In the most basic implementations, these only describe bulk mineral recoveries observed in a process as a function of specific process parameters (Wills and Finch 2015). A classic implementation in terms of particle properties is the partition curve (also known as Tromp curve, Tromp 1937), which describes the recovery in a stream based on a particle property, taking into account the uncertainties of the separation process. However, this is restricted to a single particle property such as density (Fig. 4B). In the most advanced methods, probabilities are assigned to individual particles characterised through modern imaging techniques (cf. Butcher et al. 2023 this issue), enabling a detailed process understanding (Pereira et al. 2021a). However, empirical approaches can only be used to model processes under the same conditions as those covered by the test work. Extrapolation of results to other process conditions is not straightforward.
**Population-balance approaches** describe the process in terms of a small number of particle groups. For this purpose, they use physical laws and aggregated parameters estimated from test work, e.g., the buoyancy rate of a specific particle class in a heavy liquid (King et al. 2012). The main limitation of this approach is the small number of particle classes, and thus properties, for which can be accounted. However, using physical principles allows for some extrapolation of the results beyond the coverage of test work.

**Fundamental approaches** consider the physical processes occurring at the level of individual particles (e.g., attachment of particles to bubbles in flotation; Koh and Schwarz 2006) and attempt to model these purely in terms of first principles. Unfortunately, the high number of device- and process-specific parameters, which must often be known for full implementation, limits their application. In many cases, these parameters are not directly measurable, e.g., the actual surface hydrophobicity of a mineral in the flotation cell.

While current approaches to particle-based modelling of mineral separation processes are powerful, particularly the most recent developments in empirical modelling, substantial limitations remain for each approach. A promising route for future research would be to combine particle-based empirical models with fundamental models to overcome the limitations of both approaches.

**CASE STUDY**

The following case study provides an example of the detailed process understanding that can be achieved with state-of-the-art empirical approaches for mineral separation modelling, combining modern analytical tools with machine learning. This case study aims to understand the process behaviour of individual particles in a laboratory scale froth flotation test.

The process of froth flotation first requires some explanation. Froth flotation is a wet mineral separation method, in which the hydrophobicity (i.e., repellence of water) of specific mineral surfaces is increased through mineral-specific chemical reagents and pH regulation. Air is then bubbled through the particle–water slurry and particles containing the hydrophobilised minerals attach to the bubbles and rise to the top, forming a froth (i.e., foam with particles) enriched in the target mineral. Froth flotation is a highly versatile process because many chemical additives are available that can be used to tailor its selectivity for specific minerals (Fuerstenau et al. 2007).

In the present case study, a sedimentary apatite ore containing dolomite and quartz as major gangue minerals was processed by froth flotation with pre-defined operating conditions (Hoang et al. 2018) to recover apatite. The output streams (concentrates and tailings) were characterised by automated SEM-based image analysis (Fandrich et al. 2007). The recovery probabilities of all characterised particles were then estimated following the method of Pereira et al. (2021a). This method uses multivariate logistic regression to quantify the relation between particle size, shape, modal and surface compositions, and recovery probabilities. The quantification is based on the frequencies at which particles end up in each output stream and the properties of the particles found in these streams. Figure 5 displays the relation between recovery probability to the concentrate and particle size, shape, and mineralogical composition as extracted from the trained model.

It is interesting to note the distinct behaviour of liberated apatite particles compared with those of the different gangue minerals (Fig. 5A). Apatite has a recovery probability close to 1, and particle size is not as crucial for its recovery as for the gangue minerals. Liberated apatite particles are virtually always recovered into the mineral concentrate. Furthermore, the recovery probability of fine-grained dolomite and quartz particles is almost twice as high as that of their coarse counterparts. Regarding particle shape, rounder particles (aspect ratio = 1) report to the concentrate more frequently than elongated particles (aspect ratio = 0.1), irrespective of their composition. However, some caution is required here as the analytical method considers only 2D slices of 3D particles, introducing a difference between apparent versus actual sizes and shapes (Butcher et al. 2023 this issue). Finally, Figure 5B makes it evident that mineral association strongly influences apatite flotation: apatite-bearing particles appear to float better when they contain dolomite rather than quartz.

This better flotation of dolomite-bearing particles is, in fact, a problem for the process because magnesium is a penalty element in subsequent extractive metallurgical treatments, such as leaching (cf. Chetty et al. 2023 this issue). Further milling may increase apatite liberation, but at the expense of producing even finer particles with worse separability. If the minerals are too finely intergrown such that full liberation requires very fine grinding (<10 µm), the ore might be uneconomic. Thus, early removal of ore types containing fine dolomite-apatite intergrowths may be crucial. This highlights the value of a good understanding of the major primary geometallurgical ore properties, and how they relate to deposit geology. Interested readers can
Tomp KF (1937) Neue Wege für die Beurteilung der Aufbereitung von Steinkohlen. Glückauf 6: 125-131

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Fire and Water: Geometallurgy and Extractive Metallurgy

Deshenthree Chetty1, Glen T. Nwaila2, and Buhle Xakalashe1

Keywords: hydrometallurgy; pyrometallurgy; sustainability; Witwatersrand gold fields; Kalahari manganese deposit

INTRODUCTION

Extractive metallurgy, unlike mineral processing, generally aims at extracting and purifying specific elements from ores or mineral concentrates by inducing suitable chemical changes (Dutta et al. 2018). Hydrometallurgy relates to the chemical leaching of elements into, and their recovery from, an aqueous solution (an analogous process to hydrothermal mineralization). Pyrometallurgy, on the other hand, relates to the high-temperature treatment of ores and mineral concentrates, either in the solid or liquid state (akin to metamorphic and igneous processes, respectively), to concentrate the element(s) of interest into separate phase(s).

At first sight, it may appear obvious that geometallurgy should focus on the link between primary ore characteristics and mineral processing outcomes as minerals are preserved during mineral processing operations (Pereira et al. 2023 this issue; Frenzel et al. 2023 this issue), but destroyed in extractive metallurgy. However, primary ore characteristics will also impact the performance of extractive metallurgy operations. This is particularly important where ores are subjected to direct chemical treatment with minimal or no prior mineral concentration, as is common for some ferrous metal ores (e.g., Fe, Cr, and Mn), as well as other ore-types (e.g., some Cu, Au, and U ores). Some ore characteristics may also be inherited by mineral concentrates, and this can affect subsequent extraction processes, despite the concentrates meeting certain physical and chemical specifications for downstream processing.

Whether extractive metallurgy is applied directly or follows mineral processing, full optimization of the entire value chain from ore body to refined product is only possible if the effects of primary ore characteristics on all stages of the chain are well integrated and understood. This contribution outlines the current efforts to extend geometallurgy to extractive metallurgy operations. The relevance and impacts of the approach are examined in two case studies.

HYDROMETALLURGY

In hydrometallurgy, the process of leaching raw materials can be classified into four broad categories: in-situ leaching, percolation leaching, tank/vat leaching, and agitated leaching. In-situ leaching extracts metals directly from ores that remain in the ground (Habashi 1999). These ores must have sufficient permeability, a mineralogy amenable to leaching, and a geological context suited to guide and contain the leaching solutions (lixiviants). Percolation, or heap leaching, typically involves allowing a suitable lixiviant to seep into and through a mass of crushed ore at the surface. Tank and vat leaching involve placing milled and sized ore (or mineral concentrates) into large tanks or vats containing the lixiviant at suitable conditions (e.g., ambient or elevated pressure and temperature) to leach the valuable metals from the ore into the aqueous solution. Agitation leaching is a modification of tank/vat leaching, used for very fine particles that require agitation in a slurry with the lixiviant in order to extract metals. In all cases, the pregnant (i.e., metal-containing) solution is treated further through processes, such as solvent extraction and selective precipitation, to recover the valuable metals. Mineralogy and microfabric no longer play a role in these latter processes, although the primary ore will influence the chemical composition of the pregnant solution. The solid leach residues, by contrast, are essentially chemically modified primary ores.

Leaching processes are affected by many of the same primary ore characteristics as mineral processing operations (Table 1). Of particular importance are mineral grain sizes and associations, ore and gangue mineralogy and mineral abundances, as well as mineral liberation in the crushed material. An understanding of ore type and valuable metal distribution/liberation is thus essential for predictive modelling purposes in leaching operations.

The extractive metallurgy of gold provides typical examples for all principal types of leaching, as well as the critical influence of primary ore characteristics. Based on gold
deportment, mineral association, liberation and microfabric, and the resulting process behavior, three principal types of gold ores may be distinguished (Habashi 1999):

- **Free-milling gold ores** mostly contain native gold (or electrum) that is easily liberated during milling operations, with >90% of Au recoverable by conventional tank/vat leaching.

- **Refactory gold ores** mostly contain gold as submicroscopic grains or atomic-scale substitutions (sometimes misleadingly called “invisible”) in minerals such as arsenopyrite or pyrite. Such ores require excessive reagent usage and/or additional pre-treatment processes, such as roasting (a pyrometallurgical process; see below), to recover an economically feasible amount of gold.

- **Complex gold ores** from which high gold recoveries are possible, but only under modified or more intense leaching conditions due to the presence of deleterious elements and minerals.

The following case study illustrates the importance of geometallurgical knowledge for the successful leaching of gold in the world’s largest gold province, the Witwatersrand gold fields in South Africa.

## OPTIMIZATION OF GOLD RECOVERY FROM WITWATERSRAND ORES

With more than 52,000 t of gold produced in almost 140 years of mining and more than 30,000 t remaining in geological resources, the Witwatersrand gold fields constitute the world’s largest gold province (Fig. 1; Frimmel and Nwaila 2020). The Witwatersrand ore bodies (referred to as “reefs”) are bound to quartz-pebble conglomerate horizons of Archean age that can often be correlated across distances of >300 km (Minter et al. 1993). Most of the Witwatersrand gold occurs in two sedimentary facies: thin pebble lags (residual accumulation of surface rock fragments after removal of finer material by winds) representing aeolian (deflation surfaces, often associated with kerogen (carbonaceous matter) seams; and conglomeratic, high-energy fluvial channel deposits (Frimmel 2005). Whilst the richest ore bodies were decimeter-thick conglomerates with grades of >20 g/t Au, mined reefs currently contain between 3–9 g/t Au. Uranium (100–350 g/t U) is an important by-product in some operations.

Gold-bearing quartz-pebble conglomerates of the Witwatersrand Basin usually contain quartz, pyrite, and sheet silicates (pyrophyllite, mica, chlorite), with variable amounts of kerogen, other sulfides (e.g., arsenopyrite, chalcopyrite, pyrrhotite), and many trace minerals (e.g., chromite, zircon) (e.g., Hallbauer and Maske 1986). Native gold (free-milling) is the most important carrier of gold, whereas uranium occurs mostly in uraninite and more complex oxide minerals (e.g., brannerite). Although the Witwatersrand gold ores share many general mineralogical and chemical characteristics, localized variations exist. For example, some ores contain a high proportion of solid kerogen, while others have a high proportion of minerals related to post-depositional hydrothermal overprints (e.g., pyrrhotite, chalcopyrite).

Gold is usually recovered from the Witwatersrand ores using a conventional cyanide-based tank leaching process (Fig. 2). Recovery is challenged by the fine grain size of the native gold (<100 μm; Hallbauer and Maske 1986), its close association with reactive sulfide minerals (e.g., pyrite, arsenopyrite), and the abundance of kerogen. These challenges are addressed by selective mining to separate ores based on their mineralogical composition, fine milling to achieve surface liberation of the gold, and varying the concentration of reagents and hydrometallurgical plant configuration (cf. Habashi 1999).

The process of blending (i.e., mixing of ores extracted from different reefs) is indispensable for extending the life-of-mine of large-scale gold operations in the Witwatersrand gold fields. Downstream processing must then be able to adapt to such blended ores. The benefits of blending include: (a) enhanced extraction efficiency, (b) lower reagent consumption, (c) reduced feed variability, and (d) recovery of valuable metals from low-grade ores blended with high-grade counterparts.

An example of gold mining operations where ores with different primary properties are blended is the Driefontein mining complex in the Carletonville gold field, where one gold cyanidation plant processes ores from four different reefs: the Black Reef (BR), Carbon Leader Reef (CLR), Middelvlei Reef (MR), and Venterdorp Contact Reef (VCR). Based on this context, Nwaila et al. (2020) combined quantitative data on ore properties with experimental observations concerning the performance of the hydrometallurgical process route. Diagnostic leaching tests involving blends with various proportions of ores extracted from the BR, CLR, and VCR were conducted to optimize gold recovery. The interactions of the three ores were also recorded in terms of mineralogy, gold deportment, leaching rates, and Au recovery.

![Figure 1](image-url) Geology of the Witwatersrand gold deposits showing (A) the paleogeography of the Witwatersrand Supergroup, the Venterdorp Contact Reef, and the Black Reef.

**Artist:** Lina Jakaite in cooperation with Glen Nwaila.

![Figure 1](image-url) Typical Witwatersrand-type auriferous conglomerate showing quartz and pyrite. **Photo:** Mark Burnett.
A ternary diagram with the three studied ore types as end members illustrates the expected gold recoveries depending on ore blend composition (Fig. 3). Ore blends with high contents of kerogen and trace amounts of copper and arsenic (i.e., high BR proportions) yield lower gold recovery rates. In contrast, high Au recovery is expected when CLR and VCR dominate the blend (Fig. 3). This is due to the high degree of Au liberation and the presence of leachable kerogen in the CLR. Consequently, mineralogy and texture strongly determine the feasibility of blending. These results, as summarized in Figure 3, are currently applied at Driefontein to minimize gold losses associated with ore blending. Modelling of intrinsic ore variation relative to reagent concentration or pressure–temperature leach conditions may further enhance Au recovery outcomes.

PYROMETALLURGY

Chemical changes in the pyrometallurgical treatment of ores and concentrates occur at high temperatures, ranging from 100 to 3000 °C (Dutta et al. 2018). Various processes are applied, depending on the products required. Roasting, for example, may be used to convert sulfide minerals to oxide phases more amenable to hydrometallurgical treatment. Direct smelting of sulfide-rich mineral concentrates (e.g., from flotation) produces a matte (sulfide-melt containing, e.g., Cu, Ni) and a slag (oxide-melt containing unwanted residues). The matte is then exposed to further pyrometallurgical and/or hydrometallurgical treatment to produce refined metals (e.g., Cu, Ni, Pt).

For some ferrous metals (e.g., Fe, Mn, Cr), the ore is mixed with a reductant, typically coking coal, and fluxes, like dolomite and quartz, to reduce the oxidic ore minerals to a metal alloy and promote the formation of a slag. Solid-state pre-reduction in the furnace first often produces divalent oxides. Subsequent melting and reduction of these divalent oxides forms an alloy, which can be separated from the slag. In some instances, the commodity of interest is captured by the slag for further processing (e.g., Ti from ilmenite smelting). Lastly, volatiles and dust are produced in pyrometallurgical processes and may be a source of by-products (e.g., sulfuric acid in Cu smelting).

**Table 1** IMPACT OF GEOMETALLURGICAL ATTRIBUTES, SUCH AS MINERALOGY, TEXTURE, AND MICROFABRIC, ON THE PERFORMANCE OF EXTRACTIVE METALLURGICAL PROCESSES FOR SELECTED COMMODITIES.

<table>
<thead>
<tr>
<th>Primary ore characteristics</th>
<th>Commodity examples</th>
<th>Geometallurgical approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrometallurgical processing</td>
<td>Abundance of acid-consuming minerals, e.g., carbonates, reactive phyllosilicates</td>
<td>Porphyry Cu alteration zones; calcite-hosted U; carbonatite-hosted REE;</td>
</tr>
<tr>
<td></td>
<td>Abundance of alkali-consuming minerals, e.g., reactive silica</td>
<td>Al from bauxite</td>
</tr>
<tr>
<td></td>
<td>Variations in ore mineralogy and metal deportment</td>
<td>Different Cu-(Fe)-sulfides in sediment-hosted Cu ores; supergene altered Cu ores with transitions between oxidic and sulfidic ores</td>
</tr>
<tr>
<td></td>
<td>Abundance of refractory ore minerals</td>
<td>Betafite and brannerite in U ores; chalcopyrite in low-grade Cu porphyry ores for biological heap leaching</td>
</tr>
<tr>
<td></td>
<td>Grain size distribution, liberation of ore minerals</td>
<td>Applicable to all minerals targeted by leaching operations</td>
</tr>
<tr>
<td>Pyrometallurgical processing</td>
<td>Abundance and distribution of deleterious minerals</td>
<td>Chromite, talc, Mg pyroxenes in PCM concentrates; As minerals in Cu concentrates</td>
</tr>
<tr>
<td></td>
<td>Mineralogy, texture, and porosity</td>
<td>Fe and Mn ores</td>
</tr>
<tr>
<td></td>
<td>Deposition in solid solutions; finely intergrown textures</td>
<td>Refractory Au (sulfide-hosted); lateritic REE ores</td>
</tr>
</tbody>
</table>
Pyrometallurgical treatment is of particular importance for the production of iron, ferroalloys, and steel from oxide ores. High-grade ores of Fe, Mn, and Cr require little to no prior mineral processing. Nevertheless, some ore characteristics have an important influence on the efficiency of pyrometallurgical treatment (Table 1):

- **Ore texture**, including porosity, influences the breakage behavior of the ore, and hence the particle size distribution of the furnace feed. Particle sizes of furnace feed are typically coarser than 6 mm, referred to as lumpy ore, with fines being <6 mm. Fines require sintering (process subjecting aggregate material to high temperature and pressure to compact the loose material into a solid object) or pelletization (method of agglomeration, or particle size enlargement, in which material fines are processed into pellets or granules) prior to smelting. The minimization of fines is therefore important from a resource utilization and energy efficiency perspective.

- **Mineralogy**: The presence of hydrous minerals or carbonates causes volatile loss on heating. Where their modal abundance is of significance, treatment must be undertaken prior to furnace processes. Volatiles are ideally removed through sintering, as implemented in the processing of carbonate-rich Mn ores. This has the added advantage of an upgraded sinter product through residual enrichment of the element of interest and coarsening the particle size. Sintering also improves resistance to abrasion and fines generation during transport. The occurrence and abundance of OH- and H₂O-bearing ore minerals, such as goethite (FeOOH), must be monitored, as these can release water in the furnace, and thereby create fines through physical breakage from volatile release.

In the following case study, mainly mineralogy is considered to illustrate its impact on energy consumption in the pre-reduction of high-grade Mn ores from the Kalahari manganese deposit (KMD) in South Africa.

### IMPACT OF ORE VARIABILITY IN THE KMD ON FURNACE ENERGY CONSUMPTION

The KMD accounts for 78% of global land-based Mn resources, making South Africa the world’s leading producer of Mn (~37% of global production). Manganese ore in the KMD occurs as three distinct sedimentary layers intercalated with banded iron formations. Together, these comprise the Paleoproterozoic Hotazel Formation of the Transvaal Supergroup (Chetty 2008). Three main ore types occur in the KMD: sedimentary-diagenetic ores (low grade, ~38 wt.% Mn), hydrothermally altered ore (high grade, >45 wt.% Mn), and supergene ores (intermediate and high grade, 38–45 wt.% Mn). The low-grade ores occur throughout the KMD, accounting for 97% of the total resource. The high-grade ores are restricted to the northern part of the deposit, and account for <3% of the resource, with the supergene ores constituting <1%, and geographically restricted to the southeastern margin of the deposit. The three ore types are mineralogically and texturally distinct. Braunite (Mn²⁺Mn³⁺₉O₄(SiO₄)) and kutnahorite (Ca(Mn²⁺,Mg²⁺)(CO₃)₂) predominate as ore minerals in the low-grade sedimentary-diagenetic ores, whereas hausmannite (Mn²⁺(Mn³⁺,Fe³⁺)₂O₄), braunite II (Ca(Mn²⁺,Fe³⁺)₅(SiO₄)₂), and bixbyite ((Mn³⁺,Fe³⁺)₉O₈) are key minerals in the high-grade hydrothermally-altered ores. The intermediate-to-high grade supergene ores comprise todorokite ((Na,Ca,K)₂(Mn⁴⁺,Mn³⁺₃)O₁₂·3·4·5(H₂O)), cryptomelane (K(Mn⁴⁺,Mn³⁺)₈O₁₆), and pyrolusite (Mn⁴⁺O₂).

This case study focuses on the high-grade hydrothermally-altered ores, as these show the most complex and variable mineral assemblages with more than 100 minerals reported. Infiltration of hydrothermal fluids along north-south striking faults caused extensive alteration of the sedimentary-diagenetic protolith, forming high-grade ore through carbonate dissolution and recrystallization (Chetty 2008).

