Elements
An International Magazine of Mineralogy, Geochemistry, and Petrology

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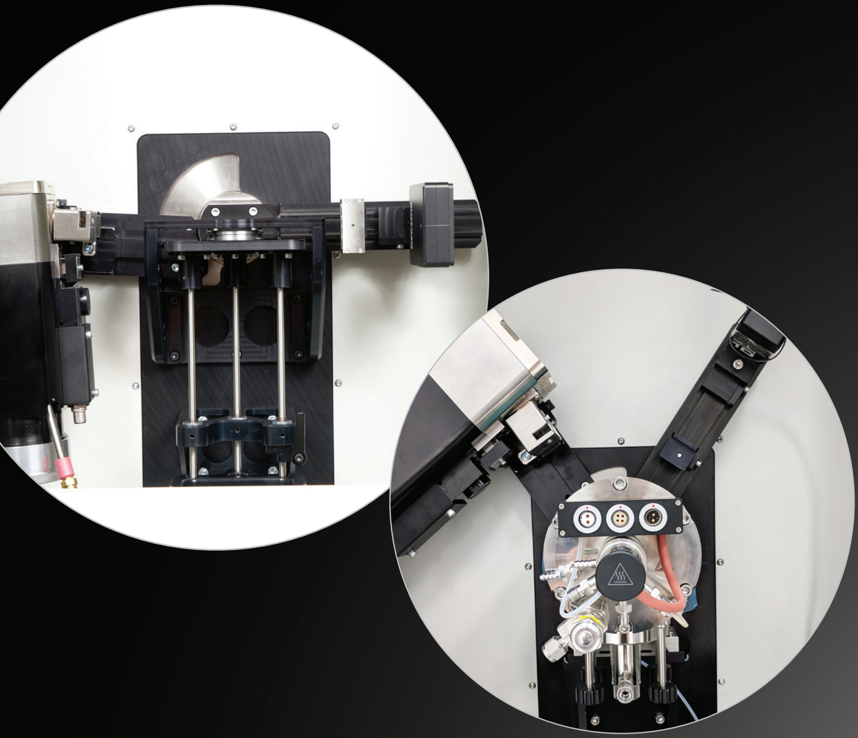
Deep-Ocean Mineral Deposits

PAUL A. J. LUSTY and BRAMLEY J. MURTON, Guest Editors

Metal Resources & Windows into the Earth
Hydrothermal Activity & Seafloor Massive Sulfides
Ferromanganese Crusts & Critical Metals
Metal Extraction from Ferromanganese Deposits
Ecological Risks of Mining
International Regulatory Challenges

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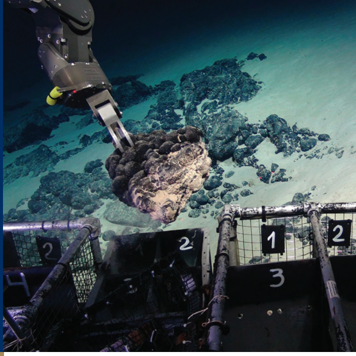

A sample of ferromanganese crust collected from the top of Tropic Seamount (northeast Atlantic Ocean) by the UK's remotely operated vehicle *Isis* during Marine E-tech cruise JC142 on the RRS *James Cook*. The 120 Ma seamount hosts abundant crusts from its top, at 1,000 m depth, to its bottom, at 4,000 m. *Isis* is operated by the National Oceanography Centre. ©UKRI 2018

Deep-Ocean Mineral Deposits

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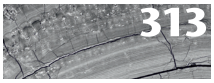

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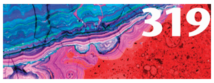

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DEPARTMENTS

Elements is published jointly by the Mineralogical Society of America, the Mineralogical Society of Great Britain and Ireland, the Mineralogical Association of Canada, the Geochemical Society, the Clay Minerals Society, the European Association of Geochemistry, the International Association of GeoChemistry, the Société Française de Minéralogie et de Cristallographie, the Association of Applied Geochemists, the Deutsche Mineralogische Gesellschaft, the Società Italiana di Mineralogia e Petrologia, the International Association of Geoanalysts, the Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), the Sociedad Española de Mineralogía, the Swiss Society of Mineralogy and Petrology, the Meteoritical Society, and the Japan Association of Mineralogical Sciences. It is provided as a benefit to members of these societies.

Elements is published six times a year. Individuals are encouraged to join any one of the participating societies to receive *Elements*. Institutional subscribers to any of the following journals—*American Mineralogist*, *Clay Minerals*, *Clays and Clay Minerals*, *Mineralogical Magazine*, and *The Canadian Mineralogist*—also receive one copy of *Elements* as part of their 2018 subscription. Institutional subscriptions are available for US$165 (US$180 non-US addresses) a year in 2018. Contact the executive editor (jrosso.elements@gmail.com) for information.

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The Mineralogical Society of America is for individuals interested in mineralogy, crystallography, petrology, and geochemistry. Founded in 1919, the Society promotes, through research, education, and publications, the understanding and application of mineralogy by industry, universities, government, and the public. Membership benefits include Elements magazine, access to the electronic version of the *American Mineralogist*, as well as discounts on journals, Reviews in Mineralogy & Geochemistry series, textbooks, monographs, reduced registration fees for meetings and short courses, and participation in a society that supports the many facets of mineralogy.

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The Mineralogical Society of Great Britain and Ireland is an international society for all those working in the mineral sciences. The society aims to advance the knowledge of the science of mineralogy and its application to other subjects, including crystallography, geochemistry, petrology, environmental science and economic geology. The society furthers its aims through scientific meetings and the publication of scientific journals, books and monographs. The society publishes *Mineralogical Magazine* and *Clay Minerals*. Students receive the first year of membership free of charge. All members receive *Elements*.

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The Mineralogical Association of Canada was incorporated in 1955 to promote and advance the knowledge of mineralogy and the related disciplines of crystallography, petrology, geochemistry, and economic geology. Any person engaged or interested in these fields may become a member of the Association. Membership benefits include a subscription to *Elements*, reduced cost for subscribing to *The Canadian Mineralogist*, a 20% discount on Topics in Mineral Sciences, formerly Short Course series volumes, and special publications, and a discount on the registration fee for annual meetings.