For pyrometallurgical processing, the high-grade manganese-oxide ores of the KMD are combined with flux and coke and fed into a submerged arc furnace (SAF). This furnace contains three equidistant electrodes submerged in the burden of reacting raw materials, as well as a coke, slag, and alloy bed in its lower part (Fig. 4). Electrical energy is dissipated into the material through a combination of arcing and resistive heating of the coke–slag–alloy bed (Steenkamp et al. 2020). The price of electricity is a key cost driver for SAF smelting of the Mn ores, accounting for 45%–50% of smelter costs. Energy consumption,
which is mostly influenced by solid-state reactions in the pre-reduction zone of the SAF, therefore becomes an important parameter to minimize. Figure 4 shows the key Mn oxide reactions that take place between 200 and 800 °C, all of which are exothermic. Ideally, the final reaction of MnO to Mn should be the only endothermic reaction. However, above 800 °C, the reduction of Mn3O4 to MnO also becomes endothermic because of the simultaneous highly endothermic reaction of CO2 with solid C (the Boudouard Reaction; Olsen et al. 2007), which greatly reduces energy efficiency.

The various Mn oxides present in the KMD (Fig. 4) may be approximated by simple minerals such as pyrolusite (Mn4+O2), bixbyite (Mn32+O3), and hausmannite (Mn3+Mn22+O4). Because Mn has different oxidation states, the reduction of these minerals will release/consume very different amounts of energy (Fig. 4). Furthermore, the reactivity of minerals in the pre-reduction zone appears to be dependent on the type of minerals present. Tangstad et al. (2001) found that ores with tetravalent Mn minerals reduced faster than those with divalent and trivalent Mn minerals, although details were lacking on the quantitative mineralogy of the ores tested. Kinetic behavior will influence the degree to which Mn3O4 is reduced before the Boudouard reaction begins and, therefore, will influence energy consumption.

Considering the possible relationship between Mn grade and bulk oxidation state, Chetty and Gutzmer (2018) studied the modal mineralogy of drill cores from different parts of the northern KMD, as well as some supergene ores from the southeastern margins. Modal mineralogy and mineral chemistry data were combined to calculate bulk assays for validation purposes. Considering Mn valence states and their partitioning in the minerals, the total contents of divalent, trivalent, and tetravalent Mn of the studied ores were determined. Figure 5 shows that the Mn grade of ores from the KMD does not covary with bulk Mn oxidation state. Different bulk mineral assemblages can reflect very similar bulk oxidation states. For example, most high-grade hausmannite-rich ores display virtually identical bulk Mn oxidation states to low-grade braunite–kutnahorite-rich ores. This result emphasizes the need to understand the mineralogy, not only the grade or total Mn-associated oxygen, to optimize energy efficiency in the reduction of the manganese ores of the KMD.

It is important to note that the bulk Mn oxidation states for high-grade ores of the northern part of the KMD show a broad systematic variation in space, with lower ratios exhibited by hausmannite-rich ores that are more prominent in the east, and higher ratios displayed by braunite II–bixbyite ores that dominate in the west (Fig. 6). This distribution has been tentatively linked to fluid–rock ratios during hydrothermal alteration (Chetty 2008). For pyrometallurgical processing, this geologically controlled distribution can be used to predict possibly faster pre-reduction and lower energy consumption in the SAF as mining progresses westward in the northern KMD. Furnace conditions should be adapted accordingly, as these may oversupply electricity to drive reactions that are more exothermic than for previously mined high-grade ores.

As noted already, ore texture and porosity are important drivers for ore breakage characteristics during mining and ore handling. Given the changes in mineralogy, as well as variable porosity imparted to the ores during hydrothermal alteration in the northern KMD, quantitative texture and porosity assessment should be conducted to link mineral assemblages with ore hardness and strength properties, as well as energy consumption, to provide a holistic integration of variables and their impacts on smelting with continued mining. Consequently, operational flexibility can be implemented to optimize Mn alloy production and resource utilization.

GEOMETALLURGY AND SUSTAINABILITY

To assess the sustainability of extractive metallurgy operations, the following parameters must be considered: reagents, water, energy, recoveries of valuables in product and by-product streams, waste generation, environmental impact of residues, and emissions. The above examples illustrate how geometallurgical approaches can positively impact some of these parameters and, thus, the sustainability of extractive metallurgy operations.

The minimization of reagent consumption in leaching is important for operational expenditure. In a geometallurgical context, ore variability must be understood to manage this parameter. The recycling of reagents is also important for process efficiency in developing leaching and extraction flowsheets, particularly in arid regions where water is scarce, and remote areas where reagent transport becomes prohibitively expensive. More environmentally friendly reagents may also be sought, such as alternatives to cyanide for gold leaching. In all these endeavors, the entire life cycle of the reagents and associated impacts must be considered, and all must feature in a geometallurgical model.
Pyrometallurgical processes are often carbon and energy intensive, as in the production of ferroalloys, iron, and steel. There is a strong drive toward decarbonizing the industry. Reductants with low carbon footprints, such as biomass and green hydrogen (generated using renewable energy sources), are gaining momentum as useful alternatives. A wide range of possible technological approaches already exists for iron production using hydrogen as a reductant (Souza Filho et al. 2022). There are also efforts to incorporate renewable energy into pyrometallurgical processes, such as solar thermal heating of feed and product streams (e.g., Hockaday et al. 2020) or the use of solar electricity to power furnaces. Energy efficiency can be further increased by heat recovery from furnace off-gas streams and slags for electricity generation. Understanding feed variability will help to optimize the impact of such initiatives.

Pyrometallurgical processes are further characterized by the generation of slags, which are generally discarded as waste. However, this leads to the loss of incompletely reduced metal oxides and metals entrained in the slag. Consequently, slag reprocessing is common, particularly for the recovery of high-value metals like cobalt (Jones and Pawlik 2019). From a circular economy viewpoint, slags should be considered by-products, and during process design, conditioned slags should be produced for further treatment, whether for metal reclamation or utilization of the slag itself, e.g., as construction material. Quantitative characterization of the slags and other by-product streams is vital in all waste valorization approaches toward sustainable processing, as the phases, crystallinity, porosity, and texture of the slag are the main factors that dictate the viability of potential products. Well-understood ore characteristics and good knowledge of their interactions with other raw materials in the furnace, complemented by advances in thermochemical modelling, offer an opportunity for predictive slag design to enable further use as a by-product.

Given the steady depletion of grades in increasingly complex primary ores available for extraction, as well as associated higher mining and processing costs, efficient utilization of secondary resources will be required to meet future metal demand. The generation of increasing volumes of tailings is of similar relevance and requires consideration for environmental and socio-economic risk mitigation, as well as value extraction (Parbhakar-Fox and Baumgartner 2023 this issue). The recycling of end-of-life products, sometimes referred to as urban mining, is also championed by complex materials, and rapidly growing waste streams that may pose environmental threats, but have large potential value. A notable example is e-waste. Integrated flowsheets for the physical beneficiation and metallurgical treatment of these complex materials—informated by a geometallurgical approach to material characterization and predictive process modelling—will be required for feasible value reclamation.

OUTLOOK

This paper used two well-documented geological examples to provide an indication of the inherent potential of geometallurgical approaches in extractive metallurgy. Yet, in practice, glaring gaps remain between the different knowledge silos along the value chain from exploration to metal extraction and recovery. Geometallurgy can help to bridge these gaps to realize the full value of different raw materials, and design integrated flowsheets to maximize benefit in complex process chains.

As this issue of Elements aims to bring awareness of geometallurgy, it is prudent to close with a consideration of how the concept may be better incorporated into postgraduate curriculum. Simulation-based approaches would likely be best suited to teach troubleshooting skills and critical thinking through gamification and modelling. Corresponding modules may be integrated into economic geology, as well as geological, mining, and metallurgical engineering curricula. This can help to build a new generation of professionals in this decidedly interdisciplinary field.

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OUTLOOK

This paper used two well-documented geological examples to provide an indication of the inherent potential of geometallurgical approaches in extractive metallurgy. Yet, in practice, glaring gaps remain between the different knowledge silos along the value chain from exploration to metal extraction and recovery. Geometallurgy can help to bridge these gaps to realize the full value of different raw materials, and design integrated flowsheets to maximize benefit in complex process chains.

As this issue of Elements aims to bring awareness of geometallurgy, it is prudent to close with a consideration of how the concept may be better incorporated into postgraduate curriculum. Simulation-based approaches would likely be best suited to teach troubleshooting skills and critical thinking through gamification and modelling. Corresponding modules may be integrated into economic geology, as well as geological, mining, and metallurgical engineering curricula. This can help to build a new generation of professionals in this decidedly interdisciplinary field.

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The raw materials industry produces billions of tonnes of mine waste per year. Given increasing metal demand and the global appetite for waste reduction, strategic opportunities to minimise its production must be embedded across the life-of-mine. Adopting a geometallurgical approach to total deposit characterisation—where mineralogical and geochemical data are routinely collected and used to model geoenvironmental domains—offers profound benefits for improving the understanding of the composition and environmental impact of different residues. Using established and emerging technologies, from handheld instruments and core scanners to synchrotrons, throughout a mine’s life—starting already during exploration—may assist the raw materials industry to reduce their waste footprint and adopt circular economy principles.

Keywords: mine waste; tailings; circular economy; critical metals; short-wave infrared

INTRODUCTION

Our global community hit a milestone in 2023: 8 billion humans. By 2050, this will have grown to 9.7 billion. With this comes increasing pressure on our natural resources to sustain the wellbeing of the growing population. It is the global raw materials industry that faces the challenge of finding and developing the ore deposits needed to sustain this demand. However, once found and mined, an even bigger challenge is posed. How do we manage the resulting mine waste? Approximately 100 Gt of mine waste is produced annually (Tayebi-Khorami et al. 2019). Taking just one commodity, copper (a key metal in all electrical infrastructure), Valenta et al. (2023) predicted tailings production to increase from 4.3 Gt/y in 2020 to 16 Gt/y in 2050. In total, 858 Gt of mine waste could be produced for this metal alone up to 2050. Typically, mine waste is placed into purpose-built repositories or landforms where it remains indefinitely unless another use for it is found (e.g., tailings used as backfill material for mining-related cavities in underground mines).

Since the publication of the Elements article, “Mine Wastes: Fast, Present, Future” (Hudson-Edwards et al. 2011), the attitude of industry towards mine waste has evolved.

WHAT ARE MINE WASTES?

Mine waste, as a general term, is summarised by Hudson-Edwards et al. (2011) as uneconomic, solid, and liquid materials found at (or near) mine sites. They are heterogeneous materials including relatively coarse-grained waste rock and slags, fine-grained tailings, ashes and flue dusts, and chemical- and metal-bearing waste water. Waste materials are produced at all stages of the industrial value chain of raw materials, with mine waste subdivided into three types: waste rock, tailings, and metallurgical residues (Fig. 1). During mine development and mining, non-ore rocks are removed, generating large tonnages of very coarse, highly heterogeneous material collectively termed waste rock. Both open cut and underground mining activities will produce these materials, albeit with the first producing much higher volumes. Waste rock is just a geological material and can consist of igneous, metamorphic, or sedimentary rocks that may be affected by hydrothermal alteration or surface weathering. The mineralogy, chemistry, and texture of these materials can be heterogeneous, with their physical properties varying in response to this compositional complexity. For example, particles can range from clay size (with a large available surface area for...
oxidation processes) to boulder size fragments (compara-
tively less reactive; Lottermoser 2010; Fig. 2A). Waste rock is
typically trucked to the final waste landfill (i.e., dump
or pile), where it is carefully placed based on engineering
design criteria informed by geochemical and geotechnical
assessments.

Mineral processing follows on mining (Fig. 1), with a
large variety of technologies applied to produce a mineral
cone suitable for direct use or extractive metal-
lurgical treatment (see Pereira et al. 2023 this issue).
Independent of the chosen method is the production of
a waste stream referred to as tailings (Figs. 1 and 2B).
For context, 90%–98% of copper ore processed ends
up as tailings (Valenta et al. 2023). Tailings consist of fine-
grained rock particles (10–300 µm) mixed with process
waters. Tailings typically comprise residual ore minerals,
gangue minerals, and secondary minerals that may form
after deposition of the tailings (Lottermoser 2010). They
are usually disposed via pipelines affixed with a spigot, into
purpose-built dams or storage facilities for which several
designs exist (Lottermoser 2010). Deposition of coarser
and denser particles occurs proximal to the spigot point,
with less-dense, finer-grained materials depositing distally.
Tailings deposition can be seen as roughly analogous to
sedimentary delta formation.

Metallurgical processing is undertaken to produce metals
from mineral concentrates (Fig. 1; see Chetty et al. 2023
this issue). This process generates significant volumes of
metallurgical residues, including slag, spent heap leach,
residues, red muds, dusts, and waste waters. These can be
very reactive and highly concentrated in environmentally
problematic constituents. Slags, whilst variable in composi-
tion and texture (e.g., the relation between crystallised
and glassy materials that comprise the slag) broadly fall
into two main types: ferrous and non-ferrous. Mineral-
like phases from the olivine, pyroxene, and spinel groups
dominate, in addition to amorphous glasses of variable
composition (Fig. 2C). Where reactive sulphides are present
(e.g., pyrite), there is a high probability that acid and met-
liferous drainage (AMD) will form under surficial condi-
tions, as shown in Figure 2D.

After mine closure, mining, mineral processing, and metal-
lurgical residue deposits, as well as mining voids (open pits
and underground workings) remain on site and are the
focus of rehabilitation efforts. Other types of waste gener-
at ed at mine sites (e.g., municipal and plastic waste) are
less significant in terms of tonnage and volume, and in the
case of disused equipment, may even be perceived as
an asset and sold.

PROBLEMS AND OPPORTUNITIES

If inadequately managed, mine waste can pose a range of
physical risks (i.e., tailings, storage facility (TSF) failures)
and risks of (physico)-chemical pollution (i.e., AMD, nox-
ous dust) to the receiving environment. Over the
past decade, several TSF failures have featured very promi-
iently to global society through modern communication
channels including Mt Polley (2014, Canada), Samarco
(2015, Brazil), Brumadinho (2019, Brazil), and recently
Jagersfontein (2022, South Africa). These can mostly be
attributed to design deviations and monitoring gaps and
have catastrophic consequences. Whilst the causes of
these failures have varied, it has been acknowledged that
the post-depositional mineralogical (described in Moncur
et al. 2015) and also textural evolution of tailings is not
always accounted for in the design phases, as acknowl-
dged by Robertson et al. (2019). This highlights the
importance of understanding all particle properties of
deposited tailings, as well as changes that may occur after
deposition. However, such detailed information is rarely
captured. Instead, only bulk properties like slurry density,
percentage of solids, particle size distribution, and limited
chemical data (e.g., Cu, Fe, and S in a copper operation) are
routinely recorded. There is a clear opportunity to gain
more detailed knowledge about the compositional and
textural characteristics through geometallurgical studies.
This knowledge may improve the understanding of the
physical behaviour of the tailings material and may form
part of an integrated dataset required to avoid catastrophic
physical failure, ideally before deposition and, if already in
place, to enhance the possibility of monitoring the well-
characterised material.

In pollution terms, Lottermoser (2010) explained
that mine waste is considered problematic if it contains
or may generate hazardous substances (e.g., heavy metals, metalloids, radioactive elements, process chemicals, acid-
generating minerals, and/or asbestosiform minerals). Iron
sulphide minerals (e.g., pyrrhotite, pyrite, arsenopy-
rite, marcasite) are commonly associated with
metalliferous ore deposits, and can be found in
mining, mineral processing, and/or metallurgical
wastes. If they undergo oxidation, sulphuric acid
will be generated and low-pH waters will form,
resulting in AMD (Hudson-Edwards et al. 2011;
Fig. 2D). In acidic surface and ground waters, the
mobility of metals and/or metalloids (e.g., Al, As,
Fe, Zn, Pb, Cu, Ni, Co) is greatly promoted with
associated high sulphate concentrations. The
mobilised metals then enter the receiving environ-
ment where they may cause severe environmental
impacts to flora and fauna.

The United Nations declared AMD the second
biggest global environmental challenge after
climate change (Kefini et al. 2017), as typically, once
AMD has started to form, it is very difficult to contain
(Lottermoser 2010). Whilst the engineering design of
mine waste facilities attempts to prevent AMD, the majority
fail to do so in the long run. AMD treatment methods
are then required, with two types, active or passive treatment,
typically being implemented. Active methods include the
application of alkaline chemicals to precipitate metals, and other techniques such as adsorption. Passive treatment of AMD may involve biological treatment with constructed wetlands, and/or chemical treatment with limestone drains and sulphate-reducing bioreactors (Kefni et al. 2017). When offering some environmental benefits, these treatment options are largely regarded as expensive and may not be sustainable long-term (i.e., they may be technologically complex, requiring regular maintenance; Ighalo et al. 2022). To reduce the risk of AMD, sulphide-bearing tailings are often overlain by engineered or vegetated covers. These covers are often not sufficient to de-risk a site. Penrose et al. (2022), for example, presented a case study where wombats had burrowed into a vegetation cover placed over arsenic-rich mine tailings in Tasmania and were exposed to heavy metals. There is a clear opportunity to use data acquired through thorough mineralogical characterisation of ores and major waste types already during exploration/pre-feasibility stages to identify not only all viable commodities, but to also quantify environmental risks arising from resulting residues.

Not all mine wastes pose an AMD threat, as they do not all contain reactive sulphides. However, if ‘inert’ wastes are sub-aerially deposited, e.g., waste rock and slag piles (Fig. 2), then noxious dusts can be generated through weathering processes. The Broken Hill lead-zinc-silver mine in Australia serves as an example. Mining commenced at Broken Hill in 1885 and is still ongoing. During its life-of-mine, lead-rich dust has been generated from both mineral processing operations and mine wastes, including a historic slag pile. Metal-rich dusts have been deposited into adjacent gardens and parks, and lead can enter the blood stream through hand-to-mouth soil contact (Dong and Taylor 2017). This causes very significant health risks. A thorough mitigation program is thus currently in place, including a reduction of waste pollution sources to soils and waters and development of a waste management plan for the entire mine site (New South Wales Environment Protection Authority 2016). Another excellent example of noxious dust generation by mining wastes are the crocidolite-bearing tailings around Wittenoom in Western Australia. The asbestiform crocidolite fibres in the tailings pose human health risks (mesothelioma; Rogers 2018). Dust suppression methods, such as the introduction of engineered or vegetation covers, are used to limit the impact of noxious dusts.

Common to all the mine waste problems described above is the need for better characterisation of the mine-waste properties (chemistry, mineralogy, texture, geotechnical parameters, including porosity and grain size, and even hardness) during emplacement and beyond. With increased importance placed on environmental sustainability, the mining industry finds itself at a crossroads. It can either maintain current waste management practices, which will become increasingly challenging as higher tonnages are generated to meet future ‘green’ needs (relating to the energy transition, and need for CRM mentioned in the introduction). Or it can challenge the entire paradigm of mine waste management by adopting an action (i.e., introducing preventative measures, limiting the occurrence of environmental problems early in the life-of-mine) rather than a reaction (i.e., managing issues once they have occurred) approach. Using medicine as an analogue: preventing rather than curing disease.
SOLUTIONS

In the previous section, several opportunities were highlighted to minimise residue volumes and to predict, as well as limit, the environmental impact that mine waste will have in the future. In addition, economical aspects will change over time with increased demand for certain elements and materials present in wastes, offering an economic opportunity that will be of interest in decades to come. Turning wastes into resources must be the final goal to avoid all the risks and mitigation measures discussed above. However, this will only be possible if we know what these wastes are (geometallurgically speaking) in advance (in situ) or once deposited (ex situ). Considering this, the technological innovations for multi-scale ore characterisation (in both 2D and 3D) and the data sets collected, as described in Butcher et al. (2023 this issue), must also be applied to mine waste characterisation. If this information is routinely and continuously collected over time, then better geoenvironmental (and economic) decisions can be made across the life-of-mine. The following section outlines key considerations and examples of how this can be implemented.

Exploration Phase

At early stages (i.e., exploration, pre-feasibility), areas (or domains) associated with increased environmental risks (e.g., higher pyrite content or arsenic concentrations) in structural and mineralogical imaging (geometallurgical) in advance of an ore body that is being explored should be delineated. Such an assessment should include geological stability as well as AMD risk. For the latter purpose, static and kinetic geochemical tests are the current industry-standard methods. Such tests were developed in the 1970s for the coal mining sector specifically to evaluate absolute acid formation and neutralisation potential. They have, however, been repeatedly criticised in the literature as an oversimplification for the more complex composition of metalliferous ores (Parbhakar-Fox and Lottermoser 2015 and references therein).