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The Clay Minerals Society (CMS) began as the Clay Minerals Committee of the US National Academy of Sciences – National Research Council in 1952. In 1962, the CMS was incorporated with the primary purpose of stimulating research and disseminating information relating to all aspects of clay science and technology. The CMS holds annual meetings, workshops, and field trips, and publishes *Clays and Clay Minerals* and the CMS Workshop Lectures series. Membership benefits include reduced registration fees to the annual meeting, discounts on the CMS Workshop Lectures, and *Elements*.

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The Geochemical Society (GS) is an international organization founded in 1955 for students and scientists involved in the practice, study, and teaching of geochemistry. Our programs include cohosting the annual Goldschmidt Conference^{TM}, editorial oversight of *Geochimica et Cosmochimica Acta* (*GCA*), supporting geochemical symposia through our Meeting Assistance Program, and supporting student development through our Student Travel Grant Program. GS annually recognizes excellence in geochemistry through its medals, lectures, and awards. Members receive a subscription to *Elements*, special member rates for *GCA* and *G-cubed*, and publication and conference discounts.

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Founded in 1985, the **European Association of Geochemistry** is a non-profit organization dedicated to promoting geochemistry internationally. The society is a dynamic association that organizes the Goldschmidt Conference® in Europe, publishes *Geochemical Perspectives* and *Geochemical Perspectives Letters*, recognizes scientific excellence through awards, supports Early Career Scientists, sponsors workshops and conferences in Europe, organizes Distinguished Lecture and Outreach Programs, publishes job opportunities, newsletters and blogs, and partners with other learned societies to strengthen geochemistry internationally.

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The International Association of GeoChemistry (IAGC) has been a preeminent international geochemical organization for over 40 years. Its principal objectives are to foster cooperation in the advancement of applied geochemistry by sponsoring specialist scientific symposia and the activities organized by its working groups and by supporting its journal, *Applied Geochemistry*. The administration and activities of IAGC are conducted by its council, comprising an Executive and ten ordinary members. Day-to-day administration is performed through the IAGC business office.

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The Société Française de Minéralogie et de Cristallographie, the French Mineralogy and Crystallography Society, was founded on March 21, 1878. The purpose of the society is to promote mineralogy and crystallography. Membership benefits include the *European Journal of Mineralogy*, *Elements*, and reduced registration fees for SFMC meetings.

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The Association of Applied Geochemists is an international organization founded in 1970 that specializes in the field of applied geochemistry. It aims to advance the science of geochemistry as it relates to exploration and the environment, further the common interests of exploration geochemists, facilitate the acquisition and distribution of scientific knowledge, promote the exchange of information, and encourage research and development. AAG membership includes the AAG journal, *Geochemistry: Exploration, Environment, Analysis*; the AAG newsletter, *EXPLORE*; and *Elements*.

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The Deutsche Mineralogische Gesellschaft (DMG; German Mineralogical Society) was founded in 1908 to "promote mineralogy and all its subdisciplines in teaching and research as well as the personal relationships among all members. Its great tradition in geoscience is reflected in the list of honorary fellows, which include M. v. Laue, G. v. Tschermak, P. Eskola, C.W. Correns, P. Ramdohr, and H. Strunz, to name a few. Today, the subdisciplines in the DMG are also bridging the gap with other communities such as materials science, solid state chemistry-physics, and environmental sciences. The society especially tries to support young researchers, e.g. to attend conferences and short courses. Membership benefits include the *European Journal of Mineralogy*, *Elements*, and *GMit*.

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The Società Italiana di Mineralogia e Petrologia (Italian Society of Mineralogy and Petrology), established in 1940, is the national body representing all researchers dealing with mineralogy, petrology, and related disciplines. Membership benefits include receiving the *European Journal of Mineralogy*, *Plinius*, and *Elements*, and a reduced registration fee for the annual meeting.

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The International Association of Geoanalysts is a worldwide organization supporting the professional interests of those involved in the analysis of geological and environmental materials. Activities include the management of proficiency-testing programmes for bulk-rock and micro-analytical methods, the production and certification of reference materials and the publication of the association's journal, *Geostandards and Geoanalytical Research*.

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The Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), founded in 1969, draws together professionals and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The society promotes links between mineralogical science and education and technology through annual conferences, field trips, invited lectures, and publishing. Membership benefits include subscriptions to *Mineralogia* and *Elements*.

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The Sociedad Española de Mineralogía (Spanish Mineralogical Society) was founded in 1975 to promote research in mineralogy, petrology, and geochemistry. The society organizes annual conferences and furthers the training of young researchers via seminars and special publications. The *SEM Bulletin* published scientific papers from 1978 to 2003, the year the Society joined the *European Journal of Mineralogy* and launched *Macla*, a new journal containing scientific news, abstracts, and reviews. Membership benefits include receiving the *European Journal of Mineralogy*, *Macla*, and *Elements*.

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The Swiss Society of Mineralogy and Petrology was founded in 1924 by professionals from academia and industry and amateurs to promote knowledge in the fields of mineralogy, petrology, and geochemistry and to disseminate it to the scientific and public communities. The society coorganizes the annual Swiss Geoscience Meeting and publishes the *Swiss Journal of Geosciences* jointly with the national geological and paleontological societies.

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The Meteoritical Society is an international organization founded in 1933 for scientists, collectors, and educators to advance the study of meteorites and other extraterrestrial materials and their parent asteroids, comets, and planets. Members receive our journal, *Meteoritics & Planetary Science*, reduced rates for *Geochimica et Cosmochimica Acta*, which we cosponsor, the *Meteoritical Bulletin*, and *Elements*. We organize annual meetings, workshops, and field trips, and support young planetary scientists worldwide. Through our medals and awards, we recognize excellence in meteoritics and allied fields.

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The Japan Association of Mineralogical Sciences (JAMS) was established in 2007 by merging the Mineralogical Society of Japan, founded in 1955, and the Japanese Association of Mineralogists, Petrologists, and Economic Geologists, established in 1928. JAMS covers the wide field of mineral sciences, geochemistry, and petrology. Membership benefits include receiving the *Journal of Mineralogical and Petrological Sciences* (*JMPS*), the *Ganseki-Koubutsu-Kagaku* (*GKK*), and *Elements*.