Whilst geostatistical approaches are now being taken to map spatial heterogeneity of geochemically important parameters in waste-rock piles, new technologies can also be used to enhance, or improve, the accuracy of these models. For example, technologies used in geometallurgical investigations can also be used for geoenvironmental domaining. These technologies broadly fall into two sub-sets: 1) hand-held instruments allowing for point measurements, including portable XRF (measuring elements from Mg to U), laser-induced breakdown spectroscopy (LIBS, having the added advantage of analysing lighter elements, such as the critical metal Li), hyperspectral imaging sensors (UV-VIS-NIR-SWIR), and mineral hardness testers including the EQUOtip and Hardness Impact Tester; and 2) instruments able to image larger areas, especially exploration drill cores, such as hyperspectral and chemical core scanning instruments, even including X-ray tomography. An example of their potential integration into routine geoenvironmental domaining workflows is shown in Figure 3.

Of these methods, hyperspectral technologies, also known as infrared spectral imaging drill-core techniques, are the most promising as they provide microstructural and mineralogical insights at the right scales to complement the geoenvironmental risk evaluation of a mineral deposit. Several recent developments have produced tailored workflows for evaluating geoenvironmental risks from hyperspectral imaging (Parbhakar-Fox 2019). Whilst there are associated limitations, e.g., many minerals are not spectrally active and the method only provides information from the sample surface at rather low spatial resolution (Laukamp et al. 2021; Butcher et al. 2023 this issue), this technology has the major advantage of rapidly collecting a high volume of mineralogical data about both the gangue and ore minerals in a core. Hyperspectral data are particularly suited to quantify the abundance of those minerals necessary to forecast AMD neutralisation potential and dust generation across a mineral deposit. The methods can also be used to identify other materials that are environmentally relevant such as clays for capping, aggregate materials, and ‘ore sands’ involving the recovery of quartz-rich sand during mineral processing (Golev et al. 2022).

Production Phase

During the operational phases of mining, the transportation and deposition of waste is one of the most important factors to keep an operation on track to meet its production targets. One of the main sources of environmental problems, as mentioned in the introduction, is the large volume of actively produced waste materials. Fingerprinting of the mineralogy and chemistry of the waste is not common practice for most mine sites, as it can be impractical using current technologies, with very few examples of geospatial models available in the literature (e.g., Wilson et al. 2021). The development of 3D models for mining waste repositories will require the deployment of characterisation tools that can collect compositional data as materials are being deposited. Such sensors should be widely embedded across an active mine, as resultant data may also be useful to determine if there are potential repurposing opportunities. For example, hyperspectral scanning technologies may be used to obtain knowledge of the mineralogy of a bench face, albeit at very coarse resolution (e.g., Barton et al. 2021). These will give a first-pass insight into the mineralogical signature of a targeted area, and if compared against the geoenvironmental model, could be used as a way of very crude ‘waste control’.

Sensor-based technologies can be used to track the properties of waste. A wide range of sensors are both available and in development and show promise for sorting waste material (Robben and Wotruba 2019). Several of these sensors can help identify acid generating and non-acid
generating materials, as well as several other elements of environmental interest that may need tracking during mining. Embedding such sensors as in-line monitoring tools will increase the knowledge of waste material properties and improve geoenvironmental management. An example includes blasthole scanning with hyperspectral scanners, like those scanning core, to inform not only the mine planning for ore optimisation but also help track the waste rock to the storage facility (Fig. 4).

The best practice would, of course, be the direct re-use of a residue stream for another industrial purpose, conforming to circular economy principles. One particularly obvious route is the use of mine waste as an alternative source of aggregates for civil engineering. A successful example of such re-use is the Vale factory in Brazil that transforms mining waste into products for civil construction, including interlocking floors, structural concrete blocks, or sealing blocks, among others (Vale 2020). The recovery of by-products, such as critical metals, is another possible route that is especially attractive for tailings, slags, or ashes. A highly innovative example comes from northern Sweden. Here, a pyrite-rich tailings stream of the Aitik copper mine is proposed to be used to generate sulphuric acid. This acid will then be used to extract a variety of products (phosphate, rare earth elements, gypsum, and fluorine products) from apatite that occurs in the tailings of adjacent iron ore mines (Fig. 5). Realizing such opportunities will create additional commercial value, which can then be invested in continuing to reduce mine waste volumes and therefore environmental risks.

Decommissioning and Closure

Although acting before the mine wastes are being deposited is by far the best solution, the overall economics are not yet routinely considering such options due to the lack of characterisation of mine wastes, such that re-purposing or re-processing options are never contrived or realised. The previous failure to understand mine wastes has resulted in existing mine wastes now being increasingly recognised as potential resources of metals and other sought-after materials, with circular economy principles also helping to drive this change in value perception (Kinnunen et al. 2022). Assessing the value of existing mine waste that has not been characterised during its deposition necessitates not only drilling and chemical assaying, but also full integration of quantitative mineralogical and textural assessments (Buettner et al. 2018). Appropriate strategies for invasive sampling and geostatistical modelling of the often-heterogeneous bodies of waste need to be continually developed and applied (e.g., Blannin et al. 2022). However, prior to invasive sampling, geophysical techniques could be routinely used, including microseismic, induced polarisation, and electromagnetic methods. These can improve the subsurface knowledge of a mine waste facility and help guide invasive sampling and volumetric calculations. Studies that have applied geophysical tools for characterisation and successfully integrated this mineralogical information include Moellehua-Canales et al. (2021). Finally, processing technologies suitable for mineral and metal recovery from finest, low-grade, refractory, and partially weathered mine wastes need to be developed (Whitworth et al. 2022).

To address these challenges, a geometallurgical approach (collecting data to develop block models of metal deportment and geoenvironmental characteristics) to mine waste characterisation can be applied after mine closure with national programs focussed on this having already taken place in Europe (e.g., the Horizon 2020 funded SULTAN and NEMO projects). Similar research programs are also underway elsewhere, such as in the U.S. (Payne Institute for Public Policy, Colorado School of Mines) and in Australia (Geoscience Australia and several state governments collaborating with universities to build a national mine waste atlas). The raw materials industry, too, is investing in more research and development, including the Broken Hill Proprietary (BHP) global tailings challenge launched in 2020 and the zero-waste challenge of Oz Minerals. Real examples of businesses recovering value from tailings exist (e.g., re-mining of Au-bearing tailings of the Witwatersrand Au–U deposits, South Africa where part of the realised value is, in fact, the recovery of land near Johannesburg) or are emerging, including the Century Zn Mine and the Hellyer Pb–Zn–Au–Ag Mine. Both of these are in Australia where there is growing appetite amongst smaller exploration and mining companies to tap into this business opportunity.

OUTLOOK

One of the ultimate goals for the global raw materials industry is to significantly reduce waste footprints and the environmental impact of the various categories of mine wastes. This can be achieved by integrating geometallurgical characterisation, appropriate database structures, and modelling methods throughout the life-of-mine. However, these methods must be simple, complementary to existing workflows, and, where possible, effective at identifying...
repurposing opportunities. From deposit-scale to micro-scale, technologies exist to help acquire mineralogical and textural data, In both 2D and 3D, to enhance the environmental management process. Understanding how and when to use these technologies is the key to unlocking their transformative power and gain maximum insight from multidimensional data sets—using appropriate data science tools (statistics, machine learning, artificial intelligence) that may still need to be developed. A dynamic approach with structured data, such as semantic networks, databases, time series, and dynamic block models, will bring geometallurgical characterisation to its full efficiency, especially for heterogeneous, man-made deposits like tailings and waste rock.

As the raw materials industry transitions towards a more ESG-cognisant outlook, the growing importance of the valorisation of residues, designed from the outset of a mining project, is not to be ignored and speaks to circular economy principles. Valuable data to inform this strategic decision-making process exist already, to some degree, in geometallurgical and chemical assay databases. Yet, the geoenvironmental sector has been slow to embrace the insight that can be gleaned from new characterisation technologies. As mining progresses, a cultural shift towards fingerprinting the characteristics of waste streams, measured using sensor technologies integrated into vehicles, belts, or pipelines, must be enacted to collate data relevant to temporal transitions, as new commodities become important to fuel the technologies of the future. As we revisit old mine wastes, geophysical tools must be better integrated into the characterisation workflow to improve our understanding of the mineralogical and physical properties, and to help build better geospatial models to guide future remining activities. For mines that produce significant quantities of waste (e.g., open cut metalliferous mines), a multi-commodity factory instead of a single-element extraction operation (with a few by-products at most) is potentially the only solution to really reduce mine wastes. That all residues, economic or not at a given point in time, are so well understood that they can turn economic at a future date is certainly the vision for which the raw materials industry should aim. This may well put it at the centre of a global sustainable circular economy.

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Uncertainty and Value: Optimising Geometallurgical Performance Along the Mining Value Chain

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The foundation for all mine planning and optimisation efforts generally is a well-defined mineral resource or reserve. We therefore start by describing how this is delineated, and then explain the standard routines currently used for mine design and planning.

Because sampling, and therefore knowledge, of the heterogeneous geological bodies forming a mineral deposit is always incomplete, uncertainties arise on the distribution of specific rock properties within the deposit, as well as their effects on downstream operations. If ignored, these uncertainties can lead to detrimental operational decisions, and potentially negative economic, environmental, and/or social outcomes. Therefore, the second part of this article describes how these uncertainties can be inferred and incorporated into the decision-making process to jointly (i.e., simultaneously and considering their interactions) optimise all stages of the value chain. The article closes with an account of the main aspects in uncertainty management and joint optimisation with geometallurgical data and models, which remain unresolved in both current industrial practice and academic research.

INTRODUCTION

The goal of all geometallurgical programs is to achieve optimal economic, environmental, and social outcomes along the whole value chain from ore to final product(s) and waste(s) (cf. Frenzel et al. 2023 this issue). To reach this goal, geometallurgical modelling and optimisation must integrate all relevant data on the geology and primary characteristics of an ore deposit (cf. Butcher et al. 2023 this issue) with models that describe ore behaviour in downstream mineral processing and extractive metallurgy operations (cf. Pereira et al. 2023 this issue; Chetty et al. 2023 this issue). This article focuses on the integration of knowledge to develop and optimise a mine design, i.e., the specific layout of the mine and process flowsheet, and a mine plan or mine schedule, i.e., the order in which different parts of the deposit are mined.

Keywords: geometallurgy; raw materials value chain; stochastic modelling; optimisation; uncertainty

MINERAL RESOURCES AND RESERVES

Mineral resources are proven volumes of a geological material with a quality and quantity that provide reasonable prospects for eventual economic extraction. Resources are delineated with relevant geological information (typically assayed samples from drill cores and geological mapping) according to technical guidelines set out by regulatory committees (e.g., Australasian Joint Ore Reserves Committee 2012; Pan-European Reserves & Resources Reporting Committee 2021). They are generally classified into three standardised categories—measured, indicated, and inferred—in order of increasing level of uncertainty. Mineral resources chiefly reflect the geology of a deposit and the degree to which it has been explored.

In contrast to mineral resources, reserves are defined as the economically extractable part of the measured and/or indicated resources. Probable and proven reserve categories are distinguished—with increasing certainty that extraction becomes feasible. The estimation of reserves considers not only the presence of a certain amount of ore in the ground but also demonstrates its economic potential through a pre-feasibility or a feasibility study, where all technical constraints imposed by a specific mine design are

Open pit mine in northern Chile.
Several models are required to develop a mine design and infer mineral resources and reserves. These are typically constructed with limited sample data, usually obtained from exploration drill holes (Fig. 1). A geological model of an ore deposit is generally built from drill core logs of geological attributes. It represents an interpretation of the location and extent of rock volumes with consistent properties within the deposit, also termed domains, such as a homogeneous lithology with a certain assemblage and abundance of minerals. Measured data on primary (cf. Butcher et al. 2023 this issue) and secondary (cf. Pereira et al. 2023 this issue) ore characteristics are then used to infer the properties of the rock within these domains and build a block model (Fig. 1).

A block model consists of volumes, usually regular in size, populated with rock property values inferred from the sample data. Each block should ideally contain values for all logged geological attributes as well as primary ore characteristics (e.g., concentrations of different elements, mineralogy, texture). However, in current practice mostly only the grades of the main commodities are used, while strategies to populate the block models with many of the properties mentioned above are still the subject of active research (van den Boogaard and Tolosa-Delgado 2018). Metallurgical test data on laboratory and pilot scales, together with appropriate process models (cf. Pereira et al. 2023 this issue), are often used to link the inferred primary characteristics to secondary characteristics for each block (e.g., hardness, metal recovery, acid consumption) for any given mine design and process flowsheet, such that mine-to-plant optimisation becomes possible (Ortiz et al. 2015). This optimisation generally proceeds from the larger to the smaller scale, first choosing a mine design and long-term mine plan, then optimising the performance of that design over the shorter term.

**Mine Design and Mine Plan**

To choose the best mine design and optimise the mine plan, different designs and process flowsheets must be compared, and the mine plan optimised for each. To do so, each block in the block model must be assigned an economic value, which depends on its properties. This is typically done via a formula of the form:

\[
V_b = \begin{cases} 
\text{ton}_b \cdot \left[ \text{price} - C_{\text{selling},b} \cdot x_b - C_{\text{mining},b} - C_{\text{processing},b} \right] & \text{if processed as ore} \\
- \text{ton}_b \cdot C_{\text{mining},b} & \text{if dumped as waste}
\end{cases}
\]

(Equation 1)

where \(V_b\) represents the value of block \(b\), \(\text{ton}_b\) represents its tonnage, \text{price} is the commodity price, \(C_{\text{selling},b}\) considers any selling, transportation, or refining costs per tonne, \(C_{\text{mining},b}\) and \(C_{\text{processing},b}\) are the respective mining and processing costs per tonne for the specific block and design. Note that this calculation generally will also need to account for the effects of blending different ore blocks before processing, a procedure currently used to reduce the variability of feed properties for downstream operations. Indeed, the industry standard is to filter out ore variability with blending, disregarding the additional profit that predictive adaption can provide (Tolosana-Delgado et al. 2015).

The value of the blocks is used to determine the economic outline of the deposit, that is, the envelope that can be economically mined out by surface or underground mining methods, and that maximises the total obtained economic value at a given moment. This is usually done by considering the undiscounted value of the blocks extracted, i.e., not accounting for the time value of money (cf. Frenzel et al. 2023 this issue). This approach allows for a simple determination of the mining limits to maximise the value obtained from the extraction of the ore. Furthermore, in that optimisation, accessibility needs to be considered as a constraint when deciding which blocks can be extracted. In an open pit, this requires removing the overlying blocks and accessing through a ramp. In underground mining, it requires developing access to the corresponding production point.

Once the limits of the ore bodies have been determined, the sequence of extraction of the blocks, i.e., the mine plan, can be optimised by considering the life-of-mine and the time value of money, and determining in which period each block should be removed. The sequence is optimised to maximise the discounted profit obtained from mining out the reserves, resulting in an assessment of the potential value of the entire operation, expressed as net present value (NPV, cf. Frenzel et al. 2023 this issue), for all optimal combinations of different mine designs and mine plans. Based on the comparison of these NPVs, the optimal design and schedule can be chosen.

Environmental aspects, such as CO\(_2\) emissions, can also be incorporated into the optimisation routine in addition to economic value (cf. Pell et al. 2019).

**System Optimisation**

Once a mine has been built and the operation is running, the properties and process responses of the different material streams generally become better known. The stages of the process flowsheet can then be optimised on
a smaller timescale (weeks, days, shifts) to enhance their performance and reduce potential deviations from the long-term mine plan. This partial optimisation process aims to fine-tune specific process parameters, including ore blending, without necessarily changing the mine plan. The process is best illustrated with two examples.

Example 1: *Mine to mill optimisation* focuses on the combined cost of blasting and comminution to achieve a specific particle size. Using more explosives will generate run-of-mine ore with a smaller particle size, which will reduce the amount of energy consumed during crushing and grinding. Alternatively, one can reduce the explosive consumption and generate coarser run-of-mine ore that will require more energy for comminution. However, both processes produce different particle size distributions. In particular, the excessive use of explosives in blasting may generate unmanageable amounts of unrecoverable fines. Therefore, a joint optimisation routine must be used to identify the ideal ratio of the relative energy expenditures in blasting and comminution to maximise mineral liberation and minimise total cost, emissions, and energy consumption.

Example 2: *Product specification optimisation* is illustrated in Figure 2. As explained in Pereira et al. (2023 this issue), flotation performance depends on the composition of an ore, the liberation degree of the particles, and the specific operational settings of the processing plant (Fig. 2A). These settings are controlled by an operator based on the expected characteristics of the feed to the flotation process. However, ore types usually have highly variable properties. Some types may require a higher amount of energy to be milled to a specific particle size. Two options can then be considered (Fig. 2C): (1) decrease mill throughput to ensure the materials have a larger residence time in the mill and thereby achieve the expected degree of liberation; or (2) retain current mill throughput, thereby generating a coarser product in which the ore minerals are less liberated.

Each approach will have consequences for the resulting downstream processes. Reduced throughput will often enhance recovery due to better liberation of the ore minerals and increased residence time in the flotation cells. However, economic performance may worsen because of the smaller amount of material treated per time unit, which generates lower revenues. In the second case, particles are coarser, which negatively affects flotation because ore minerals may not be fully liberated. However, the increased throughput may counter this effect, as well as some of the associated revenue loss, through the larger volume of ore being processed per time unit. The process can be optimised to find the throughput level that maximises the expected economic performance of grinding and flotation simultaneously (Fig. 2B). Microstructure-aware processing models (Pereira et al. 2023 this issue) could help here.

These are only two simple examples of specific subprocesses that illustrate some of the interactions between different parts of the process chain. In the end, the optimal operating conditions for the entire chain should be found by jointly optimising the parameters of all relevant subprocesses. This is typically done using process models and simulations.

**UNCERTAINTIES AND THEIR CONSEQUENCES**

In the past, the optimisation routines described above were usually conducted using best-fit values for all inferred quantities. That is, the separate distributions of a handful of primary ore characteristics within the deposit were modelled with simple interpolation routines, such as inverse distance-weighted interpolation or kriging (Matheron 1963), giving a single best estimate of the primary ore properties for each block in the block model. Secondary characteristics of the blocks were then inferred from process models, again assigning only best estimates. The subsequent optimisation process naturally yielded a single optimal mine design and plan. This approach is still widely used in the mining industry.

**Figure 2** Simplified example of joint optimisation for the economic performance of a grinding-flotation system.
However, the inputs to the optimisation of a mining project generally are highly uncertain and multivariate. Only a small proportion of a given mineral deposit can be sampled and analysed in a feasible manner, and the typically heterogeneous nature and spatial variability of the deposit mean that the ore between sample locations will not have identical characteristics to the available samples (cf. Box 1). Traditional interpolation methods smooth out this heterogeneity, producing modelled property distributions that do not correspond with real geological features. Furthermore, the distribution of metal grades generally is much better known than the distribution of many key mineralogical and textural properties, as well as secondary ore characteristics, as acquiring detailed data on the former properties is much cheaper (cf. Butcher et al. 2023 this issue).

Similarly, process models generally have large residual uncertainties (Rossi and Deutsch 2014). The reasons for this lie both in the usually limited availability of metallurgical test data and the inability of typical predictor variables used in current process models to account for the variations in relevant ore characteristics. The chemical composition of an ore may be a reasonable proxy for its mineralogical composition, and thus some secondary ore properties such as hardness, but is a poor proxy for ore texture and the resultant liberation behaviour of the ores (cf. Pereira et al. 2023 this issue).

It follows from these considerations that the uncertainties arising for the primary properties of each block and its process behaviour can be substantial. The important question is what effects these uncertainties have on the outcomes of optimisation routines. Will the optimal design and schedule derived from the best-fit (or average) properties of the deposit still provide the best option?

Much research has been done over the last decade to investigate this problem, showing that variability and uncertainty greatly affect the performance of a mining operation, and that ignoring them will systematically decrease both product quality and quantity with respect to the expected outcomes based on a traditional mine design and mine plan (Dimitrakopoulos 2011; Leite and Dimitrakopoulos 2014). The chief reason for this is that the process behaviour of each block is a non-linear function of its primary properties. As a simplified example, consider the block value (Eq. 1) as the target response: here, the problem arises mainly because recovery and processing costs non-linearly depend on grade, but also because blocks are dumped if their value is below a certain threshold, hence the block value no longer depends on grade. Most importantly, all these costs depend on a wide range of geometallurgical properties, not just grade. This is why geometallurgical optimisation must account for uncertainties to ensure that the best decisions are made. The following section describes how this can be achieved.