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Affiliated Societies

The International Mineralogical Association, the European Mineralogical Union, and the International Association for the Study of Clays are affiliated societies of *Elements*. The affiliated status is reserved for those organizations that serve as an "umbrella" for other groups in the fields of mineralogy, geochemistry, and petrology, but that do not themselves have a membership base.

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THE "PLASTICENE" EPOCH?

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Nancy Ross

This issue of *Elements* explores the fascinating realm of deep-ocean deposits that have the potential to provide society with many of the raw mineral resources required to meet the world's growing needs. While raw materials have always, and always will, play a critical role in meeting these demands, materials made by humans have also become increasingly important, expanding in concert along with the world's population, industry, and resource use. Most notably, plastics, which are synthetic organic polymers derived from fossil hydrocarbons, have become an indispensable part of our material world because of their remarkable number of uses and versatility. Plastic bottles, bags, credit cards, scotch tape, pipes, toys, to name a few, form part of our everyday life. Not surprisingly, the global production of plastic has increased from 2 metric tons (Mt) in 1950 to 380 Mt in 2015 (Geyer et al. 2017). By 2050, Geyer et al. (2017) estimate that roughly 12,000 Mt of plastic waste will be in the natural environment. This is a staggering amount, enough to cover the entire surface of the Earth in a thin layer of plastic! With the growing abundance of plastic, the potential for preservation in the rock record increases. What impact will synthetic materials like plastic have on future deposits in the Earth – will there be a "Plasticene Epoch"?

The fate of plastics over geological timescales is not well known. These organic polymers are relatively inert, insoluble in water, resistant to much biological decay and chemical attack, making their degradation, at least over decades, a slow process. Common forms of plastic, such as polypropylene (bottles) and polyethylene (bags), have densities less than 1 g/cm^3 so they float in water, while other forms, such as nylon (fishing nets) and PVC (pipes), have greater densities so they sink rather than float. Thus, the depositional environment is a critical factor for the preservation and incorporation of plastic in the rock cycle. Zalasiewicz et al. (2015) presented a comprehensive review of the presence of plastic in environments ranging from terrestrial, to lake and rivers, to near- and offshore marine settings. In all environments, they found evidence of macroscopic fragments of plastic (e.g. bottles, bags, etc.) and/or microscopic fragments (e.g. fibers and polyethylene microspheres). Remarkably, plastics are found in deep ocean sediments. The conditions of the deep ocean with colder temperatures and lack of ultraviolet light are especially favorable for their preservation, as are poorly oxygenated environments. In such settings, plastic material might remain preserved in sediments over geological timescales.

FIGURE 1 Plastiglomerate from Kamilo Beach (Hawaii, USA). PHOTO BY PATRICIA CORCORAN, UNIVERSITY OF WESTERN ONTARIO

One of the most fascinating examples of plastic preservation in the rock record was discovered on Kamilo Beach (Hawaii, USA). Corcoran et al. (2013) reported the appearance of a new rock, "plastiglomerate", formed in campfires that melted the plastic that had washed up on the beach. The resulting rock is a mixture of melted plastic, beach sediment, basaltic lava fragments, and organic debris (FIG. 1). The bulk densities of the clastic fragments range from 1.7 to 2.8 g/cm^3, which are much higher than clasts of pure plastic. Thus, plastiglomerate has greater potential to become buried and preserved in the rock record.

In conclusion, there is mounting evidence that plastics are becoming a significant component of the present-day rock cycle, their amount seems certian to grow, making the idea of a "Plasticene Epoch" not so far-fetched. Indeed, plastics are now so ubiquitous in the environment that they can be used as markers of the age and character of the sedimentary deposits that they were buried in. In other words, they are a key geological indicator of the "Plasticene Epoch", more correctly termed the Anthropocene, the epoch in which humans have come to dominate many surface processes (Crutzen and Stoermer 2000).

Over geological time, plastics may be preserved in rocks. Future geologists may identify the remains of plastic bottles as fossils even if the plastic itself has degraded or been replaced by other materials. The hydrocarbons released during diagenesis might contribute to future oil and gas deposits. Ultimately, rocks such as plastiglomerate may be subducted into the Earth forming interesting new metamorphic rocks that have unique compositions, properties and seismic signatures. And as plastic components have become essential components of spacecraft and placed on the surfaces of the Moon and Mars, the impact of plastic stretches far beyond Earth into space!

Nancy L. Ross, Principal Editor

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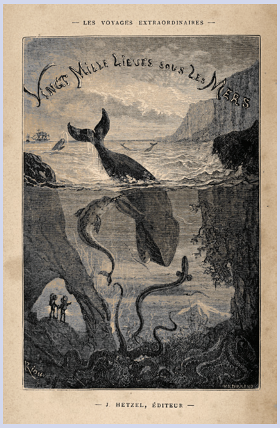
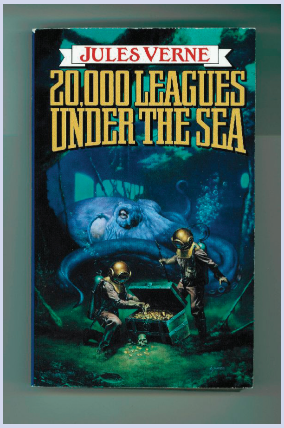
FROM THE EDITORS

ABOUT THIS ISSUE





The Voyages Extraordinaires (Extraordinary Voyages), written by the French author Jules Verne (1828–1905), is a sequence of 54 novels that have captivated the imagination of readers for more than 150 years. In the prologue of Verne's second novel, *Journeys and Adventures of Captain Hatteras*, Jules Hetzel, Verne's editor, wrote that the goal of Verne's Extraordinary Voyages was "to outline all the geographical, geological, physical, and astronomical knowledge amassed by modern science and to recount, in an entertaining and picturesque format ...the history of the universe." One of Verne's most popular works, originally published as a multipart series between March 1869 and June 1870, was *Vingt Mille Lieues Sous les Mers : Tour du Monde Sous-Marin* (*Twenty Thousand Leagues Under the Seas: A Tour of the Underwater World*). Verne allows the reader to experience the wonders of the deep-marine world though a "20,000" league (a metric league is approximately 4 km) journey through the Atlantic, Indian, Pacific and Southern Oceans on the *Nautilus*, a fictional submarine commanded by Captain Nemo.

Not long after Verne's undersea adventure was published, scientists conducted their own "tour of the underwater world" onboard the first global marine research vessel, the HMS *Challenger*. During this almost four-year-long expedition (1872–1876), the *Challenger* circumnavigated the globe, traveling over 127,000 km (or … "32,000" leagues). The six scientists and 243 crew members discovered over 4,700 new species of animals and plants, took 492 depth soundings (including the Mariana Trench and the Mid-Atlantic Ridge), and collected plant, animal and rock samples from 362 sample stations. It was during this expedition that scientists learned that polymetallic nodules (commonly known as manganese nodules and first discovered in 1868), were found to occur in most oceans of the world. It is these deposits, along with massive sulfide deposits, that are the focus of this issue of *Elements*.

We still know so little about the Earth's oceans. Yet, the oceans cover more than 70% of the Earth's surface and are essential for international commerce, transport, food, resources, and regulating Earth's temperature and weather. According to the U.S. National Oceanographic and Atmospheric Administration, more than 80% of this vast, underwater realm remains unmapped, unobserved, and unexplored. The difficulty and cost of exploring the ocean has limited our ability to learn more. Thankfully, there are governments and research organizations committed to exploring and studying our oceans. Many of the authors in this issue are part of marine research teams and have taken the time, between scientific cruises, to write about a small portion (seafloor and mineral resources) of this fascinating, yet mostly unexplored, realm. In case you are keen to learn even more about our oceans, the next issue of *Elements* will focus on another portion of the ocean: seawater.

2018 *ELEMENTS* EDITORIAL MEETING

The *Elements* editorial team held their annual meeting in Boston (Massachusetts, USA) on August 12. This is a highly productive time for the team when they can meet face-to-face for training, addressing editorial challenges, establishing editorial policies, and setting the publishing schedule.

One of the most important tasks during the editorial meeting is to discuss and evaluate submitted thematic proposals for possible inclusion into the *Elements* line-up. Prior to the meeting, we had received 13 proposals for our consideration. This was a difficult task for the editors as only four proposals could be accepted (April, June, August, October 2020 issues). The following topics will be brought to you in 2020:

***Elements* 2020 Thematic Topics**	
February	Abiotic Hydrogen and Hydrocarbons
April	Raman Spectroscopy in Earth and Planetary Sciences
June	Redox Engine of Earth
August	Lithium: Less is More
October	Archaeological Materials
December	To be determined March 2019

The editorial team welcomes the submission of proposals for our next editorial meeting in early March 2019. If you have a topic you would like to see in *Elements*, contact our editorial team and submit a proposal by February 2019.

FEEDBACK FROM *ELEMENTS* READERSHIP

In our August 2018 "From the Editors", we shared with you *Elements* Thomson Reuters 2017 Impact Factor. *Elements* publishes review articles that are being highly cited in the scientific literature. But, how do we measure the usefulness of the magazine beyond the citation rate? That was a question the editorial team posed during our editorial meeting in August. To begin answering that question, we had a "comment box" available at the *Elements* booth during the Goldschmidt2018 meeting. Attendees were welcomed to leave feedback (good or bad) about the magazine. Thanks to all of you who provided helpful and constructive feedback. Below is a sampling of some of the feedback we received:

> *"I love* Elements. *The articles are always of very high quality and appropriate to all kinds of audiences. I frequently use* Elements *in my teaching where my students (undergraduates) get in touch with state-of-the-art research in a variety of* Element's *fields."*
>
> *"I used* Elements *magazine to study for my PhD comps. The articles provide a useful review of the topic and are written in a readable and engaging manner."*
>
> *"I find* Elements *a very good journal to broaden students interests in Earth science. It is a good example of science communication in both text and illustrations."*
>
> *"I love* Elements*! It gets me to observe the multiple sides of the Earth Sciences. What I like the most is to receive hard copies, which I can comfortably read at home. I would not read electronic copies. Please keep going the way you are!"*
>
> *"A geoscience education column would be impactful for the community. Even if I'm not 100% interested in the issue topic, I always read the columns."*

We welcome your comments because they help keep *Elements* relevant and useful to our readership. You can always contact us using the Contact Form found at http://elementsmagazine.org/contact/

Friedhelm von Blanckenburg,
Nancy Ross, **Jon Blundy**, and **Jodi Rosso**

ERRATA

Suzanne M. Kay's biography and photo have been updated on page 223 of the August 2018 (Volume 14, Number 4) issue of *Elements*. Download from http://elementsmagazine.org/past-issues/central-andes/

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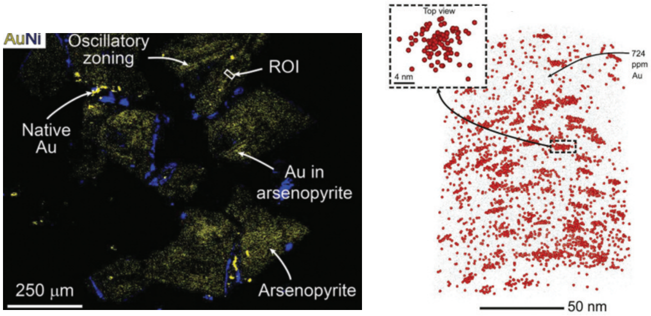

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Fougerouse, D.,et al., American Mineralogist, 101(8), 1916 (2016).

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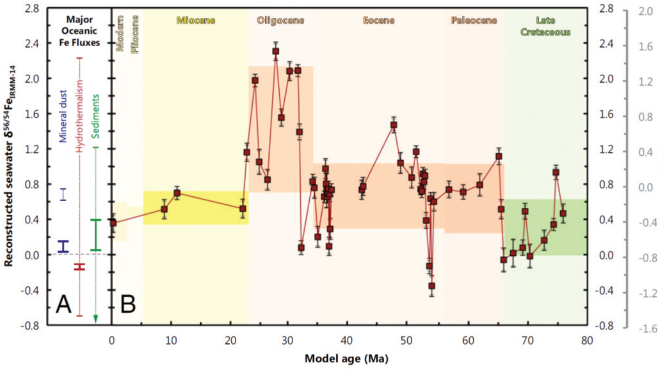

(A) Fe isotopic compositions of the major Fe fluxes in central Pacific seawater. (B) Fe isotopic history of central Pacific seawater recovered from CD29-2 spanning the past 76 Ma. Variations in $\Delta^{56/54}$Fe reveal multiple sources contributing to the total Fe budget of the region.