**UNCERTAINTY MODELLING AND STOCHASTIC OPTIMISATION**

To adequately account for uncertainties in the development and optimisation of a mine design and mine plan, two things are required: 1) adequate models of the relevant uncertainties; and 2) a stochastic optimisation routine, which can deal with the uncertain inputs generated by uncertainty modelling.

**Uncertainty Modelling**

As noted above, uncertainties mainly arise in two different parts of a mining operation. First, there is geospatial uncertainty due to the intrinsic spatial variation of ore properties throughout the ore deposit, along with limited information from samples to allow its characterisation. This geospatial uncertainty is subsequently translated into temporal uncertainty regarding the properties of the feed materials sent for downstream processing once the ore has been extracted. Second, due to the limitations of current process models, the responses of the ores in the mineral processing and extractive metallurgical stages are uncertain, even if their primary characteristics are well known. This effect is exacerbated by the first source of uncertainty, i.e., the incomplete knowledge of the primary characteristics of the feed material. A third source of uncertainty is the limited knowledge of external factors relevant to the decisions made in a mining project, including future commodity prices, labour costs, access to water and energy, etc.

**Box 1 GEOSTATISTICS FOR MODELLING GEOSPATIAL UNCERTAINTY**

Geostatistics provides a set of tools to find local estimates (predictions) and to characterise uncertainty for spatially distributed continuous and categorical variables. Geostatistical techniques are based on a probabilistic approach (Matheron 1963), where properties are modelled as random variables, that is, they can take values according to a certain probability distribution.

If an attribute is known at a given location through sampling, it has only analytical uncertainties (Butcher et al. 2023 this issue). On the other hand, attributes at unsampled locations are estimated through a weighted average of the neighbouring known sample values, assumed to belong to the same statistical population and behave as a stationary variable in space:

$$Z^*(u_0) = \lambda_0 + \sum_{i=1}^{n} \lambda_i \cdot Z(u_i),$$

where $Z^*(u_0)$ is the estimated value at location $u_0$, $\lambda_0$, $\lambda_1$, ..., $\lambda_n$ are weights that need to be determined, and $Z(u_1)$, ..., $Z(u_n)$ are the values of the $n$ neighbours surrounding samples around $u_0$. Kriging is the method used to determine the weights $\lambda_0$, $\lambda_n$ imposing global unbiasedness, and optimality, with the latter being defined as the minimisation of the error variance between the estimate and the true (but unknown) value:

$$\min_{\lambda_0, \ldots, \lambda_n} \text{Var}(Z^*(u_0) - Z(u_0)).$$

Solving for the weights requires characterising the spatial continuity of the random function (the collection of random variables in the spatial domain). This is achieved through the use of a variogram model, which measures how much the attribute can change when comparing locations separated by a given lag vector $h$. Kriging provides only best estimates of the values at unknown locations (best-fit values).

Under certain assumptions, the full probability distributions of the random variables at unsampled locations can be characterised, providing a quantification of the uncertainty around the best-fit value. This notion is extended to account for joint spatial uncertainty, through geostatistical simulation conditional to the known samples at their locations. Each simulation respects the sample data, honours the global distribution of the attribute, and reproduces the spatial continuity, as characterised by the variogram. This can be used to quantify uncertainty over volumes such as mining blocks.

In geometallurgical modelling, simulations must consider multiple attributes co-varying in space (termed cosimulation) to capture their statistical and spatial relationships in a geometallurgical assessment (Wackernagel 2003). Most cosimulation techniques decompose the multivariate relationships into a set of factors that can be modelled independently, thus simplifying the simulation process (Desbarats and Dimitrakopoulos 2000; Leuangthong and Deutsch 2003; Barnett et al. 2014). When some variables describe the ore composition (e.g., mineralogical or chemical), a previous log-ratio transformation is often required, and compositional data analysis tools can be used (Tolosana-Delgado et al. 2019). These techniques generate multiple scenarios for the spatial joint distribution of variables, respecting their sample values at sample locations, and reproducing their multivariate spatial distributions, i.e., the spatial continuity of the variables and spatial cross-correlation between them (Boisvert et al. 2013). These techniques can also be extended to categorical variables (e.g., lithologies, alteration styles, geological domains), where specific geostatistical simulation techniques generate a prediction of the probability of a location belonging to each of the several categories considered.
Geospatial uncertainties are typically modelled using geostatistical tools (see Box 1). These tools include classical interpolation routines such as kriging, as well as the possibility to generate simulations, or realisations, of more realistic potential property distributions within the deposit (cf. Fig. 3 of Frenzel et al. 2023 this issue). Each realisation is equally likely to be true and assigns a single value of each modelled property to each block in the deposit model. An ensemble of such realisations can be used to represent the overall geospatial uncertainties.

In the next step, process responses or secondary characteristics must be assigned to each block in each realisation. For this purpose, process models and their residual uncertainties can be used (cf. Pereira et al. 2023 this issue). To build these models, the behaviour of the ore streams is initially characterised through small-scale tests, which are then complemented by on-site measurements to understand how they scale to actual production volumes (Chetty et al. 2023 this issue). One issue with most process models in current use is that they are often aimed at predicting the expected value of a response property based on simple bulk chemical measurements, and do not account for the actually relevant geometallurgical properties.

To transfer the residual uncertainty of the responses from classical process models to the block model, a Monte-Carlo approach may be used. This is illustrated in Figure 3, which presents a simplified model of a hypothetical non-linear response given a primary variable. Models typically provide a best-fit estimate of the response $y(x)$ for a given input $x$. However, actual responses will generally fluctuate around the estimate of $y(x)$ according to a certain distribution. This distribution of the residual values can be modelled, allowing for the random sampling of a value from that distribution, $y_{res}(x)$, for any given value of $x$. This process can be repeated for each block in each of the realisations of the deposit generated from geostatistical simulation to yield overall realisations of the block model (cf. Fig. 3 in Frenzel et al. 2023 this issue), which, in turn, can be used in mine planning and optimisation.

Finally, different scenarios are constructed for the development of external factors such as market prices and regulatory environments. These can be used for stochastic optimisation in combination with the different realisations of the block model.

**Stochastic Optimisation**

Here, the goal of stochastic optimisation is to find the mine design and mine plan that maximise the deposit value and minimise environmental and social impacts (Leite and Dimitrakopoulos 2014). This can be achieved by first defining a set of concrete mine designs and mine plans. Each of these design/plan combinations is then applied to all realisations of the block model, under all pre-defined scenarios for the external factors (Fig. 4), to yield a probability distribution of the target performance indicator (e.g., NPV, emissions). These distributions are then compared, and the best design/plan combination is selected according to predefined risk criteria. Specifically, the mean or median of the distribution indicates the expected system performance for a specific combination, while the width and shape reflect the associated risks. Generally, the optimal design/plan combination will maximise the expected performance indicator subject to a tolerable associated risk. For a predefined risk level, stochastic optimisation allows finding the design/plan with the best performance. Alternatively, for a fixed performance, the model with the lowest risk can be identified.

**UPDATING OF MODELS AND MINE PLANS**

The previous discussion implicitly assumed that the amount of data available for the optimisation of a mining operation is fixed. However, in operating mines and associated beneficiation plants, a wealth of new data on both primary and secondary properties is continuously acquired. For instance, face mapping and production drilling generate detailed data on the geology and chemical composition of blocks just before they are blasted and processed. Online sensors in the mineral processing plant record information on chemistry, particle size distributions, reagent consumption, etc. of the various process streams. Overall metal recoveries, energy consumption, and other performance parameters of the processing plant are also typically monitored in real time.

This wealth of data, in principle, allows for the monitoring of the performance of specific volumes of ore as they pass through the process chain, and for comparison with model predictions. The data should, therefore, be used to update the various ore body and process models in real time. This is vital to reduce the uncertainties about the attributes of each mining block, the performance of the processes downstream, and the best short-term decisions (Wambeke et al. 2018; Benndorf 2020). Such updating will require fast, smart sensors and smart measurements, high-speed communication to transfer information, indirect (soft) sensors, computational infrastructure with dedicated software, and so-far non-existing methods to update models and decisions. Once properly calibrated and trained, an automated agent could assume control over decision-making processes to optimise both individual processes and overall system performance.

Unfortunately, such technology is currently only in place in some beneficiation plants, and even there the data are not used to update the block model or to re-optimise the full system.
SUMMARY AND OUTLOOK

Geometallurgical modelling should help to integrate knowledge and improve decision-making at all stages of the raw materials value chain. This is not yet the case: much of the mining industry continues to operate by defining performance metrics at each processing stage independently, where each stage is optimised disregarding the impact on other stages. This has slowly started to change, given the obvious benefits of jointly optimising the whole value chain. However, the necessary transition is in its infancy, and there is still a lack of understanding about the effects of variability in process performance, and the impact of uncertainty in decision making.

This article provided a brief discussion of how uncertainty can be incorporated into the various models used for mine design and mine planning, and how the joint optimisation of different processes (or the entire value chain) can be achieved in the shadow of uncertainty. However, much work is still needed to fully implement such routines in automatic control systems. Implementation will require not only that boundaries between the traditional departments within mining companies are overcome, but also that interactions occur between different companies. The last aspect is critical to achieve full integration along the value chain, including extractive metallurgy operations (Chetty et al. 2023 this issue), as these are often located at different sites and are owned by different companies.

Another area for future research is the improvement of uncertainty models, and development of methods and routines that can further reduce uncertainties. At present, four major factors hinder uncertainty reduction and uncertainty modelling:

Figure 4 Uncertainty propagation for stochastic optimisation: Spatial uncertainty (A) is transferred by a particular sequence of extraction to predicted properties of run-of-mine ore (B) that, through processing models, yields a distribution of process performances (C). The optimal sequence of extraction is obtained by maximising the expected process performance subject to a specific tolerable risk. Examples: (A) chalcopyrite grade; (B) chalcopyrite grade, hardness index, and average chalcopyrite grain size; (C) Cu grade of product, water consumption, and tailings tonnage. Adapted from Riquelme and Ortiz (2021).
Limited sampling and limited sample quality at different stages of the various process streams. Particularly high-frequency online measurements of ore properties (directly relevant or proxies) are needed for real-time process control and uncertainty reduction.

Limited analytical capabilities to acquire not only large amounts of data, but large amounts of the right data, such as mineralogical and textual information (cf. Butcher et al. 2023 this issue), which is much more relevant to the modelling of processing operations than bulk chemical data (cf. Pereira et al. 2023 this issue). This is currently limited by the availability and cost of suitable technology.

Limited process understanding. As discussed in detail in Pereira et al. (2023 this issue), there are currently some major gaps in process models, particularly those used for comminution processes, which limit their ability to incorporate detailed data on ore mineralogy and texture. This imposes limitations on both the modelling of the processes (uncertainty reduction) and the understanding and quantification of the uncertainties that arise during this modelling, all effects that are compounded by the limited availability of relevant analytical data (see previous point).

Limited geospatial modelling techniques exist that can deal with geometallurgical variables, such as texture, modal mineralogy, or deportment. New multivariate interpolation and simulation methods will be needed to ensure full incorporation of these properties into the geometallurgical block models.

REFERENCES


If these limitations are overcome, more robust geometallurgical models may be constructed to make mining operations more sustainable, maximising the recovery of relevant commodities, while minimising the potential negative impacts of their extraction and ensuring the responsible use of land, water, and energy. This can be extended to the re-processing and valorisation of mine wastes (cf. Parbhakar-Fox and Baumgartner 2023 this issue).

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The IMA is honored to present its 2023 Medal of Excellence in Mineralogical Sciences to Prof. Tetsuo Irifune. Distinguished Professor at Ehime University in Japan, Prof. Irifune is Director of the Geodynamics Research Center (GRC) at the same University, as well as Principal Investigator of the Earth-Life Science Institute (ELSI) of Tokyo Institute of Technology, Japan.

As a major contributor to the development of high-pressure techniques and their applications to Earth sciences and materials science, Prof. Irifune has reached the highest level of scientific excellence and eminence within the international mineral physics community. He has set new standards in the performance of high-pressure experiments with applications to deep-Earth processes, and to materials science. His outstanding contributions to the mineral sciences have had a profound impact on high-pressure mineralogy, as attested by his tremendous publication list.

Prof. Irifune completed his BSc and MSc studies at Kyoto University, Japan (1978) and Nagoya University, Japan (1980), respectively, and earned his PhD from Hokkaido University, Japan (1984). After a Postdoctoral Fellowship at the Japan Society of Promotion of Science (1984) and at the Research School of Earth Sciences, Australian National University (1984–1987), Prof. Irifune joined the Department of Geological Mineralogy of Hokkaido University, Japan, as an assistant professor (1987–1989) and later at Ehime University, where he worked as an associate professor (1989–1995), professor (1995–2001), professor and director of the GRC (since 2001), and distinguished professor (since 2012).

Throughout his career, Prof. Irifune’s research has spanned over a wide range of research fields, from the study of the phase relations of mantle rocks by the quench method, to the determination of phase transitions using in-situ X-ray diffraction, sound velocity measurement of mantle minerals in their stability fields, and synthesis of nano-poly crystalline diamond and ceramics. Among his many scientific achievements are the exquisite experimental determination of phase relations involving ringwoodite, majorite, davemaoite, and bridgmanite; and the seismic sharpness of the upper-lower mantle boundary. Prof. Irifune has also developed multi-anvil facilities, including multi-anvil synchrotron beamlines, for the synthesis of ultra-hard materials and the deformation of transition-zone minerals. He is recognized for his contribution to the coordination of high-pressure mineralogy research in East Asia, and for helping colleagues around the world to set up multi-anvil laboratories.

Prof. Irifune has also demonstrated high dedication and commitment to serve the scientific community by sitting on several committees, commissions, and boards; as well as his excellent leadership capabilities, which brought him to conceive and establish the Geodynamics Research Center, which he has brilliantly coordinated for over two decades, making it an undisputed reference center not only for the high-pressure experimental petrology, but also for related fields, like mineral physics and geodynamics. He also founded The Asian Network for Deep Earth Mineralogy (http://www.grc.ehime-u.ac.jp/legacy/g-coe-shinp01-tandemgaiyou-h20.pdf), and served as the President of International Association for the Advancement of High Pressure Science and Technology (AIRAPT).

Prof. Irifune’s high international reputation has been recognized through many prestigious honors and awards, including the Mineralogical Society of Japan (MSJ) Award, 1998; Ishikawa Carbon Prize, 2004; Alexander von Humboldt Research Award, 2007; Fellow of American Geophysical Union (AGU), 2008; Japan Society of Powder and Powder Metallurgy, Innovatory Research Award, 2008; Japan Society of High Pressure Science and Technology (JSHPST) Award, 2009; Geological Society of Australia (GSA), A. E. Ringwood Medal, 2014; Medal with Purple Ribbon, Government of Japan, 2015; European Geoscience Union (EGU) R. W. Bunsen Medal, 2016; Fellow of Japan Geoscience Union (JpGU), 2017; Japan Association of Mineralogical Sciences (JAMS), Applied Mineralogy Award, 2020; International Association for the Advancement of High Pressure Science and Technology (AIRAPT), P. W. Bridgman Award, 2021.

We heartily congratulate Prof. Irifune on this prestigious award. Prof. Irifune represents today’s international mineralogy at its best, both as a scientist and a citizen of the community. He continues to be an active and creative scientist, and we look forward to his new discoveries and achievements.

From our inventory of over 200,000 specimens, we can supply your research specimen needs with reliably identified samples from worldwide localities, drawing on old, historic pieces as well as recently discovered exotic species. We and our predecessor companies have been serving the research and museum communities since 1950. Inquiries by email recommended.

Pure samples suitable for standards are readily available. Pictured above are: Zircon from Malawi, Fluorapatite from Mexico, and Spinel from Myanmar.

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EUROCLAY 2023

Euroclay 2023 was held in Bari, Italy on 24–27 July 2023, with 337 participants, 215 oral presentations, 105 posters, and a large student cadre aided by 14 scholarships provided by the conference organizing committee (F Andreola, S Fiore, A Fiore, A Lettino, P Ragone, R Sinisi, and V Summa). Sessions were wide-ranging and featured an international scope, from clays in natural environments to ceramics and industrial materials with many environmental and industrial applications. Plenary lectures where given by Javier Huertas (Strytan hydrothermal system), Tiziana Missana (radioactive waste repositories), Janice Bishop (recipient of George Brown Award, clays on Mars), and Thorsten Schäfer (clay-based nanomaterials).

AIPEA Student Best Oral and Poster Awards are designed to encourage excellence in research and presentation skills by students in clay science. Four presentations were recognized for their excellence at EuroClay 2023.

Klaudia Dziewiątka (AGH Univ Sci Tech, Krakow, Poland) was awarded best oral presentation for “TiO₂-loaded nanotubular materials based on kaolin group minerals as spatially confined nanoreactors for photodegradation of deoxynivalenol” and Gabriela Maria Matos Demiti (Dept Chem Eng, State Univ Maringa, Brazil) was awarded best poster presentation for “Modified zeolites in the treatment of water contaminated with cephalexin.”

Andrea García-Vicente (Univ Salamanca, Spain) and Eike Radeisen (Fed Inst Geosci Nat Resources, Germany) were also recognized as runners-up in the oral presentation category for “Advances in morphological and textural characterization of halloysite in relation to disordered kaolinite” and “Deformation dependent water retention curves for the representation of memory effects in bentonites,” respectively. Students are pictured with AIPEA President Bruno Lanson.

AIPEA CLAY Conference Series

After much discussion, the ICC and Euroclay conference series will be combined into a single series of conferences that will take place in odd-numbered years. The 18th ICC (https://icc.aipea.org/) will be held in Dublin on 13–18 July 2025 as the final “ICC.” The first of the new CLAY series will be CLAY2027, to be held in Madrid in June 2027 and hosted by colleagues from the Spanish clay society (SEA). Proposals to host CLAY 2029 should be submitted to the AIPEA Secretary (secretary@aipea.org) four weeks in advance of the 18th ICC with a proposal submission date of 15 June 2025.

EUROCLAY 2023 Plenary Lecturers

Javier Huertas
Tiziana Missana
Janice Bishop
Thorsten Schäfer

OBITUARY—JEFFREY WILSON

This past summer the clay science community lost a great scientist and colleague. M. Jeffrey (Jeff) Wilson passed away on 20 July 2023, leaving the legacy of his 40-year career that produced significant advances in our knowledge of soil clay mineralogy and its importance in agricultural and environmental systems. From 1982 to 1997, Jeff was Head of the Division of Soils and Soil Microbiology at the renowned Macaulay Institute (now Hutton Institute) in Aberdeen, Scotland, UK. Jeff published over 200 journal articles, edited four books, wrote a clay minerals textbook, taught soil mineralogy at the University of Aberdeen, built strong international collaborations, and mentored younger generations of soil researchers. He was awarded the first Schlumberger Medal for excellence in mineralogical research by the Mineralogical Society in 1990, and gave the 4th George Brown Lecture to the Society in 2003. In 2005, Jeff received the Bailey Award of the Clay Minerals Society (CMS’ highest award for scientific excellence). He will be missed, as a colleague and friend.

Peter C. Ryan
AIPEA Secretary-General
After some years of online courses, it was the first time to meet again in-person for the diffusion modeling short course taking place at Ruhr-University Bochum. In the end of March 2023, around 35 participants made their way to the Ruhr region to learn about diffusion, and have some hands-on modeling experience, advised by the experts of that field, Sumit Chakraborty and Ralf Dohmen. The group of international scientists, ranging from student to professor level, was keen and highly motivated to learn, model, and connect!

This one-week course covers a broad mix of theoretical and practical units, which are perfectly synchronized to each other and thereby ideal for participants to learn the basics step-by-step and to dive deeper into diffusion modeling. After a quick introduction and some basic knowledge provided by Sumit Chakraborty, Ralf Dohmen introduced us to the mathematical background and some applications. Sumit taught about loads of diffusion and model theory, complex research questions, and gave further insights into fascinating case studies. In between, there were also some specialized talks from other contributors on, e.g., experimental methods (Harald Behrens), phase field theory (Julia Kundin), the application of AI (Renat Almeev, Artem Leichter), and diffusion on the isotope level (Martin Oeser-Rabe).

In the practical units, we started with some simple Excel-based approaches to model step profiles using the Gauss function and learn to fit diffusion curves in general. Afterwards, we worked on more advanced and applied tasks such as modeling the Arrhenius equation, restraining residence times of crystals or cooling rates of magmatic systems. On the last day, we were using Matlab to re-do all of the previous tackled applications, which was a challenge but definitely a highlight of the course!