Horner et al. PNAS vol. 112-5 p. 1292–1297 (2015).

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Abbie S.A. Chapman is a PhD candidate at the National Oceanography Centre in the University of Southampton (UK) under the Southampton Partnership for Innovative Training of Future Investigators Researching the Environment (SPITFIRE) program. Her work comprises a trait-based approach to examine the biodiversity of hydrothermal vents, using characteristics affecting the fitness of species that might also influence key ecosystem processes. She also assesses the relative uniqueness of a species to a given vent community. Abbie holds an MSc in oceanography and has worked for Oil Spill Response Limited modelling oil spills for environmental impact assessments.

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James R. Hein received a PhD in Earth sciences from the University of California at Santa Cruz (USA) in 1973 and has been a marine geologist with the US Geological Survey (USGS) since 1974. In 1976, he began working on marine mineral deposits as a member of the Deep Ocean Mining and Environmental Studies (DOMES) team, studying Ni- and Cu-rich Fe–Mn nodules from the Clarion–Clipperton Fracture Zone of the Eastern Pacific Ocean. Since then, his research has expanded to include ferromanganese nodules and crusts, seafloor massive sulfides/sulfates, phosphorites, barite deposits, and potential land-based analogs of these deposits. He studies these from three perspectives: their potential as metal resources, their role in the geochemical balance of the oceans, and the paleoceanographic history recorded in ferromanganese crusts. He has participated in and led many oceanographic research cruises and currently runs the Marine Minerals Program at the USGS.

Daniel O.B. Jones is a principal scientist at the National Oceanography Centre in Southampton (UK). His work aims to understand both the natural and the anthropogenic changes in patterns and processes in marine ecosystems. He has authored over 80 scientific papers, primarily related to deep-sea ecology and environmental impact assessments. He has participated in over 30 industry and science research expeditions, including several that visited areas of deep-sea mining interest, such as the Clarion–Clipperton Zone and the Mid-Atlantic Ridge.

Pierre Josso obtained his engineering diploma in energy and mineral resources from UniLasalle (France) in 2013 and a PhD from the University of Southampton (UK) in 2017. His PhD was on the rare-earth elements resource potential of hydrothermal metalliferous sediments of the Troodos ophiolite (Cyprus). He is now a post-doctoral researcher at the British Geological Survey (UK), exploring the stratigraphy, structure and critical element concentration of deep-ocean ferromanganese crusts as part of the MarineE-Tech project, which itself is part of the UK's Natural Environment Research Council–funded Security of Supply of Mineral Resources programme.

Berit Lehrmann is based at the National Oceanography Centre in Southampton (UK). After completing her PhD in economic geology at the James Cook University of Townsville (Australia), she held a research position at the Federal Institute for Geosciences and Natural Resources (Germany). Her research is focused on understanding the formation and alteration of seafloor massive sulfides. She does this by using high-resolution petrography and micro-analytical methods.

Michael W. Lodge is Secretary-General of the International Seabed Authority where he has also served as Deputy to the Secretary-General and Legal Counsel prior to his election in 2016. He has served as Counsellor to the Round Table on Sustainable Development, OECD (2004–2007) and the Legal Counsel to the South Pacific Forum Fisheries Agency (1991–1995). With extensive knowledge of the United Nations and international organizations, he has facilitated high-level multilateral and bilateral negotiations at international and regional level. He has authored many books and articles, and given numerous keynote speeches and formal lectures on the law of the sea, seabed mining and high seas governance. He holds an LLB from the University of East Anglia (UK) and an MSc in marine policy from the London School of Economics and Political Science.

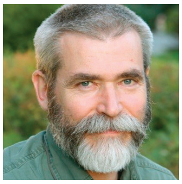
Paul A.J. Lusty is an economic geologist at the British Geological Survey (UK), where he leads the Ore Deposits and Commodities research team. He is a Chartered Geologist with many years of commercial and research experience in the minerals and hydrocarbons sectors. His research has evolved from land-based orogenic gold, to volcanic massive sulfide deposits, to modern seafloor hydrothermal systems, to understanding how extinct seafloor massive sulfide deposits might have been preserved. His most recent interests are in the formation of deep-ocean ferromanganese crusts and their potential as critical metal resources and in recovering by-product metals from enhanced geothermal systems. He was a member of the Royal Society's working group that published *Future Ocean Resources: Metal-rich Minerals and Genetics* (2017).

Bramley J. Murton is Associate Head of the Marine Geoscience Group and a professor at the National Oceanography Centre in Southampton (UK). For the past 25 years, he has been a research scientist investigating the construction of oceanic crust and its interaction with the ocean. During this time, he has been principal investigator on numerous national and internationally funded studies of mid-ocean ridges, hydrothermal activity, seafloor massive sulphides and ferromanganese crusts. Between 2010 and 2013 he led the international mid-ocean ridge research consortium InterRidge, and he now runs the seafloor minerals research team at the National Oceanography Centre.

Sven Petersen received his PhD from Freiberg University (Germany) in 2000 after spending a number of years in Germany and Canada working on seafloor hydrothermal systems. He remained in Freiberg until 2004 when he joined GEOMAR at the Helmholtz Centre for Ocean Research in Kiel (Germany). His research focuses on understanding the processes that form and change seafloor hydrothermal systems. He has participated in over 35 research cruises. The major aims of his research are to understand the chemical variability and resource potential of seafloor massive sulfide occurrences and to develop and use various technologies for their exploration and assessment.

Pawel K. Plucinski obtained his MSc in chemical engineering at the Wrocław University of Technology (Poland), from where he also gained his PhD. He moved to the Technical University of Munich (Germany) in 1986 and then to the Department of Chemical Engineering at the University of Bath (UK) in 1998. Pawel researches reaction kinetics in heterogeneous systems (liquid/liquid, gas/liquid, and gas/liquid/solid). Of particular interest are homogeneous and heterogeneous catalysis; the extraction of metals and biomolecules; the use of micelles, microemulsions, and soft interfaces for reactions and separations; and catalytic processes that involve compact multichannel reactors.