A big thank you to the organizing committee at Bochum University including course-leaders Sumit and Ralf, and science coordinator Linda Sobolewski, who all did a great job to handle all kind of problems—from minor and major difficulties during the practicals to organizing the transport on Monday (public transportation strike). We really appreciate that!

The pleasant atmosphere and high-quality catering provided by Ruhr University, and especially during the Conference Dinner on Thursday (Yamas Meze restaurant in Bochum City, fantastic Greek-Mediterranean cuisine!!), were perfect conditions for networking with other young scientists, having inspiring discussions on and off-topic with colleagues, and for considering future cooperation. The course is perfect for everyone who wants to dig deeper into the field of diffusion, and is highly recommended not only for PhD candidates and students, but for everyone who is interested to work on diffusion topics and connect with other like-minded people. In summary, it was an interesting and enjoyable week in Bochum!

Anne Sturm (Heidelberg University)

20th DMG Shortcourse “Solid-state NMR Spectroscopy,”
30 May–2 June 2023

A short course on NMR spectroscopy was also organized this year by the DMG/DGK. Under the direction of Dr. Michael Fichtelkord, participants from a wide variety of disciplines (e.g., cement chemistry, petrology, or chemical engineering) were able to address in detail the analytical possibilities of solid-state NMR spectroscopy.

This course offered PhD students and scientific staff the interesting opportunity to combine a repetition of the physical basics of the methodology with practical examples to obtain a comprehensible introduction to NMR spectroscopy. While the theoretical foundation and plans for the day were worked out in the morning, the afternoon was devoted to practical work. In addition to the preparation of samples to be measured, the course participants were even able to carry out measurements on the device themselves.

Using the example of the $^1$H spin lattice relaxation of tetramethylammonium iodide and the calculation of activation energies and correlation times for the discovered relaxation signals of the ammonium and methyl environments, it was also shown how strong the influence of the experimental temperature can be on the obtained NMR spectra. The course day ended with drinks and food in the “Filou” pub, where the participants got to know each other better.

The next day, dipolar and chemical shift interactions were presented and their influence on the spectra obtained was explained. We were able to determine that, for example, signals from the sample cannot be easily distinguished from rotating sidebands and impurities. Here, the evaluation software DMFit2020 proved to be a very helpful tool. As in the history of NMR spectroscopy, Wednesday afternoon marked a crucial turning point in the course.

The removal of anisotropy effects using magic angle spinning (MAS) probe heads opened up completely new analytical possibilities. This technique was used in the practical part to study $^{29}$Si, $^{31}$P, and $^1$H nuclei in synthetic phlogopites. This clearly showed that NMR spectroscopy is excellently suited as a complementary technique to diffraction methods and is of particular interest when doped or naturally “contaminated” minerals are to be observed and their structural peculiarities elucidated.

The third day of the course dealt with the possible applications of multipulse techniques and the basics of the cross-polarization experiment (CP). In the practical part, a contact-time dependent CPMAS experiment
Mineralogical Collection of the Faculty, as well as excursions to the host showcased diverse research in the field of geosciences. A reception were also several poster sessions over the course of several days that history, gemmology and gemstones, and mineral teaching. There ore deposits, there were also open lectures on topics such as mineral applied mineralogy; lithosphere, geochemistry, and mineralogy; and research. In addition to lectures in mineralogy and crystallography; logical science and related disciplines, ranging from basic to applied MinWien focused on the broad spectrum of mineralogical and petro-

was performed on kaolinites. Subsequently, atomic distances between Si and H nuclei were determined. This could be done with a simple spreadsheet.

The last day was dedicated to the quadrupolar nuclei (spin quantum number I > 0.5). As examples, the nuclei $^{23}$Na and $^{27}$Al were measured and analyzed in different salts and corundum.

In the theoretical part, the focus was on other NMR methods such as “double rotation” (DOR) or multi-quantum magic-angle spinning (MQMAS) and satellite transition spectroscopy (SATRAS). At this point, at the latest, it became clear that it would take four years rather than days to understand all solid-state NMR methods and to be able to apply them in practice.

However, there was enough time to develop a general idea for the different approaches and to understand which information can be obtained with which method. In general, it can be said that the overview given is very helpful for planning future projects and for evaluating scientific questions that have already been asked.

**Christian Felten, Henning Kruppa, and Michael Wenzel**
(RWTH Aachen)

**ANNUAL DMG MEETING 2023**

From September 17 to 21, 2023, the joint meeting of the Austrian Mineralogical Society (ÖMG), the Slovakian Mineralogical Society (SMS), and the German Mineralogical Society (DMG) – MinWien2023 – took place in Vienna, Austria. The meeting was organized by the Institute of Mineralogy and Crystallography of the University of Vienna, among others, in honor of Josef Zemann, who had been an important member of the Mineralogical Society and the University of Vienna, and passed away late last year at the age of 99.

MinWien focused on the broad spectrum of mineralogical and petrological science and related disciplines, ranging from basic to applied research. In addition to lectures in mineralogy and crystallography; applied mineralogy; lithosphere, geochemistry, and mineralogy; and ore deposits, there were also open lectures on topics such as mineral history, gemmology and gemstones, and mineral teaching. There were also several poster sessions over the course of several days that showcased diverse research in the field of geosciences. A reception in the City Hall of Vienna, a Young Scientist meeting, the visit of the Mineralogical Collection of the Faculty, as well as excursions to the host country Austria and the neighbouring country Slovakia completed the conference. A special highlight was a lecture for the public by F. Melcher (Leoben) about raw materials for the Green Deal and pointed out in detail current problems of raw material supply in Europe.

In addition to the conference, the DMG general meeting 2023 also took place, in which the list of candidates for this year’s election was approved. The positive progress of the DMG was also reported and, among other things, the statutes were updated. This year the DMG again honored scientists for their outstanding work. The Paul Ramdohr Award went to E. A. Runge (Tübingen) and M. C. Gentzmann (Berlin), the Beate Mocek Prize to V. Kohn (Vienna), the Abraham Gottlob Werner Medal to T. Oberschütz, the Agricola Medal to C. Weidenthaler, the Victor Moritz Goldschmidt Prize to B. Walter, and the Doris Schachner Medal to R. Stalder.

Thus, MinWien2023 showed once again how important the mentioned disciplines are for today’s society. It offered an outstanding opportunity to present new research results, to discuss these or other results constructively, to establish new contacts, and to launch new projects.

**Fabio Joseph, LMU Munich**

**DMG SHORT COURSES 2024**

As before, DMG will support several short courses next year. All courses will be aimed primarily at advanced-level undergraduate and graduate students but, as always, are open to more senior researchers as well. Nonlocal student members of DMG will be eligible for travel support to the amount of € 100. At this time five courses can be announced. Further information can be found at https://www.dmg-home.org/aktuelles/doktorandenkurse/.

1. **High-Pressure Experimental Techniques and Applications to the Earth’s Interior**, Bayerisches Geoinstitut/University Bayreuth, Florian Heidelbach, 19–23 February 2024 (florian.heidelbach@uni-bayreuth.de)

2. **Metal Stable Isotopes as Fingerprints in the Earth and the Environment**, GFZ Potsdam and FU Berlin, Geosciences, Friedhelm von Blanckenburg, Dr. Patrick Frings, 8–13 April 2024, (patrick.frings@gfz-potsdam.de, f.v.b@fu-berlin.de)

3. **Solid-state NMR Spectroscopy**, Institute for Geology, Mineralogy and Geophysics, Ruhr University Bochum, Dr. Michael Fechtelkord, 21–24 May 2024 (michael.fechtelkord@rub.de)

4. **In situ Analysis of Isotopes and Trace Elements by Femtosecond Laserablation ICP-MS**, Leibniz University Hannover

5. **Application of Diffusion Studies to the Determination of Timescales in Geochemistry and Petrology**, University Bochum
2022 GLOBAL GEOCHEMISTRY SURVEY – THE RESULTS ARE IN...

Geochemists work on diverse, societally relevant, environmental challenges and fundamental understanding concerning Earth’s evolution and Solar System history. To develop creative, innovative approaches to solve these challenges, make important discoveries, and optimise productivity, it is essential to attract and retain a diverse workforce. But just how diverse are we as a geochemistry community? And is anything getting in the way of recruiting, supporting, retaining, and progressing the very best talent?

Global Geochemistry Survey goals
1. To understand the community composition and experiences of geochemists
2. To investigate barriers to diversity and inclusion in geochemistry

Respondents
Of the 1560 respondents to the 2022 Global Geochemistry Community survey, 75% are members of one or both Societies (the European Association of Geochemistry (EAG) and Geochemical Society (GS)). The geographical distribution of respondents is similar to the members (see Table).

Survey methodologies are well-established approaches to studying communities, and care was taken to share the survey widely whilst adhering to international data protection law and ethics of data collection. Because responding to such a survey is optional, the findings are not representative of Society membership or of global geochemists as a whole.

Nevertheless, these data provide the first-ever constraints and insights for the geochemistry community. They include descriptions of the community’s demographics, career experiences, work–life balance, access/support of needs, and experiences of exclusionary behaviours.

The survey results could be scrutinised further to obtain additional insights into the diversity of the geochemistry community; for example, investigating the relationship between community diversity and seniority. The data also provide a reference frame with which results of proposed future 5-year surveys can be compared.

First of all, we would like to celebrate that our overall geochemistry community is very diverse with respect to country of origin, language, ethnicity, gender and gender identity, sexuality, disability, and much more!


Key Finding: High Prevalence of Exclusionary Behaviours
On the other hand, the survey highlights that many in geochemistry have reported experiencing exclusionary behaviours. For example, 40% of survey respondents reported that they have felt unsafe, threatened, or undermined in professional settings.

In comparison, other studies have shown that the incidence of harassment and discrimination varies from 20% to >50% of women respondents depending on the definitions used (National Academies of Sciences, Engineering, and Medicine (NAS) 2018; Porter et al. 2022). Scientists from under-represented groups (including people of colour, women, and gender-diverse individuals, those with a disability, and those who identify as LGBTQIA+) may more frequently experience harassment and discrimination (NAS 2018; Marin-Spiotta et al. 2023). For example, in a recent survey, 18% of LGBTQIA+ respondents experienced exclusionary behaviour, compared with 10% of non-LGBTQIA+ respondents (Institute of Physics, Royal Astronomical Society, and Royal Society of Chemistry 2019).

Next Steps?
All of us at the EAG and GS are individuals, limited by our own lived experiences, so we need your help to decide on our next steps. We are specifically interested in what you think the Societies can do about the prevalence of exclusionary behaviours in geochemistry...

Read the full report at https://www.eag.eu.com/about/dei/survey-report-and-questionnaire/ and suggest actions!

Finally, we are deeply grateful to all those who responded to this first survey of our international community. All engagement and contributions are valued and assist in united, cooperative efforts to improve geochemistry. Thank you!

The 2022 Global Geochemistry Community Survey was a joint initiative of the Diversity, Equity and Inclusion Committees of the European Association of Geochemistry and the Geochemical Society. Data analysis was carried out by survey specialists Dr Rachel Ivie and John Tyler.

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Institute of Physics, Royal Astronomical Society and Royal Society of Chemistry (2019) Exploring the Workplace for LBGT+ Physical Scientists, 55 pp
Marin-Spiotta E and 8 coauthors (2023) Exclusionary behaviors reinforce historical biases and contribute to loss of talent in the earth sciences. Earth’s Future 11: e2022EF002912

2023 Global Geochemistry Community Survey: Global Report and Findings
ON THE EAG BLOGOSPHERE: CAREERS OUTSIDE ACADEMIA

New on the EAG Blogosphere from Thaïs Couasnon (EAG Communications Committee) is a compilation of testimonials from geochemists working outside academic science. Thaïs writes, “Each tells the journey that led the interviewees to work where they are today after an early career researcher experience. Their shared experience in diverse fields, such as education, public policy, climate science, communication and management, museum conservation or laboratory engineering, may help you to discover a new job title, a transition approach or, on the contrary, convince you to fight for a permanent academic position.” Read short extracts below and visit the EAG blogosphere at https://blog.eag.eu.com/categories/non-academic-careers/ to read the full interviews.

Rachael Moore, Senior Energy Consultant at the World Bank
Energy, carbon capture utilization and storage (CCUS), and industrial decarbonization implementation

What aspect of your work are you most excited about at the moment?
“What I am enjoying most is being at the nexus of innovation, policy, and implementation. Today, there is significant momentum growing behind energy transition. It is really exciting to be part of it and to translate the technical aspects of projects and technologies into digestible and clear messages and actions for policy makers.”

What advice do you have for PhD students/academic staff who are thinking of leaving academia?
“I’m clearly biased, but come to the energy sector! Opportunities for geoscientists are exploding, given that energy transitions need huge volumes of critical minerals, more geothermal, CCUS, etc. That said, a big advantage we have as geoscientists is that we are well practiced in cross-disciplinary thinking and multidisciplinary work. Our work is also very applied. Personally, I lost sight of that when I was first applying for jobs outside of academia. Initially, I tried to sell my very niche and specific expertise, rather than my substantial skills in managing projects, synthesizing and translating technical information, and solving problems. When leaving academia, I recommend individuals present their geoscience expertise as value added, but unless it is key to the role, it should not be the focus. Rather than focusing on WHAT you did, focus on HOW you did it. As part of that, be sure to have a succinct and clear CV.”

Caroline Thaler, Climate Tech Project Entrepreneur at Marble
Climate tech, Deeptech, start-ups, environmental impact, CO₂ storage, and biomineralization

What helped you to be aware of the alternative career paths to academia?
“From the moment I decided to look for funding to develop my project outside of academia, I started to participate in any event/program related to entrepreneurship that was advertised in my academic mailing lists. I became aware of funding opportunities, startup clusters, and working groups. Once you are in the network, it is easier. For example, Marble organizes evenings and climate tech events once every two months in Paris. In such events, I met someone that allowed me to be further connected in the American/international Climate tech network.”

What skills acquired during your academic experience are the most valuable for you today? What are some new skills that you have learned in your current job?
“Communication skills definitively helped me integrate into the climate tech environment. In addition, knowledge in science (biogeochemical cycles, reactions like alkalinity, thermodynamics, and kinetics of carbonates formation/dissolution) is a major asset for me today. I am now learning new things about the climate tech ecosystem and how to actually build a startup.”

David Au Yang, Analytical Research Engineer at CEREGE
High school teaching, lab engineering, analytical development, and stable isotope analysis

Did you initially plan on this career at the onset of your PhD?
“Before my PhD, I wanted to be a high school teacher. However, when I was involved in my PhD, I was focused only on my academic career, hoping that I would not have to take any other exam. I wanted to be the equivalent of a lecturer in France. At the end of my first post-doctoral contract, 2 years after my PhD, I applied to post-doctoral job offers and wrote proposals and funding grants such as Marie Curie. As I didn’t get the funding, I finally decided to work for a year as a contract teacher to see if the teaching experience in high school would fit me. After a very pleasant experience, I applied to the research engineer offer because I was missing performing experience in the laboratory and the ability to work on innovative subjects in geosciences. Moreover, I still have the opportunity to teach in this position.”

What aspect of your work are you most excited about at the moment?
“At the moment, I really like the analytical development part. I like to fix a problem within a context for collaborators working on very distinct topics such as phytoliths or meteorites. Besides, there is eventually a possibility to teach at the university within my current job.”

Marie Kuessner, Scientific Referee at the German Federal Office of Radiation Protection
Radiation protection and society

What aspect of your work are you most excited about at the moment?
“I really appreciate that I work independently on my projects but can always get feedback from my boss. As a scientific referee, you also have the opportunity to collaborate with working groups of people with different profiles, which is exciting. For example, on a project concerning radioactivity, drinking water, and the involvement of drinking water devices, I work with engineers, academics, including chemists and biologists, as well as other regional officers. I also work on constructing emergency plans for drinking water, which I find very impressive. It fulfills my curiosity.”

What advice do you have for PhD student/academic staff who are thinking of leaving academia?
“I have actually several. Always be open for new things. Don’t be anxious about what is coming. Have the courage to go out of your comfort zone. In German they say, "Sie kochen auch nur mit Wasser"—you also only cook with water—which means that other people are also only human and have their own flaws. Do things with your own character, as most decisions are driven by feeling, instinct, interhuman interactions. Have the courage also to try things and be allowed to fail.”

The past two years have been a time where we tried to negotiate a post-pandemic world. The pandemic brought many challenges, but also opened the opportunities for remote participation in conferences in various forms—first coming to be as an online mode, followed by a hybrid mode. Going forward, a major topic of discussion is what the shape of future conferences will be. Meeting people face-to-face and chance interactions are what have made conferences what they are—the primary mode of exchange of ideas and discussion of results. However, for a lot of people—caregivers, people strapped for travel funds, people affected by travel restrictions (e.g., visa requirements), and many more—the online mode opens up possibilities to participate that did not exist before. These modes come with different demands on finances. One of the major topics of ongoing discussion is which features of a hybrid conference are most useful and how to best optimize costs versus utility. This discussion will probably continue for some time to come, but in the end, we are certainly going to have more inclusive conferences that bring together a wider array of people than has been the case in the past. It has been a privilege to observe this transition happening from the front row. I welcome all of you to chip in with your thoughts, opinions, and suggestions—just drop a mail to me.

Increased mobility and ability to communicate are opening up participation in conferences and other activities (e.g., workshops) to a population from a much wider section of the globe. In particular, the demographics of Goldschmidt conferences has shifted substantially—a large section (more than 35% at the last couple of conferences) of participants are students and early career scientists. Participation in conferences or writing research grant proposals is no more the domain of seasoned veterans, and this has also brought forth the need for mentoring. The Geochemical Society and the European Association of Geochemistry have jointly launched a round-the-year mentoring program (different from the well-established and used programs at Goldschmidt conferences). I request those of you who are in a position to be mentors to volunteer for this program—there are mentees who are looking forward to help from you.

It seems it was just the other day that I was writing you at the start of my term as President of the Geochemical Society; now it is already my last column—Liz Sikes will be taking over as President in 2024. The time has gone by quickly, or at least it seemed so, not least because all of you—exclusively volunteers in one form or the other—have stepped in to help from you. All of your mails with various thoughts and suggestions, as well as the interactions with all the committee members, the Board, the Executive, and the office have been pleasant and great learning experiences for me. I take this opportunity to thank everyone that was involved, and to send all my good wishes to Liz for her term as President.

Sumit Chakraborty
GS President, 2022–23

VOLUNTEER APPRECIATION

The Geochemical Society thrives thanks to the efforts of many dedicated volunteers. Our sincere gratitude goes to the following GS members whose board and committee terms conclude in 2023.

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GOLDSCHMIDT® 2024
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Join scientists from more than 70 countries for the year’s premier conference on geochemistry and related subjects!

IMPORTANT DATES
- 10 January 2024: Abstract Submission, Grant, and Student Helper Applications Open
- 15 March 2024: Grant Application Deadline
- 29 March 2024: Abstract Submission Deadline
- 1 July 2024: Early Registration Deadline
EQUALITY, DIVERSITY, AND INCLUSIVITY (EDI) AT THE MINERALOGICAL SOCIETY

The Society’s EDI committee is composed of representatives from all eight of its Special Interest Groups and is working to implement short- and long-term objectives identified following our 2022 survey. We e-meet regularly to discuss how to effectively develop best EDI practices to ensure fair, equitable treatment and opportunities for all current and aspiring members of our Society.

The committee is chaired by Dr Laura Kelly, lecturer in Microbiology at Manchester Metropolitan University, and the vice-chair is Dr Ana Santos, research fellow at the Natural History Museum, London.

Laura Kelly
Ana Santos

We are currently prioritizing four major pillars of development: (1) Meetings and events; (2) Membership; (3) Awards and Grants; and (4) Publishing. The first three, described further below, are well under way and initial plans of actions have been discussed by the Society’s Officers and at Council. We plan to discuss EDI issues surrounding Society publishing in early 2024.

Here is an overview of key developments in the areas mentioned above:

1. **Meetings and events**: We have put together a ‘how-to’ guide to help event organizers to promote diversity of attendance and inclusivity of participation at events across the Society.

2. **Membership**: We are reviewing Society membership fees to encourage participation from a wider community, including those from economically disadvantaged backgrounds, on a career break or between positions, self-funded PhD students, etc. We are working on increasing the value of our membership, e.g., by offering training and networking opportunities.