Philomène A. Verlaan is an oceanographer (biogeochemistry/ecology of oceanic ferromanganese deposits), an attorney-at-law (specializing in law of the sea, deep-sea mining, marine scientific research, marine environment), and a visiting colleague at the Department of Oceanography at the University of Hawai'i (USA). She advises on the Law of the Sea Convention, other marine treaties, and intergovernmental marine projects. She represents the Sargasso Sea Commission at the International Seabed Authority and the Advisory Committee on Protection of the Sea at the London Convention/Protocol. She has 50 publications and has been involved in 23 research cruises. She is a Fellow of the Institute for Marine Engineering, Science and Technology, and a member of the Florida Bar, the International Marine Minerals Society, the Marine Technology Society, the Oceanography Society, the Society for Underwater Technology, and the World Commission on Environmental Law.



Mikhail V. Zubkov is a sea-going, microbial ecologist whose research focuses on elucidating the roles and interactions of key bacteria and protists in ocean-wide ecosystems. These ecosystems range from the sunlit surface to the abyssal depths, including marine ferromanganese encrustations. His research career in the UK started in 1993, and, from 2002, he has been working at the National Oceanography Centre, Southampton (UK), where he is a professor of research. He is currently on a four-year sabbatical at the Scottish Association for Marine Science in Oban (Scotland). He has written over 120 peer-reviewed publications, including papers that have challenged and changed ecological thinking: for example, the planetary significance of the smallest plants that feed on bacteria and control biological CO_2 fixation in the ocean.

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DEEP-OCEAN MINERAL RESOURCES

John F. H. Thompson[1,2]

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The mysteries and promise of the deep ocean rose to attention on the heels of military interest and technology after World War 2. Despite accounting for 70% of the Earth's surface, almost nothing was known about the deep-ocean seafloor. That changed dramatically over the following 60–70 years, although our knowledge still remains patchy at best.

On land, exploration and discovery of mineral resources was led by prospectors and mining companies. Governments and researchers supported this process through mapping and via geophysical and geochemical surveys, which provided the basic data to guide exploration; only rarely did governments and academic researchers participate directly in land-based discoveries. By contrast, governments and researchers played a significant role in seafloor discoveries. Although polymetallic nodules were first discovered in the late 19th century, it was only from 1950 onwards that researchers discovered the Red Sea brines, black smokers, accumulations of massive sulfides, and polymetallic crusts. The nature of these discoveries attracted public, and eventually commercial, attention.

International expeditions led by Australian, Canadian, European, Japanese, US and other researchers developed new technologies and methods, including submersible equipment, to explore the deep ocean. This eventually led to ocean drilling expeditions that are ongoing to this day, a recent example being the drilling on Brothers Volcano in the southwest Pacific Ocean by the International Ocean Discovery Program. Research has increased our knowledge of numerous Earth and biological processes and our understanding of land-based analogues to these mineralizing systems, especially volcanogenic massive sulfide deposits.

With ocean research well established, several phases of resource exploration and evaluation on the seafloor followed. The first phase in the 1960s to 1980s was focused on polymetallic nodules in the Pacific Ocean and predominantly involved major mining companies. Although many technical issues were solved, declining metal prices and uncertainty over ownership eventually curtailed activity.

The second phase followed the numerous discoveries of hydrothermal systems and massive sulfides in the deep ocean during the 1990s and early 2000s, especially in the complex arcs and basins of the southwest Pacific. Declining metal prices post-2009 took a toll on this effort, although one company, Nautilus Minerals, continued to advance the Solwara deposit (in the seas off Papua New Guinea) through engineering, permitting, and ownership negotiations with the government of Papua New Guinea. Solwara is an extinct hydrothermal system that contains base- and precious-metal-rich massive sulfide; it is located in the Manus Basin within the national waters of Papua New Guinea, a country with an established mining framework.

The commodity boom that occurred during this second phase, also generated renewed interest in polymetallic nodules, particularly in the Clarion–Clipperton Zone of the eastern Pacific. Unlike the first phase, ownership issues were largely solved by the formation of the International Seabed Authority and the associated regulatory framework. This work involved nations, technology companies, and small resource companies, but major resource companies were largely absent.

Each phase of seafloor resource exploration faced four challenges: 1) the discovery and efficient assessment of resources; 2) the recovery of minerals from the deep ocean and how to process complex ore to produce metals; 3) the assessment of baseline environmental conditions and local biodiversity, including strategies to minimize and monitor mining-related disturbance; 4) the demonstration of economic viability, which had to be equivalent or better than conventional land-based mining and extractive processes.

John Thompson divides his time between Cornell University (New York, USA), where he is the Wold Professor of Environmental Balance for Human Sustainability, and Vancouver (British Columbia, Canada) where he acts as a consultant on exploration, mining, and sustainability. John has over 35 years in the mining industry and related research, and he has had diverse leadership roles in many organizations, including Resources for Future Generations 2018, Genome British Columbia, Society of Economic Geologists, Geoscience BC [British Columbia], Canada Mining Innovation Council, the World Economic Forum, and on the boards of several exploration and technology companies.

Increasing activity in the deep oceans has also attracted concern and attention. Mining's historical reputation, combined with heightened sensitivity to oceans, is a potent mix, something that is further exacerbated by our limited knowledge of roughly 90% of the deep oceans. Inauguration of the International Seabed Authority may help, although trust in government and international agencies is generally not high.

So, what does the future look like for deep-ocean mineral resources? Accepting the ongoing demand for metals and minerals to meet societal needs for water, sanitation, clean energy, transportation, and communication, what role will the seafloor play compared to conventional land-based mining?

There are advantages of deep-ocean resources: mining on the seafloor can be more selective than land-based mines; a ship-based plant that moves from deposit to deposit will be far more efficient than multiple land-based mines; there will be no mine workers facing safety issues; the lack of waste rock and tailings significantly decreases the potential for long-lasting acid drainage; and, the absence of (human) communities removes pressure on local water, agriculture, and culture.

Conversely, although working in the deep ocean is entirely feasible, developing an understanding of complex ores that contain multiple metals is challenging. Similarly, processing these complex and variable ores and finding the appropriate facilities on tidewater will not be easy. A further challenge will be to establish an environmental baseline dataset at an appropriate, but yet to be determined, scale.