3. **Awards and Grants**: We are changing the way we recognise the excellence of hard work. Our existing awards are going through a major re-vamp to ensure all-round diversity and inclusivity and to include services to the community (e.g., teaching, public outreach) as an assessment criterion. Self-nominations will be accepted and application forms/templates will become available on our website in due course.

There is a lot more to come. Watch this space!

Laura Kelly and Ana Santos

**EDI Committee**

*European Mineralogical Conference 2024*

The Mineralogical Society will host the fourth iteration of the European Mineralogical Conference in Dublin on 18–23 August 2024.

Our new conference poster is shown below. Please download a copy of this poster from the Conference website and post it in your place of work/study. Consider attending the event and presenting your work.

Online registration is now available through the website at www.emc-2024.org

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**E-Bulletin**

The Mineralogical Society E-Bulletin is sent to members regularly (at least monthly). If you are not receiving your copy, please contact the Editor (kevin@minersoc.org) to let him know. He will do what he can to restore service.

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**Student Bursary**


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**COVADONGA BRIME**

A member of the Society and friend of the Mineralogical Society has departed this world. Covadonga Brime was a regular delegate at clay conferences and was easily recognized by her warm welcome and ready smile. Farewell.
Recent content in Mineralogical Magazine (https://www.cambridge.org/core/journals/mineralogical-magazine)

- The oxidation state and distribution of Fe in pumpellyite from the Northern Chichibu Belt in the Hikjawa district, western Shikoku, Japan: Masahide Akasaka, Yumi Goishi (Imaizumi), Masayuki Sakakibara, Yoshinori Nakama

- Okruginite, Cu2SnSe3, a new mineral from the Ozernovskoe deposit, Kamchatka peninsula, Russia: Anna Vymazalová, Vladimir V. Kozlov, František Laufek, Chris J. Stanley, Ilya A. Shkilev, Sharapat Kudaeva, Filip Košek

- Tellurium-rich stibiogoldfieldite and Se-bearing dantopaite from Goldfield, Nevada, U.S.A.: new crystal chemical data: Silvia Musetti, Jiří Sejkora, Cristian Biagioni, Zdeněk Dolníček

- Kalyuzhninite-(Ce), NaKCaSrCeTi(Si8O21)OF(H2O)3, a new mineral from the Darai-Pioz alkaline massif, Tien-Shan mountains, Tajikistan: mineral description, crystal structure and a new double (Si8O21) sheet: Atali A. Agakhanov, Elena Sokolova, Vladimir Yu. Karpenko, Frank C. Hawthorne, Leonid A. Pautov, Anatoly V. Kasatkin, Igor V. Pekov, Vitaliya A. Agakhanova

- Newsletter 75: Ferdinando Bosi, Frédéric Hatert, Marco Pasero, Stuart J. Mills

- Letnikovite-(Ce), (Nao)Ca2Ce2[Si7O17(OH)]F4(H2O)4, a new mineral from the Darai-Pioz alkaline massif, Tajikistan: mineral description, crystal structure and a new single [Si7O17(OH)] sheet: Atali A. Agakhanov, Elena Sokolova, Fernando Cámara, Vladimir Yu. Karpenko, Frank C. Hawthorne, Leonid A. Pautov, Anatoly V. Kasatkin, Igor V. Pekov, Vitaliya A. Agakhanova

- Secondary uranyl arsenates-phosphates and Sb-Bi-rich minerals of the segnitite-philipsbornite series in the oxidation zone at the Prakovce-Zimná Voda REE-U-Au quartz vein mineralization, Western Carpathians, Slovakia: Martin Ondrejka, Štefan Ferenc, Juraj Majzlan, Martin Števko, Richard Kopáčik, Bronislava Voleková, Stanislava Milovská, Jörg Göttlicher, Ralph Steininger, Tomáš Mikuš, Pavel Uhér, Adrián Biroň, Jiří Sejkora, Alexandra Molnárová

Recent Content in Clay Minerals (https://www.cambridge.org/core/journals/clay-minerals)

- Differential dissolution of interlayer, octahedral, and tetrahedral cations of vermiculite in oxalic acid: Yu Zhang, Hongjuan Sun, Tongjiang Luo, Liming Luo, Li Zeng

- Changes in the basic structure and strength deterioration of clay minerals with different hydration degrees: Jiuy Lin, Daoyong Wu, Jiwei Jia, Jing Yan, Lingtong Cai

- Microstructural observations of clay-hosted pores in black shales: Implications for porosity preservation and petrophysical variability: Hongjian Zhu, Shuangjian Li, Zongquan Hu, Yiwen Ju, Yanpan Yang, Yanjun Lu, Mingbo Wei, Weidong Qian

- Photon-shielding properties of alkali- and acid-treated Philippine natural zeolite: Mon Bryan Z. Gili


- Adsorption of gold nanoparticles on illite under high solid/liquid ratio and initial pH conditions: Ping Zeng, XinNie, Zonghua Qin, Suxing Luo, Wenbin Yu, Wenbing Yang, Weiqi Liu, Hai Yang, Quan Wan

- Magnetic sepiolite/iron(III) oxide composite for the adsorption of lead(II) ions from aqueous solutions: Osman Uygun, Ayşenur Murat, Gaye Ö. Çakal

- Prospecting and characterization of plastic clays from the state of São Paulo, Brazil, as raw materials for porcelain stoneware tile production: Sérgio Ricardo Christofoletti, José Francisco Marciano Motta, Eduardo Camargo Meneghel, Fábio Gomes Melchíades
PRESIDENT’S LETTER

MSA: Mineral Sciences for All

Over the years, I have had a like-hate relationship with strategic planning. The planning process can be interesting and constructive—or the opposite. In academia, many things can and do change during planning or soon after a beautifully crafted plan is unveiled, making the plan obsolete before it can be implemented. As a department head, I found myself quoting former U.S. president Dwight D. Eisenhower with alarming frequency: something along the lines of “plans are worthless, but planning is everything.”

More than a year ago, the 2022 MSA President, Pamela Burnley, realized that the Society did not have a good track record of effective planning. In cases in which plans had been developed after considerable time, effort, and creativity by MSA members, the plans tended to languish until, at some later time, the process started again. It is with confidence and optimism that I confirm that this has changed. Pamela launched a strategic planning task group that met regularly for about a year and produced a report that 2023 President Jeffrey Post, Executive Director Ann Benbow, and I distilled into a concise and actionable plan, which is on the MSA website in the About section (www.msaweb.org). This plan was approved by the MSA Council in October.

Implementation has already begun. One initiative that I am particularly excited about is the inception of a program of MSA Student Chapters. In this new program, students will meet regularly to explore their interests in the mineral sciences and related fields, learn more about mineral-related topics through a variety of activities, and meet other students and professionals in the many and various mineral-related employment sectors. The groups will be student-led, with assistance from a sponsoring professional who is a member of MSA. The program will run initially for a three-year trial, with some funding provided to support chapter activities such as field trips or visits to museums, labs, or businesses. Dr. Adrian Castro of Wellesley College, USA has agreed to head up this effort on behalf of MSA, for which we are very grateful.

If you are interested in starting such a group, either as a sponsoring professional or participant, please contact the MSA Business Office at business@minsocam.org. Another way to support student chapter activities is with a donation to the MSA Annual Fund with a designation that your donation be used for student chapter support. Those funds will then be used in the next year to provide small grants to student chapters.

Donna Whitney
2024 MSA President

NOTES FROM CHANTILLY

- **Renewal Season!** It is time to renew your memberships for 2024, as well as subscriptions to MSA’s publications. Member dues are: Regular Members and Fellows ($85); Early Career Members ($45); Student Members ($20); Senior Members ($0); Sustaining Members ($135 – membership plus a $150 contribution to support MSA’s many activities). You can renew via the home page of MSA’s website: www.msaweb.org. At that time, we hope that you will also make a contribution to one or more of MSA’s funds. These funds support our student research grants, lecture series, websites, education and outreach activities, awards, and much more.

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2023 MSA FELLOWS

MSA is pleased to announce the new Fellows for 2023. Fellows are MSA members who have contributed significantly to the advancement of mineralogy, crystallography, geochemistry, petrology, or allied sciences and whose scientific contributions used mineralogical studies or data. They are designated as Fellows upon proper accreditation by the Committee on Nomination for Fellows and election by the MSA Council. This year’s Fellows are:

- **Matteo Alvaro**, Università di Pavia, Italy
- **Janne Blichert-Toft**, École Normale Supérieure de Lyon, France
- **Michel Cuney**, Université de Lorraine, France
- **Laurence Galoisy**, UPMC-Sorbonne Université, France
- **Sang-Heon Dan Shim**, Arizona State University, USA
- **Carl Spandler**, The University of Adelaide, Australia
- **Marco Scambelluri**, Università di Genova, Italy
- **Hidenori Terasaki**, Okayama University, Japan
- **Max Wilke**, Universität Potsdam, Germany
- **Anthony Withers**, Universität Bayreuth, Germany
25- AND 50-YEAR MSA MEMBERS

MSA wishes to acknowledge and thank its members who have reached the 25- and 50-year marks of continuous membership. They are:

50-Year MSA Members
Hubert Barnes
Mark Barton
Lawrence Bernstein
Nabil Boctor
Ernst Burke
Kenneth DeNault
Stephen Guggenheim
Roderick Hill
Toshikazu Kawasaki
Paul Kraatz
Philip Kyle
Theodore Labotka
Takeshi Mori
Yoshihiro Nakamuta
George Rossman
Douglas Smith
Paul Tambuyser

25-Year MSA Members
Jaime Barnes
Rachel Beane
Florie Caporuscio
Christine Clark
Dennis Eberl
John Emmett
Yingwei Fei
Charles Fipke
Reinhard Fischer
Matthew Goring
Christopher Herd
Astrid Holzheid
Janusz Janeczuk
Brian Joy
Shun-Ichiro Karato
Tatsuhiko Kawamoto
Daniel Kile
Takahiro Kuribayashi
Jannick Ingrin
Janusz Janeczuk
Brent Owens
Burkhard Schmidt
Ulrike Troitzsch
Chin Ho Tsai
Mariette Wolthers
Michael Zieg

EVENTS

Geological Society of America Annual Meeting: This conference took place in Pittsburgh, Pennsylvania, USA on October 15–18, 2023. MSA had its Awards Luncheon there on Tuesday, October 17, as well as the Awards Lectures and a joint reception at the Carnegie Museum of Nature and Science with the Gemological Institute of America that same day. There were also a number of MSA-sponsored presentations.

MINERALS DAY 2023

This annual event, which began in 2020 as part of Earth Science Week (American Geosciences Institute), was held on Monday, October 9, 2023. The theme this year was Critical Minerals in our Lives. MSA created an interactive poster on critical minerals. Clicking on the poster images took visitors to pages of resources describing the critical minerals that make up each of the objects in the image. In observance of Minerals Day, there was also a webinar on the GemKids Project from the Gemological Institute of America.
Mineralogical Association of Canada

www.mineralogicalassociation.ca

THE CANADIAN MINERALOGIST NEWS

Highlights

Our September issue includes a new feature for CJMP, short communications, this time a practical contribution on “Picture-Perfect Petrography: Affordable Thin-Section Scanning for Geoscientists in the Digital Era” from Derek Leung and Andy McDonald. Additional short comms. are in the pipeline. Our research content commences with a cautionary tale on the use of pyrite composition as a prospecting tool for gold mineralization with an example from northern Canada. This encouragingly international issue also features characterization studies of pegmatite-hosted carlsobarbosait, a critical metal-bearing (U and Nb) pegmatite mineral from Argentina, and stibiotantalite (Sb and Ta) from China. A pentavental U-bearing mineral, shinkolobweite, has been described from the Democratic Republic of Congo, and a new platinum alloy mineral, sidorovite (PtFe₃), reported from Russian placer deposits. In addition, Louis Cabri and Andy McDonald strike borishanskiite and platarsite, two platinum group metal alloys, off the list of accredited alloy mineral, sidorovite (PtFe₃), reported from Russian placer deposits. The opaque grains intergrown with the

Shinkolobweite, from the Shinkolobwe Mine, Democratic Republic of Congo: A New Mineral Containing Uranium in the Rare Pentavalent Oxidation State, by Travis Olds, Aaron Lussier, Václav Petříček, Jakub Plašíl, Anthony Kampf, Allen Oliver, Peter Burns, Mateusz Dembowski, and Ian Steele (Vol. 61, 2023), mentioned above and already burning up the airwaves.

In second place is our July issue’s leader, Trace Element Characteristics of Tourmaline in Porphry Cu Systems: Development and Application to Discrimination by Christopher Beckett-Brown, Andrew McDonald, and Beth McClenaghan, also from volume 61, from earlier this year.

Running close behind is the new short communication for the practically-minded petrologist, Picture-Perfect Petrography: Affordable Thin-Section Scanning for Geoscientists in the Digital Era, by Derek Leung and Andrew McDonald.

We can’t easily report on our most-cited paper, and this is also relevant for those for whom impact factors are a critical parameter in your lives, do not panic; all is well (numbers aside).

Our Associate Editors

As a means of both gratefully acknowledging and promoting the efforts of researchers in the mineralogical and geoscience community who donate their time to the necessary task of facilitating effective peer review, we continue to use this space to feature our Associate Editors (AE’s). In this issue, we feature two more of our long-standing contributors from our expertise base.

MATTHEW STEELE-MacINNIS

Dr Steele-MacInnis works from the Department of Earth and Atmospheric Sciences at the University of Alberta (Canada). Following his BSc (Hons) at Memorial University of Newfoundland (Canada) and his PhD from Virginia Tech. (USA), he conducted a postdoc at ETH Zurich (Switzerland) and was an Assistant Prof. at the University of Arizona (USA), before joining U of A in 2017. His research interests include the properties and roles of fluids in the Earth, especially those that form ore deposits. He has published more than 90 papers and his works have been cited over 3200 times to date. His research group website can be found at https://sites.ualberta.ca/~steelema/index.html. He has served as an associate editor of CJMP since 2016.

YUANMING PAN

Dr Pan is employed by the University of Saskatchewan (Canada) Dept. of Geological Sciences. His research encompasses almost all aspects of diverse minerals from chemical compositions to crystal structures, defects, physical properties, formation mechanisms, and environmental and technological applications. His work appears in a broad selection of journals from Earth Sciences, including The Canadian Mineralogist to Chemistry, Physics, and Material Sciences, and they have been cited over 10,000 times to date. Much of his recent work involves the study of compositional and crystallographic vagaries of quartz, but also includes environmental, geochemical, and mineralogical studies of a variety of minerals and elements, including arsenic, cadmium and thorium, among others. His research profile can be found at https://artsandscience.usask.ca/profile/YPan#Publications. He has been serving as an associate editor for CJMP since at least 2012, and he advises this editor that his very first paper was published in The Canadian Mineralogist.

FEATURED MINERAL/TEXTURE

The accompanying image illustrates the paragenetic complexity demonstrated in the Critical Zone of the Bushveld Complex, South Africa. In a sample from the new Ivanplats exploration, we see an anhedral olivine (orange and purple birefringence) intergrown with chrome spinel (chromite), in the rock type known locally as feldspathic harzburgite. This has been interpreted as postcumulus growth of olivine which has become stabilised in a magmatic cumulate by increased volatile content, in this case produced by the proximal thermal dehydration of dolomitic xenoliths derived from the floor rocks, tens of metres below. A band of optically continuous peritectic orthopyroxene at the centre of the image separates olivine from spinel.

A feldspathic harzburgite from the northern limb of the Bushveld Complex, South Africa, showing coarse-grained amoeboidal olivine, intimately intergrown with surrounding cumulus-textured primocryst enstatite, showing fine lamellae exsolution of calcic pyroxene, and interstitial plagioclase feldspar. The opaque grains intergrown with the olivine or as subhedra adjacent to it are chromites. Photo courtesy of Siyasanga Dyan.
**Call for papers – Thematic Issue in honour of Jim Franklin**

Dear Friends, students, and colleagues of Jim Franklin:

It has been a while since Jim retired as Chief Geoscientist at the Geological Survey of Canada and he continues as a consultant and principal for several companies. Jim influenced so very many, near and wide, with his ideas on the formation of massive sulfide and many other ore deposit types; his dedication to the earth sciences covers the gamut of mentoring, researching, managing and outreach. To recognize the impact he has had and continues to have on our science, a special issue of *The Canadian Journal of Mineralogy and Petrology* (CJMP), formerly *The Canadian Mineralogist*, is being developed in his honour. We personally invite you to be part of this initiative and to consider submitting a paper to this very special issue.

Jim has always had a passion for ore deposits research, and it is our intention to formulate a special issue around this theme. He also delved into many aspects of ore deposits, ranging from their geochemistry, mineralogy, geological setting, isotopic signatures, etc., so a contribution that falls into any of one these related areas would be welcomed. Our goal is to showcase research that highlights Jim’s long-term contributions.

The plan right now is to have contributions submitted by March 2024, followed by reviews being conducted shortly thereafter. This would provide ample time to assemble those contributions accepted for publication into a special issue, which would be published later in 2024. *The Canadian Journal of Mineralogy and Petrology* is entirely digital, and thus there will be no strict guidelines as to how many papers may be included in an issue. Another goal that we are working on is to be able to provide partial or complete open access for the articles published in this issue. Having this special issue formulated in an open access basis, available to the entire world, would be an incredible way to honour Jim.

If you are interested in providing a submission, please send an email to one of the guest editors, Dan Marshall: marshall@sfu.ca, Steve Piercey: spierecy@mun.ca, or Lyn Anglin: anglin.cd@gmail.com an idea of what your paper will involve. If you are unable to contribute, you may be willing to serve as a reviewer for the contributions received and we would equally welcome hearing from you.

We thank for your consideration, and we look forward to a positive response, with sincere regards,

Dan, Steve, Lyn & the editorial and CJMP team

**MAC TRAVEL AND RESEARCH GRANT AWARDS IN 2022**

The Mineralogical Association of Canada (MAC) awarded eighteen Student Travel and Research Grants in 2022 that totaled $15,000. Report excerpts from three of the recipients follow.

Dana Šílerová is an MSc student at Simon Fraser University (Canada) under the supervision of Dr. Brendan Dyck. Her research focuses on the structural and metamorphic evolution of the Great Slave Lake shear zone, a Paleoproterozoic continental transform boundary in northwestern Canada. She uses in situ U-Pb dating of accessory minerals via laser ablation-inductively coupled plasma-mass spectrometry in conjunction with field mapping and petrography to generate new information about the timing and duration of ductile shear along the shear zone. The MAC Travel Grant allowed her to attend the 2022 GAC-MAC-IAH-CNPCSPG Joint Annual Meeting in Halifax, where she gave a talk about her MSc research in the highly relevant petrochronology session titled “It’s about time”. The conference provided her with a fantastic opportunity to meet other researchers in her field and to have many valuable discussions with them, both about her work and theirs.

Dany Savard is a PhD candidate at the Université du Québec à Chicoutimi (UQAC), Canada, under the supervision of Dr. Paul Bédard and Dre. Sarah Dare. He received the MAC Travel Grant to present his work on a new mapping protocol using a rapid response cell for laser ablation coupled to a time-of-flight mass spectrometer (LA-FF-ICP-TOF-MS) for the simultaneous quantification of multiple minerals at the 11th Geoanalysis 2022 conference in Freiberg (Germany). Presenting and assisting at such specialized international conferences is essential to learn from and discuss with other researchers to build a borderless network and follow the latest development in microanalytical chemistry. Dany’s research is directed toward quantitative 3D-analysis at micrometer scale by LA-ICP-MS of major and trace elements in magmatic melt inclusions and their host minerals. With an emphasis on iron-oxide apatite (IOA) deposit, the 3D-mapping protocol would allow a better and wider characterization and understanding of trapped melt in various geological environments.

Colton Vessey is a 4th year PhD candidate at the University of Alberta (Canada), under the supervision of Drs. Sasha Wilson, Anna Harrison, and Majia Raudsepp. His research examines how environmental conditions (temperature, redox, aqueous speciation) impact carbon mineralization — storage of CO$_2$ as benign carbonate minerals — processes relevant to CO$_2$ sequestration in natural and mining environments. Carbon mineralization of (ultra)mafic mining wastes can both offset emissions and reduce mobility of potentially toxic contaminants; however, the impact of redox-sensitive metals (e.g., Fe) and anionic species on carbon storage rates and efficiencies is poorly constrained. The MAC Travel Grant assisted Colton in travelling to Centre National de la Recherche Scientifique (Toulouse, France) for a six-week research trip to conduct in-situ Raman spectroscopy experiments that will contribute to his PhD thesis. Initial results from this work show dissolved silica may both inhibit or enhance carbon mineralization depending on the environmental conditions.