Arguably the greatest challenge is that new seafloor sources of base, precious, and critical metals must compete in the market with established mining. For example, the major product in polymetallic nodules is manganese; but there are sufficient resources of this metal in land-based mines to last many decades. Similarly, the cyclic base-metal market and volatile prices of minor metals makes major investment decisions difficult for land-based mining, and such decisions will be even more challenging for new ventures in the deep ocean.

There is little doubt that the deep oceans contain major resources that could meet the needs of humans well into the future. An improved understanding of the deep-ocean environment will prepare us for more benign mining and extractive techniques and for better protection of the seafloor ecosystem. Based on our land-based experience, however, none of this will guarantee successful economic seafloor operations unless major efforts are made to explain and transparently document all of our work on the seafloor. Open and engaged collaboration between industry, governments, regulatory agencies (such as the International Seabed Authority), nongovernmental organizations, and researchers will be a vital prerequisite.

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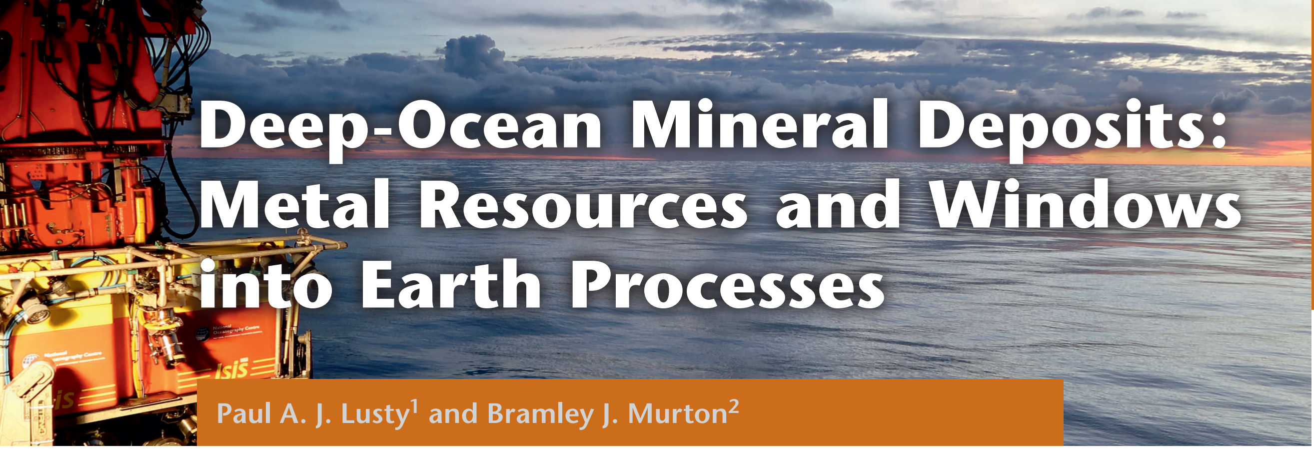

Deep-Ocean Mineral Deposits: Metal Resources and Windows into Earth Processes

Paul A. J. Lusty[1] and Bramley J. Murton[2]

1811-5209/18/0014-0301$2.50 DOI: 10.2138/gselements.14.5.301

Deep-ocean mineral deposits could make a significant contribution to future raw material supply. Growing metal demand and geopolitics are focussing increasing attention on their resource potential and economic importance. However, accurate assessment of the total amounts of metal and its recoverability are very difficult. Deep-ocean mineral deposits also provide valuable windows through which to study the Earth, including the evolution of seawater and insights into the exchange of heat and chemicals between the crust and the oceans. Exploration for, and potential extraction of, deep-ocean mineral deposits poses many geological, technical, environmental and economic challenges, as well as regulatory and philosophical questions. Great uncertainty exists, and the development and stewardship of these deposits requires an incremental approach, encouraging transparency and scientific and civil societal input to balance the interests of all.

Keywords: ocean floor, mineral deposits, ferromanganese nodules, Fe–Mn crusts, sulfides, metals, resources, International Seabed Authority

THE BLUE PLANET: EARTH'S FINAL FRONTIER

The Earth's oceans form a continuous body of saltwater covering more than two thirds of the planet and storing 97% of its water. With an average depth of about 3,700 m (Charette and Smith 2010), the oceans are widely considered to be Earth's final frontier. They control global climate and weather and have provided humanity with many resources for millennia. Extending away from land, the oceans are divisible into three main regions: the continental shelf, where water depths are generally less than 200 m; the continental slope; and the flat or gently sloping abyssal plain, typically occurring at depths greater than 4,000 m (Fig. 1). Although a poorly defined term, the 'deep' ocean may be considered to be seafloor below 200 m where, with little penetration of sunlight, photosynthesis is not possible. The deep seafloor covers about 60% of the Earth's surface and hosts a spectrum of geological settings, geomorphologic features and ecosystems. This diversity, and its long and dynamic history, results in the deep seafloor hosting mineral deposits that are both similar to those found on the continents as well as types unique to the oceans.

Despite its fundamental importance, due to its sheer size, we lack basic information about many aspects of the deep ocean. The challenges of sensing what lies below the water surface in an alien environment for humans, makes access difficult, costly and reliant on technology. After decades of ocean exploration, only about 10% of the ocean floor has been surveyed by ship-based sonar systems (Becker et al. 2009), and these provide only an average resolution of about 100 metres squared.

A Brief History of Deep-Ocean Mineral Exploration

Oceans have fascinated humans throughout history and the notion of deep-ocean mining goes back to at least 1870 when, in Jules Verne's classic book *20,000 Leagues under the Sea*, Captain Nemo announced that, "In the depths of the ocean, there are mines of zinc, iron, silver and gold that would be quite easy to exploit." Metal-rich nodules from the deep-ocean floor were described during the HMS *Challenger* expedition (1872–1876) and the potential economic importance of these nodules was acknowledged even at this time. In the 1960s, the oceanographer John L. Mero sparked considerable interest in these deposits when he estimated huge ferromanganese (Fe–Mn)-nodule resources in the Pacific Ocean and predicted an essentially endless supply of metals such as Mn, Cu, Ni, and Co (Mero 1965). The interest in Fe–Mn nodules prompted investigations during the 1980s and 1990s into similar Fe–Mn-rich crusts that can coat rocks on the seafloor.