**BRANDON GAC-MAC-PEG 2024 JOINT ANNUAL MEETING**

May 19–22, 2024
Brandon University, in Brandon, Manitoba, Canada

The 2024 Joint Annual Meeting of the Geological Association of Canada (GAC) and the Mineralogical Association of Canada (MAC) will be held on May 19–22, 2024, at Brandon University, Manitoba, Canada. This meeting will include all the expected GAC and MAC programming, as well the 10th International Symposium on Granitic Pegmatites with field trips and special sessions.

The preliminary program is now available, and abstract submission is open. Early submissions (before January 20, 2024) will receive a substantial fee reduction. Abstract submission will close on February 15, 2024. Registration will open on February 1, 2024: lower registration fees will be applied to those who register before April 7, 2024.

Visit https://event.fourwaves.com/gacmac2024/pages to view the program and submit your abstracts.
The 85th Annual Meeting of the Meteoritical Society was held in August 2023 on the campus of the University of California – Los Angeles (UCLA) in Westwood, California, USA. MetSoc2023 was the fifth time the Society has met at UCLA, the most recent prior meeting being in 2002.

Scientific talks were presented in two parallel sessions at the Luskin Conference Center, either live or streamed via Zoom; there were also two in-person poster sessions held on Tuesday and Thursday evenings. There were 332 scientific contributions, approximately equally split between talks and posters. A very large majority (94%) of the 342 meeting attendees made the trip to Los Angeles, and most were housed on campus (at the Luskin Hotel, the UCLA Guest House, or student dormitories). All events during the conference were hosted on the UCLA campus including a welcome party at the Sculpture Garden; the annual banquet, held outdoors in front of Royce Hall; and the Barringer Invitational Lecture, held at the Fowler Museum on Monday evening. Amy Mainzer of the University of Arizona, USA presented the Barringer Lecture to an attentive audience of conference attendees and the public; her talk was entitled “Earth-Approaching Asteroids and Comets: Opportunity and Risk.” A pre-conference town-hall was organized by the Impact Cratering Committee of the Meteoritical Society to discuss “Goals, Perspectives, and Challenges” in Earth-based crater research. Conference attendees also had opportunity to learn about the Astromaterials Data System at a luncheon and town-hall.

As usual, Wednesday morning witnessed the presentation of Society Awards and distinguished lectures. The Leonard Medal Lecture, “Pallasites to Presolar Grains: Looking Inside Asteroids, the Solar Nebula, and Stars with Isotopes and Trace Elements,” was given by Andy Davis; and the Barringer Medal Lecture, “Spinels in Sediments and the Astronomical Perspective on Earth’s History — What Can 20 Tons of Rock and 40,000 Litres of Hydrochloric Acid Tell Us?” was presented by Birger Schmitz. In lieu of the semi-traditional Wednesday afternoon “boat trip” (or equivalent local cultural exploration), the conference organizers collaborated with the UCLA SPACE Institute to sponsor a plenary symposium about current and planned exploration missions and sample return from inner Solar System bodies. Excellent talks and discussions were presented by planetary scientists leading these efforts, including Laurie Leshin, Nancy Chabot, Linda Elkins-Tanton, Hal Levison, Shogo Tachibana, Lindsay Keller, Tomohiro Usui, and Meenakshi Wadhwa. UCLA’s Dean of Physical Sciences, Miguel Garcia-Garibay, welcomed the public to the event, which was followed by a garden reception and, soon afterward, the banquet. Guests enjoyed a lovely SoCal evening, so typical for this time of year that meeting organizers had earlier confidently quipped that “we have arranged for it to not rain.” Those same folks (i.e., us) were simultaneously sobered and amused when five days later, tropical storm Hillary soaked LA, the first such storm to hit Los Angeles in 84 years! And, in case you’re wondering, there really was no “plan B” for the banquet (but perhaps Frederick Leonard was looking out for us?). With the conference ending at noon on Friday, a few dozen folks stayed around to take advantage of some. With the conference ending at noon on Friday, a few dozen folks stayed around to take advantage of some.

SOCIETY AWARD WINNERS

The Society gives five major awards each year. For more information on individual awards, please see the Call for Nominations and the Society webpage. Congratulations to the highly deserving awardees, and thank you to all our members who took the time to nominate your colleagues for consideration and who serve on award committees.

The Leonard Medal is given to individuals who have made outstanding original contributions to the science of meteoritics or closely allied fields. The Meteoritical Society presents the 2023 Leonard Medal to Andrew M. Davis for his profound contributions to deciphering early Solar System processes by improving the chronology, constraining the differentiation of planetesimals, exploring diffusion and condensation/evaporation processes, and revealing stellar nucleosynthetic pathways; and for advancing the chemical and isotopic microanalytic of meteoritic materials. Full citation: https://doi.org/10.1111/maps.14044

The Barringer Medal is given for outstanding work in the field of impact cratering and/or work that has led to a better understanding of impact phenomena. The Meteoritical Society presents the 2023 Barringer Medal to Birger Schmitz for his groundbreaking use of micrometeorites in the sedimentary record to discern the history of impact processes; and to understanding the effects of impact bombardments on Earth’s systems. Full citation: https://doi.org/10.1111/maps.14037

The Nier Prize is given for significant research in the field of meteoritics and closely related fields by an early career scientist under the age of 35 or whose PhD was awarded <7 years ago. The Meteoritical Society presents the 2023 Alfred O. Nier Prize for a distinguished young scientist to Jessica Barnes for her contributions to volatiles in astromaterials and their use in advancing understanding of the inventory, origin, and
evolution of volatiles in the inner solar system; and for developing advanced NanoSIMS methods for analysis. Full citation: https://doi.org/10.1111/maps.14038

The Service Award honors members who have advanced the goals of the Society to promote research and education in meteoritics and planetary science in ways other than by conducting scientific research. The Meteoritical Society presents the 2023 Service Award to Hasnaa Chennaoui Aoudjehane for her initiatives in support and promotion of meteoritics and planetary science in African and Arabic countries; for her untiring mentoring of students; and for her service to the Meteoritical Society, scientific community, and public outreach efforts. Full citation: https://doi.org/10.1111/maps.14029

The Jessberger Award is given for outstanding research in the field of isotope cosmochemistry by a female scientist in the middle of her career who has received her doctorate at least 10 years and not more than 20 years before. The Meteoritical Society presents the 2023 Elmar K. Jessberger Award to Jamie E. Elsila for her influential role and strong leadership in isotope cosmochemistry; and for determining compound-stable isotopes of organic compounds in meteorites and lunar rocks. Full citation: https://doi.org/10.1111/maps.14039

The GORDON MCKAY AWARD and WILEY-BLACKWELL AWARDS from the 2022 meeting in Glasgow will be announced in a later issue of Elements.

CALL FOR AWARD NOMINATIONS

Please consider nominating a colleague for one of the Society’s awards. Nominations should be sent to the society secretary at (metsocsec@gmail.com) by 15 January (31 January for the Pellas-Ryder Award and the Service Award). For more information and details on how to submit a nomination for any of these awards, please see the latest Newsletter at the Society website or email the secretary.

UPDATED ANNUAL MEETING CALENDAR

<table>
<thead>
<tr>
<th>Year</th>
<th>Meeting</th>
<th>Dates</th>
<th>Location</th>
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<tr>
<td>2024</td>
<td>(86th Annual Meeting)</td>
<td>28 July–2 August</td>
<td>Brussels, Belgium (EU)</td>
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<tr>
<td>2025</td>
<td>(87th Annual Meeting)</td>
<td>14–18 July</td>
<td>Perth, Australia</td>
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<tr>
<td>2026</td>
<td>(88th Annual Meeting)</td>
<td>July/August TBD</td>
<td>Frankfurt, Germany (EU)</td>
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<tr>
<td>2027</td>
<td>(89th Annual Meeting)</td>
<td>July/August TBD</td>
<td>Flagstaff, Arizona, USA</td>
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RENEW YOUR MEMBERSHIP NOW!

Please renew by 31 March 2024; after that date, a $15 late fee will be assessed. You can renew online at https://meteoritical.org/society/membership.

The IAGC also presented 2020–2022 awards in person. Award presentations included the Vernadsky Medal (2020) to Yousif Kharaka, the Ebelman Award (2020) to Zimeng Wang, the IAGC Fellow Award (2021) to Yanxin Wang, and the Harmon Distinguished Service Award (2022) to Neus Otero. The IAGC would like to thank Secretary General Noriyoshi Tsuchiya (Tohoku University, Japan) and the local organizing committee for hosting the joint WRI-17 and AIG-14 meeting!

We are also excited to announce that the 3rd IAGC International Conference will be held in Cagliari, Italy in June 2025. This conference will be hosted by Giovanni De Giudici at the University of Cagliari, Italy. More information about the joint Water-Rock Interaction (WRI-18) and Applied Isotope Geochemistry (AIG-15) meeting will be available in 2024.
**GENERAL ASSEMBLY**

The IAGOD general assembly was held on Friday, August 25, 2023 at the historic Fountains Abbey in London, United Kingdom. The general assembly was attended by 15 members in person and 7 online, and included the appointment of a new executive council and wider council with past president, vice presidents, and regional councillors.

The following prestigious IAGOD awards have been granted at the General Assembly:

- **IAGOD Honorary Life Member**: Prof. Richard Kyle, University of Texas at Austin, Texas, USA;
- **IAGOD Distinguished Travelling Lecturer 2024–27**: Prof. Huayong Chen, Editor-in-Chief of Ore Geology Reviews;
- **Kutina-Smirnov Medal**: Dr. Richard Sillitoe (London, UK); Prof. Reimar Seltmann (NHM London, UK).

The society activities included sponsorship of the 16th Biennial SGA Meeting in Rotorua, New Zealand (March 2022); a short course in Geology and Mineral Deposits of Central Asia at Satbayev University in Almaty, Kazakhstan (November 2022); sponsorship of the 14th International Platinum Symposium in Cardiff, Wales (June 2023); and the establishment of a general secretariat at the China University of Geosciences in Beijing, China.

A particular highlight has been the co-sponsorship of the very successful Ore Deposits Hub (https://oredepositshub.com/). This popular initiative by early career researchers offers open-access seminars on the geology of ore deposits and has attracted significant global interest. This proved particularly timely for community building during the COVID-19 period.

The IAGOD general assembly elected a new council for 2024–2028 that will take office from January 2024. The Executive Committee will be led by Dr. Tania Martins (president), Dr. Wei Jian (secretary general), Dr. Alla Dolgopolova (chief treasurer and membership secretary), Prof. David Lentz (promotion manager), and Prof. Jens Andersen (publication manager and webmaster).

**OPEN ACCESS APC WAIVERS FOR ORE GEOLOGY REVIEWS**

The society’s flagship journal, *Ore Geology Reviews* (published by Elsevier), changed to open access in 2023. As part of this change, IAGOD has secured a number of annual waivers for article publication charges for members in good standing. These waivers will be distributed with particular focus on members from economically disadvantaged countries.

**IAGOD AT SEG 2023, LONDON**

IAGOD was well represented at the 2023 conference of the Society of Economic Geologists (SEG) in London, United Kingdom, where committee members delivered four presentations and were involved in the organisation of a workshop and residential field trip to Southwest England.

With the colourful display of past *Elements* issues, *Ore Geology Reviews*, and flyers for the 16th Quadrennial IAGOD symposium, the IAGOD booth attracted great interest among the 900 conference participants. The booth was staffed by members of the Executive and General Council, as well as leaders of national groups from Kazakhstan, Uzbekistan, China, and Mongolia. The booth was a unique opportunity to promote the activities of the association and to attract new membership.

**EVENTS**

**May 23–24, 2024**, 10th International Geosciences Conference of Young Researchers, Kyiv, Ukraine. IAGOD is pleased to sponsor the 10th International Geosciences Conference of Young Researchers. The conference theme is “Ideas and Innovations in Earth Sciences” and aims to bring together young researchers (PhD students, post-docs, and early career researchers). The conference will be online, and registration is free. For information and registration information, please visit https://gc.igs-nas.org.ua.


**August 30 to September 2, 2026**, 16th Quadrennial IAGOD Symposium, Porto, Portugal. The quadrennial symposium will be co-hosted by the University of Porto and welcomes suggestions for thematic sessions, workshops, and offers of field trips. See https://iagod.org/.

**Prof. Jens C Andersen**
Camborne School of Mines
University of Exeter
United Kingdom

**Dr. Alla Dolgopolova**
Natural History Museum
London
United Kingdom
The Japan Association of Mineralogical Sciences (JAMS) is proud to announce the recipients of its 2022 society awards. The JAMS Award for Young Scientists is awarded to two scientists who are under 37 years of age and have made exceptional contributions to mineralogical and related sciences. The JAMS Award for Applied Mineralogy is awarded to one scientist who has made a remarkable contribution to the field of applied mineralogy.

JAMS Award for Young Scientists to Naoki Nishiyama

Naoki Nishiyama is a research scientist at the Geological Survey of Japan of the National Institute of Advanced Industrial Science and Technology (AIST) (Japan). He obtained his PhD from Osaka University (Japan) under the supervision of assistant professor Tadashi Yokoyama and professor Satoru Nakashima. He is interested in mass transport and rock–water interactions in geological media. One of the most important achievements in the field of mass transport is the study of the relationship between permeability and pore structure. He compiled data from ~200 samples and showed that the “critical pore radius,” which corresponds to the smallest radius of the widest flow path penetrating the medium, is a controlling factor of the permeability. Based on this result, he proposed an equation for predicting the permeability over a range of ~12 orders of magnitude. This study has been widely cited in various fields, including environmental, life, and material sciences. His pioneering work in the field of water–rock interaction is the study showing the importance of a “water film” in rock dissolution under unsaturated conditions, where water and air coexist in pores. He conducted flow-through experiments using saturated and unsaturated sandstone and found that the dissolution rates are almost the same under both states, indicating that even in air-filled pores, dissolution occurs through the water film covering the pore surfaces. He is now studying how pore structure and permeability are changed by CO₂–water–rock interactions during CO₂ capture and storage, and CO₂-enhanced geothermal systems in basalt. He has also begun studying CO₂ mineralization during enhanced rock weathering, which is a new technology for CO₂ negative emissions.

JAMS Award for Young Scientists to Toru Matsumoto

Toru Matsumoto is an assistant professor at the Hakubi Center for Advanced Research, Kyoto University (Japan). His work focuses on the chemical and physical modification of solid materials exposed to the space environment, commonly referred to as “space weathering.” After participating in the initial analysis of regolith samples recovered from the asteroid Itokawa by JAXA’s Hayabusa mission, he turned his attention to surface microstructures of regolith grains from airless bodies. Space weathering is mainly caused by the impacts of micrometer-sized meteorites and solar wind implantation. He showed that surface morphologies formed by space weathering can be observed by scanning electron microscopy. From the surface observation of Itokawa particles, he proposed that space-weathering processes affecting Itokawa would have developed with regolith activities under microgravity conditions. One of his notable discoveries is the selective loss of sulfur from the surface of iron sulfide on space-weathered Itokawa particles, resulting in the growth of metallic iron whiskers. Sulfur depletion on asteroids is a long-standing, yet unresolved phenomenon that is fundamental to the interpretation of the evolution of asteroid surface. Toru’s discovery provided the clearest evidence for sulfur loss during long-term space exposure. Iron whiskers on iron sulfide are a novel and unexpected aspect of crystal growth on airless bodies. His research extended to lunar regolith particles, where he also identified iron whiskers similar to those on Itokawa. He proposed that sulfur compounds escaping from space-weathered iron sulfides could travel across the lunar surface, with some fraction eventually reaching the lunar polar ices, which are rich in sulfur. Toru has recently participated in the initial analysis of regolith samples recovered from the carbonaceous asteroid Ryugu. He has made significant contributions to unravelling the space weathering of hydrous minerals.

JAMS Award for Applied Mineralogy to Yuki Sugiura

Yuki Sugiura is a senior research scientist at Health and Medical Research Institute, AIST, Japan since 2022. He earned his bachelor’s and master’s degrees in crystal growth and mineralogy from Tohoku University (Japan). In March 2015, he earned his PhD degree in applied mineralogy at Waseda University (Japan). Since April 2015, he has worked as an assistant professor at the Faculty of Dental Science, Kyushu University (Japan). His expertise area lies in fine ceramic-based advanced biomaterials for bone regeneration in clinical operations. He is dedicated to addressing critical issues in clinical procedures, such as postoperative infections and low bone regeneration ability. Sugiura’s strategy involves hybridizing drug and bone substitute materials using crystal engineering processes. He introduced a novel process of incorporating antibacterial drugs and bone growth factors, namely silver and silica, into octacalcium phosphate (OCP). The newly fabricated OCP-based bone substitutes have demonstrated excellent biocompatibility, bone regeneration ability, and antibacterial properties through animal experiments. In addition to bone substitute fabrication, Sugiura has developed various dental materials, including dental implants and oral care products. He explores the interactions between minerals and biological entities, such as cells and tissues, at different scales. With this extensive knowledge, he has been working on a novel biomaterial fabrication, presenting biological phenomena related to biominerals, and creating new materials and ecosystems for a sustainable society.
THE PRESIDENT’S CORNER

You may not be aware of the services offered by the Clay Minerals Society.

One opportunity is the Reynolds Cup competition, named after Bob Reynolds for his pioneering work in quantitative clay mineralogy and his great contributions to the clay science Reynolds Cup Competition – The Clay Minerals Society. Check out www.clays.org/reynolds/.

Would you like to test the performance of your methods to analyze geological samples, especially in characterizing and quantifying clay minerals? We suggest you participate in the 2024 12th Reynolds Cup competition. The competition is a biennial event supported by the Clay Minerals Society and the German-Austrian-Swiss Clay Group (DTTG). Its primary goal is to stimulate improvements in analytical techniques and individual skills. This is offered as a service to the scientific community, and depends on the goodwill and fairness of all involved.

The Reynolds Cup Competition is open to anyone interested in quantitative mineral analysis, with particular emphasis on clay mineralogy. The competition is free for all to enter on the understanding that participants will submit their results. The Reynolds Cup competition provides three test samples, which are carefully prepared to represent realistic rock or soil mineral assemblages. The three samples are made available to individuals in commercial, industrial, government, or academic laboratories to use any method(s) to obtain the most accurate quantitative phase analysis.

The top three contestants of the 12th Reynolds Cup will be announced at the 61st Annual Meeting of the Clay Minerals Society in Hawaii (June 3–6) 2024 Meeting – The Clay Minerals Society. Only the names of the top three contestants will be published; details and other participants are kept confidential.

Additionally, if you wish to test, tune, and try your methods at a later time, Reynolds Cup samples prepared for previous competitions can also be purchased using the CMS Source Clay Pro Forma Order Form. These samples represent clay-bearing rocks, soils, or raw materials in the broadest sense and even include a ‘Martian’ sediment. Since its inception in 2002, over 1800 sets of results have been submitted to the Reynolds Cup competition. So join in the fun and blind test just how good your methods of quantitative phase analysis are! Samples for the 12th Reynolds Cup should be ready for distribution by end of January 2024. Registration is available on the CMS website (www.clays.org).

Enjoy it!

Sabine Petit, CMS President

JOURNAL UPDATE: CLAYS AND CLAY MINERALS

A new chapter in the life of Clays and Clay Minerals begins at the start of 2024. We have completed our five-year agreement with SpringerNature and have decided to partner with Cambridge University Press from 2024 onwards. We are grateful to Ron Doering and his colleagues at SpringerNature, and we now look forward to working with the team at Cambridge including Catherine Hill and Chris McEntee.

Submit your paper:

Author guidelines are available at https://www.cambridge.org/core/journals/clays-and-clay-minerals/information/author-instructions.

To submit your paper to Clays and Clay Minerals at its new home, visit https://www2.cloud.editorialmanager.com/claysacm/default2.aspx.

The journal has a comprehensive and proactive policy in relation to Open Access. You can find information about the journal’s OA policy here: https://www.cambridge.org/core/journals/clays-and-clay-minerals/open-access. Note that Cambridge has signed ‘Transformative Agreements’ with almost 3000 institutions worldwide. Please check if your institution is one of them; if so, you will be able to publish your work Open Access without further charge.

Editors

We are fortunate that most of the members of the Editorial Board (https://www.cambridge.org/core/journals/clays-and-clay-minerals/information/about-this-journal/editorial-board) will continue to work with us. We welcome the new members of the Board: Marcelo Alves (ESALQ/USP, São Paulo, Brazil), Arek Derkowski (IGSPAS Research Centre, Krakow, Poland), Liva Dzene (École Nationale Supérieure de Chimie de Mulhouse, France), Rawil Fakhrullin (Kazan Volga Region Federal University, Kazan, Russian Federation), and Bharat Tadikonda (Indian Institute of Technology, Guwahati, India). We thank Geoff Bowers, Katja Emmerich, Warren Huff, and Jana Madejova, who have served for many years and are taking a well-earned break. Also stepping down is Robert Preston, who has served as the journal’s copy editor for a number of years and, before that, its typesetter—many thanks to Robert for all of his years of dedicated service.

Professor Joseph W. Stucki, who has served as the Editor-in-Chief since 2008, continues in this role and we are grateful to him. Kevin Murphy is also continuing as Managing Editor.

Read the journal

The full journal archive is available at https://www.cambridge.org/core/journals/clays-and-clay-minerals. If your institution’s subscription is no longer active, please ask your library to contact Cambridge University Press to have it reinstated.

IMPORTANT ANNOUNCEMENT

Join CMS

Join CMS with new types of membership! Please visit www.clays.org or contact the Business Office at cms@clays.org.

Deadline to Remember

The Student Research Grant deadline is Feb 1, 2024, and nominations for the Brindley, Bailey, and Jackson awards are due March 1, 2024.

Save the Date!

The 61st Annual Meeting of The Clay Minerals Society and the 5th Asian Clay Conference
Location: Honolulu, Hawaii
Time: June 3-6, 2024
THE END OF HOSTILITIES

Almost immediately after the Japanese surrender on September 2, 1945, ending the Second World War (WWII), a handpicked unit of American civilian and military scientists and intelligence specialists that grew out of the Manhattan Project entered Japan. Their task was to determine if the Japanese had a wartime project to build a nuclear weapon. Modeled after the Alsos mission that sought out German scientists and nuclear materials, it included civil engineer Major Robert Furman, Chief of Foreign Intelligence for the Manhattan Project, and nuclear physicist Dr. Philip Morrison who had received his doctorate in 1940 under J. Robert Oppenheimer.

What began thereafter and continued until the early 1950s was a surveillance, control, and impoundment program, overseen by the Economic and Scientific Section of General Douglas MacArthur’s occupation-forces staff, and carried out in concert with the American 8th Army. The laboratories of nuclear physicists and radiochemists were targeted. Cyclotrons that had the potential to separate the fissile $^{235}\text{U}$ isotope were dumped in the Tokyo harbor. Attention also focused on the raw materials of an atomic bomb, and stockpiles of uranium and thorium ore, as well as laboratory quantities of uranium and thorium salts, would be inventoried and eventually seized and shipped to the United States. But before the discovery of nuclear fission (by physicists Lise Meitner and Otto Frisch) in the waning days of 1938 (December 1938, during Christmas break), the field of radioactivity and the nuclear industry itself really meant radium, and for the most part, the $^{226}\text{Ra}$ decay product $^{226}\text{Ra}$ (Fig. 1). The investigative group’s findings, summarized in a report written just 26 days after the Japanese surrender, was titled Atomic Bomb Mission, Japan: Final Report, Scientific and Mineralogical Investigation and noted on page 1: “The use and present disposition of Japanese radium supplies were investigated as an item of interest in determining any new radium resources of Japan” (Furman 1945).

CHANGE OVER TIME: DOING HISTORY AS A GEOSCIENTIST

I have been working on the records of that postwar mission at the National Archives (formally the National Archives and Records Administration; NARA), located adjacent to the University of Maryland-College Park campus. The material reads like an interleafing of the latest issue of Economic Geology with your favorite James Bond novel. The very same topics covered in this Elements thematic issue on geometallurgy—mineralogical characteristics of deposits, beneficiation strategies, and extraction flowsheets—were often at play for these investigators. It is not just the text contained in these files that grabs you. It is the physicality of the materials:

- the original TOP SECRET, SECRET, or CONFIDENTIAL stamps everywhere, and the need to place a declassification “slug” (Figs. 2 and 3) on copies of these formerly classified documents;
- the cryptic wording of radiograms from the Pentagon;
- the often revealing, handwritten annotations of formal memos;
- the fragility at the edges, yet the remarkable strength and crispness of sheets of 75-year-old onionskin paper (thin, lightweight, strong, often translucent paper not actually made from onions but resembling the thin, paper-like skins of onions); and
- the reports written on the backs of U.S. Army Map Service topographic sheets that a few months earlier might have been used in the planning and execution of an Allied ground-force landing on the coast of Japan.

Indeed, just the names on the document boxes, such as Formerly Top Secret Nuclear Physics Correspondence File, 1947–1951, make a career geoscientist feel that this is not a day like every other day.

There are strict rules that govern the handling of documents by researchers at the National Archives—one folder at a time, with the pages turned one at a time. It’s unlike reading a book, where you might jump back and forth between the index and text. Here, the data present themselves to you one frame at a time, in a fixed sequence. After many months of learning who were the players on each side, and what were the materials of concern, one such frame caught me by surprise. It was in a folder designated TARGETS containing information on otherwise unrelated companies—ranging from papermills to pharmacies—where the Japanese romaji-alphabet name started with an “S.”

The Uranium-238 Decay Chain

Only main decays are shown
Gamma emitters are not indicated

93
92
91
90
89
88
87
86
85
84
83
82

\[ \begin{array}{cccccccc}
\text{Po-218} & \text{Po-218} & \text{Po-218} & \text{Po-218} & \text{Po-218} & \text{Po-218} & \text{Po-218} & \text{Po-218} \\
3.05 \text{ m} & 3.05 \text{ m} & 3.05 \text{ m} & 3.05 \text{ m} & 3.05 \text{ m} & 3.05 \text{ m} & 3.05 \text{ m} & 3.05 \text{ m} \\
\end{array} \]

Figure 1. Uranium-238 decay scheme. From Duval et al. (2004) (https://pubs.usgs.gov/of/2004/1050/PalosVerdesRadium.htm#uranium.htm).
In March of 1948, about two and a half years into the occupation, a routine inspection was conducted at the Kyoto factory of the Shimadzu Industrial Company. Shimadzu is a familiar name today for its scientific and medical instruments, ranging from mass spectrometers and particle size analyzers to medical diagnostic imaging systems. Founded in Kyoto in 1875 by Genzo Shimadzu Sr., the company specialized in instrumentation for chemistry and physics laboratories and classrooms. In 1896, his sons assisted in experiments on X-ray production (at a high school that would later become Kyoto University), which yielded the first radiographs made in Japan. By 1909, the Shimadzu company was manufacturing medical X-ray devices (Shimadzu Corporation History, undated). The following year (Fig. 2), the company purchased 1.0 grams of radium sulfate (see Box 1). During the next 33 years (1910–1943), consumption of that radium sulfate supply had amounted to only 3.16 milligrams (out of the original 1,000 milligrams). This quantity was apparently used as a check and calibration source for the manufacture of commercial meters to measure the intensity of radiation coming from X-ray machines in operation. But why did Shimadzu purchase so much more radium than was needed for this purpose? And what does “consumption” mean in the context of this purchase?

Radium was an elusive element. First identified by Marie Curie in 1898, it took her four more years to isolate just 0.1 grams (or 100 milligrams) of radium chloride from 13 tons of pitchblende-bearing tailings mined and processed at Joachimsthal, Bohemia, the goal being to determine the atomic weight of this new element. In 1910, by authority of the International Congress of Radiology and Electricity, one curie (Ci), named for the late Pierre Curie who had died in 1906, was defined as the radioactivity of one gram of pure 226Ra, or more precisely, the quantity of 222Radon in equilibrium with a gram of 226Ra (Rutherford 1910). Readers interested in the historical details on the naming of the curie unit and its revised present-day acceptance as referring to both Marie and Pierre Curie are referred to Frame (1996). This mass of radium equates to $3.7 \times 10^{10}$ disintegrations per second ($3.7 \times 10^{10}$ becquerels in the SI system). Marie Curie attended the 1910 meeting in Brussels and was chosen to prepare the first international radium standard, of about 20 milligrams Ra (element), in her laboratory; it would then be securely stored at a site maintained by the International Bureau of Weights and Measures in Sèvres, a suburb southwest of Paris, France (Coursey 2017, Ariouet 2021).

By virtue of the 1910 definition, 226Ra is unique among all radioisotopes in that 1 gram = 1 Ci. But a curie is a huge quantity of radioactivity and, thus, fractional units would be the norm in the practical world. Physicians would typically deal with millicurie sources. When environmental concerns regarding radium in uranium mill tailings emerged in the 1970s, concentrations in soil and water would be reported in picocuries (one trillionth of a curie) per gram or liter.
While radiation dosimetry methodology and exposure standards were not yet established in 1910, early radium workers who handled the tubed salts with their bare hands, most notably Pierre Curie, soon developed severe fingertip burns (Fröman 1996). The radium sources in such cases would have been in the tens of milligrams range. Shielding with lead during transport and storage, and remote handling tools would eventually become the learned response within the industry and user community during the next decade. How the Shimadzu staff dealt with their very large radium source is not known.

Flipping to page 2 of the target report revealed much more of the story, providing a case history of how radium was typically used in a non-consumptive, use-and-store mode (Fig. 3). The remainder of the radium sulfate (i.e., the initial 1,000 milligrams minus the 3.16 milligrams used, most likely as a sealed source, for meter calibration equates to 996.84 milligrams) was sold to the Osaka University School of Medicine around 1910—the very same year that it was acquired. The Shimadzu Company, with well-established ties to the scientific supply community in Europe, served as the broker on the deal; by 1923, it had established an office in Berlin that imported state-of-the-art equipment to Japan. The early 20th century was a time of intense interest in radium, and in industry, most commonly in luminous paint. Japan certainly had the technical capability to support a radium production industry but lacked the uranium-ore resources. All its radium therefore had to be imported. Early production of radium (~1900–1912) was centered in Europe, using pitchblende (uraninite) ores and tailings from Joachimsthal, a region of Bohemia with a mining tradition dating from the early 1500s that is well depicted in the writings and woodcuts of Agricola’s De re metallica (1556).

Following Marie Curie’s laboratory experiments, pilot-scale extraction, and refining operations in Paris, the Austrian government established a factory at Joachimsthal, which, by 1910, had produced 10 grams of radium (Landa 1982). Given the date that the Shimadzu radium was purchased, it seems likely that it came from the Austrian factory. While the radium purchased in 1910 is listed in Figure 2 to have come from Czechoslovakia, the region, Bohemia, was part of the Austro-Hungarian Empire at that time. Czechoslovakia, initially established after the end of WWI, following the dissolution of the Empire, was recreated as an independent nation at end of WWII. Joachimsthal is now the spa town of Jáchymov in the Czech Republic, noted for its radioactive thermal springs. The Joachimsthal region was annexed by Nazi Germany in 1938 as the so-called Sudetenland. German pilot-scale experimentation on the military applications of nuclear fission used ore from Joachimsthal, as well as ore from the Congo that had been seized at a processing plant in Belgium following the fall of that nation.

The Joachimsthal radium factory produced about 2.2 grams annually from 1909 to 1936 (Robison 2015). The Shimadzu purchase was therefore sizeable for this early period of commercialization and time of expanding medical usage. Major production of radium in the U.S. began in 1913, using carnotite (a radioactive potassium uranium vanadate mineral) ores from the Colorado Plateau; and from 1913 to 1922, the U.S. would be the leading supplier in the world (Lubenau and Landa 2019). In line with industry practice, the quantity of radium would generally be submitted to the U.S. National Bureau of Standards (NBS; now NIST—the National Institute of Standards and Technology) for measurement and certification. For the fiscal year 1920 as a case in point, NBS records show Japan to be the leading export market for U.S. radium among 14 nations, with over 500 milligrams exported (Bert M. Coursey, PhD, former division chief for radiation standards at NIST, email communication, 15 May 2023). This likely reflects the rise of radium therapy for cancer treatment in the country.

The United States’ position as lead radium supplier was supplanted in 1922 by the discovery of higher-grade ores from the Congo and later Canada. A combination of these three ore sources, originally tapped for their radium content, supplied the uranium used in the “Little Boy” bomb dropped on Hiroshima, Japan (August 6, 1945), and in the plutonium-production reactors at Hanford, Washington, USA, that supplied the first atomic bomb test—the Trinity Test (July 16, 1945)—near Alamogordo, New Mexico, USA, and the “Fat Man” bomb dropped on Nagasaki, Japan (August 9, 1945).
Imperial University (Nakao 2021). Thus, the 997 milligrams supply arriving at Osaka some seven years later would have been a quantum leap forward in terms of source strength and therapeutic utility. It was likely divided into smaller sources for greater flexibility in treatments, although for some applications, such as the irradiation of deep-seated tumors, multiple sources totaling one gram or more were bundled into a teletherapy machine termed a radium element pack or radium bomb (Chu 2011). Figure 4 shows a radium bomb apparatus in use at Westminster Hospital (UK) in the early 1930s. The device was typically loaded with 1–4 grams of radium (Flint et al. 1934); by the 1950s, radium bombs would reach 50 grams of radium (for example, at Roosevelt Hospital in New York City in 1952; Landa 1982). The need to protect the medical staff from excessive radiation exposure when using large quantities of radium was noted by the Westminster Hospital physicists and surgeons, for whom the bomb terminology clearly resonated: “But whatever may be done to guarantee the safety of the workers the fact remains that the bomb is a weapon calling for careful handling. The chief factors in protection are ultimately distance and common sense.”

**HOT SPOT: THE EBB AND FLOW OF INTEREST IN RADIUM IN JAPAN**

During the 1910s, geoscientists carried out investigations on the radon (222Rn, the short-lived decay product of 226Ra, then commonly referred to as radium emanation) content of waters at hot springs in Japan. Their findings of elevated levels of radon meshed with the Japanese culture’s affinity for onsen as places of renewal and healing. This view fed into the public wonderment about all-things-radium, and the belief that inhaled and ingested radium and radon might have curative powers in line with those of the externally applied sources. The aura of Marie Curie reigned over the scene as probably the best-known western scientist of the era, and in 1913, The Radium Institute, complete with a spa and its Madame Curie Cafe, opened in the Ginza District of Tokyo (Nakao 2021). Remnants of this tradition can be seen in the town of Misasa in Tottori Prefecture. Thermal springs here have some of the highest radon levels in Japan (Oshima et al. 1954), and the town boasts a bust of Marie Curie and an annual Curie festival (see https://misasaonsen.jp/en/about/index.html, https://www.tottori-tour.jp/en/accommodation/819, https://www.youtube.com/watch?v=r8KiDyaXvc0).

During the period from the first inspections in 1945 until at least the Fall of 1948, U.S. military interest in the uranium and thorium stockpile was likely two-fold:

1. The fact that 226Ra is a decay product of 238U; simply put—where you find radium, you might find uranium and possibly gain insights on nuclear secrets and technology capabilities.
2. Radium–beryllium (RaBe) sources could be used in the laboratory to produce neutrons and thereby study nuclear fission. Scale-up for military applications, such mixed sources could function as initiators of chain reactions in nuclear weapons. Manhattan Project scientists first looked at RaBe sources to supply the needed flux of neutrons. But estimates of required radium quantities of more than 30 g, and the intense gamma radiation associated with such a supply, shifted attention to 210Po, a shorter half-life and higher specific activity (i.e., high Ci per gram; see Box 1) decay product of 226Ra rather than the long-lived 226Ra itself. Tailings from radium and uranium extraction in Canada were processed as part of a lesser-known (compared with Oak Ridge, Hanford, and Los Alamos) Manhattan Project operation in Dayton, Ohio, USA, to produce polonium sources for use as neutron initiators (Rhodes 2012; Thomas 2017; Reed 2019). The American field investigators, in particular physicist Philip Morrison who was the co-head of the Manhattan Project team that loaded the plutonium core and the polonium-beryllium initiator into the “Fat Man” bomb dropped on Nagasaki (World War II Multimedia Database, undated), would clearly have been aware of such usage.

**FAST FORWARD**

Despite names like radium bombs, it was uranium—not radium—that was weaponized during WWII. The trail of radium in postwar Japan revealed no military secrets. But radium is an element with a curious history and one that captured the public’s imagination from its point of discovery—much of this interest entwined with the real and imagined life story of Marie Curie. Radium’s legacy in the postwar era lay in the way it opened the field of radiation therapy and in its role as a soil contaminant at numerous sites connected to the front end of the nuclear fuel cycle, including sites involved in the Manhattan Project and in the Cold War nuclear weapons production program. The history of radium intake in the early 20th century is one of tragedy, stemming from both inadvertent ingestion during the application of radium-bearing lumi-
nous paint to devices for civilian and military use, as well as the injection of radium solutions for what were then deemed therapeutic purposes. The painful lessons learned here provided, by analogy, some of the early indications of how bone-seeking fission products, such as $^{90}\text{Sr}$ (a major component of nuclear weapons fallout), and transuranic elements, such as plutonium, might behave in the human body—the physiological mechanism being isomorphous substitution of these radionuclides for calcium in skeletal hydroxyapatite. Indeed, this interest was the driver for systematic study of radium in humans during the 1950–1990 era at MIT, Argonne National Laboratory, and other radiobiology laboratories (Stebbings 1982; Rowland 1994). Radioecologist Nicole Martinez and co-workers (2022) have recently revisited the subject of internally deposited radium in an aptly termed “back to the future” paper, with the hope that there might be potential applicability to other scenarios, such as medicine and environmental contamination. At 125 years since discovery, the saga continues.

ABOUT THE AUTHOR

Edward Landa is a soil scientist and adjunct professor in the Department of Environmental Science and Technology at the University of Maryland-College Park, USA. His first experience with radium was in the summer of 1969, using a radium–beryllium neutron probe for in-situ measurement of soil moisture, as part of a tree growth study at The Charles Lathrop Pack Demonstration Forest, Warrensburg, New York, USA. A USGS Emeritus Scientist, Ed’s research has spanned both terrestrial and marine environments, focusing on biogeochemical processes that control the mobility of radionuclides from uranium mill tailings and other nuclear fuel cycle materials, as well as the fate and transport of metals and microplastics (tire wear particles). Ed was selected as the 2023 recipient of the Bernard L. Majewski Research Fellowship in the history of economic geology at the American Heritage Center of the University of Wyoming, USA.

ACKNOWLEDGMENTS

Because of its unique properties, occurrences and applications, interest in radium—125 years since its discovery—spans from historians of science and technology to practitioners of physics, chemistry, medicine, and public health, as well as multiple branches of the Earth sciences. It is a pleasure to recognize my colleagues within this community who have provided valuable dialogue and review comments: David Allard, Bert Coursey, Paul Frame, Stephan Heinitz, Joel Lubenau, Cameron Reed, Roger Robison, and Sam Walker.

REFERENCES


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### 2023


### 2024

**January 8–12** 3rd Rocky Worlds meeting, Zürich, Switzerland. Web page: zurich2024.rockyworlds.org/.


**February 21–23** Planet Characterization in the Solar System and the Galaxy Workshop, Houston, TX, USA, and virtual. Web page: www.hou.usra.edu/meetings/planetcharacterization2024/.

**March 17–21** American Chemical Society Spring Meeting, New Orleans, LA, USA. Web page: forthcoming.

**April 22–26** MRS Spring Meeting, Seattle, WA, USA. Web page: forthcoming.


**July 14–18** International Congress on Ceramics, Montreal, Quebec, Canada. Web page: ceramics.org/event/international-congress-on-ceramics/.

**July 28–August 1** Microscopy & Microanalysis 2024, Cleveland, OH, USA. Web page: forthcoming.


**August 12–14** Museums & Mineralogy 10, Cardiff, Wales. Web page: mm-10.org/.

**August 18–22** American Chemical Society Fall Meeting, Denver, CO, USA. Web page: forthcoming.


**August 18–25** 2024 Goldschmidt Conference, Chicago, IL, USA. Web page: forthcoming.

**August 20–24** European Crystallographic Meeting (ECM-24), Padova, Italy. Web page: https://www.ecm34.org.

**September 3–6** Granulites & Granulites 2024, Verbania, Italy. Web page: granulites2024.sfmc-itc.org/.

**September 16–20** 13th International Conference on Acid Rock Drainage (ICARD 2024), Halifax, NS, Canada. Web page: icard2024.cim.org/.


**November 9–11** New Mexico Mineral Symposium, Socorro, NM, USA. Web page: geoinfo.nmt.edu/museum/minsym/home.cfm/.


**December 1–6** MRS Fall Meeting, Boston, MA, USA. Web page: www.mrs.org/meetings-events/fall-meetings-exhibits/2024-mrs-fall-meeting.


**July 6–11** Goldschmidt Conference, Prague, Czech Republic. Web page: forthcoming.


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