Major deposits of metalliferous, sulfide-rich sediments were discovered beneath the Red Sea in the mid-1960s, at what is known as the Atlantis II Deep. Although volcanism was long considered a potential source of metals to the marine environment (e.g. Murray and Renard 1891), and seafloor hydrothermal activity had been postulated, direct, visual verification only came with the discovery of metal-bearing 'submarine thermal springs' or 'hydrothermal vents' on the seafloor of the Galapagos Rift in 1977 (Corliss 1979). Further hydrothermal vents and actively forming 'massive ore-grade' sulfide deposits, now known either as seafloor massive sulfide or polymetallic sulfide deposits, were subsequently observed on a mid-ocean ridge called the East Pacific Rise (Francheteau et al. 1979). Recognition that these were the modern analogues of the volcanogenic massive sulfide deposits preserved in ancient oceanic crust on land promoted a flurry of further exploration of the deep seafloor.

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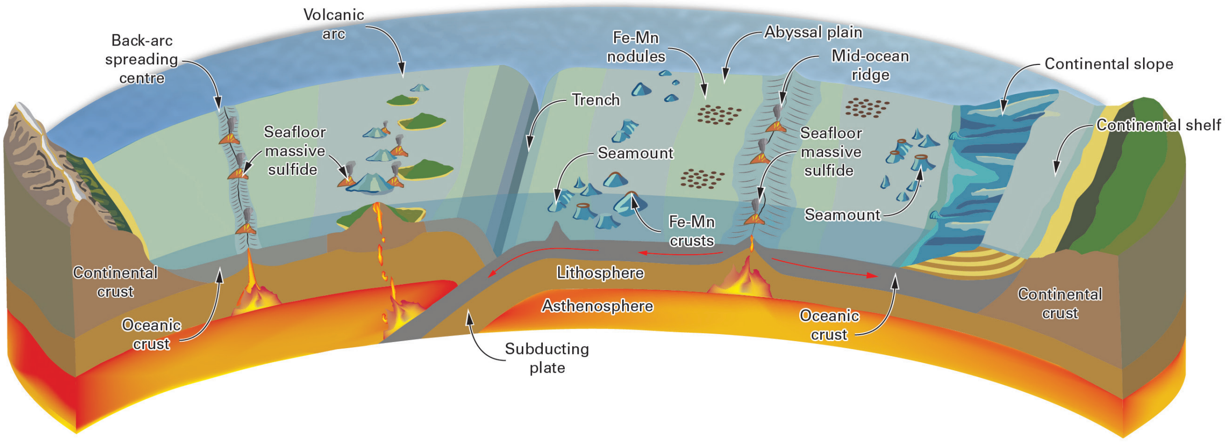

FIGURE 1 A cross-section through the Earth's crust showing the different types of plate boundary, the topography of the ocean floor and the distribution of the major metal-rich deep-ocean mineral deposits. IMAGE: IAN LONGHURST (COPYRIGHT BRITISH GEOLOGICAL SURVEY © UKRI 2018).

METALLOGENY OF THE DEEP OCEAN: AN EVOLVING PERSPECTIVE

A long-held view was that the ocean basins were relatively static features, in which particulate and dissolved matter that had been weathered from the continents accumulated over eons of time. This model adequately explained many near-shore marine mineral deposits that have been exploited for decades. The theory of plate tectonics and the concept of plate boundaries radically transformed this view (FIG. 1). We now understand the importance of magmatic processes on ocean-basin formation – including the flux of heat, fluid and chemicals between the mantle, crust and oceans. This, and the awareness of plate boundaries acting as loci for active mineralization (FIGS. 1, 2), has had a huge impact on our appreciation of the geological controls on mineral deposit formation and, hence, on the resource potential of the deep-ocean floor (Rona 2008).

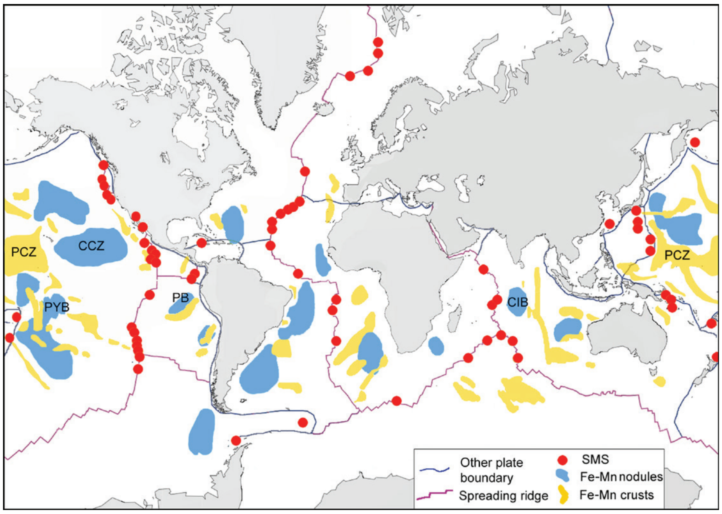

FIGURE 2 Global distribution of the three primary classes of metal-rich deep-ocean mineral deposits: seafloor massive sulfides (SMS); ferromanganese (Fe–Mn) nodules; and ferromanganese (Fe–Mn) crusts. Spreading ridges and other plate boundaries are shown. Abbreviations: CCZ = Clarion–Clipperton Zone; CIB = Central Indian Ocean Basin; PB = Peru Basin; PCZ = Prime Crust Zone; PYB = Penrhyn Basin. Map created using the NOAA National Geophysical Data Center and redrawn from multiple sources, including Murton et al. (2000), Beaulieu et al. (2013), and Hein et al. (2013). COPYRIGHT BRITISH GEOLOGICAL SURVEY, NATIONAL OCEANOGRAPHY CENTRE ©UKRI 2018.

Primary Classes of Deep-Ocean Mineral Deposits

Commercial interest, scientific research and regulatory activity is currently focused on three classes of metal-rich deep-ocean mineral deposits, each with distinct geology (i.e. processes of formation and metal tenors), environments of formation, associated ecosystems, specific technological requirements for exploration and extraction, and regulatory challenges.

Ferromanganese Nodules

Ferromanganese (or 'polymetallic') nodules are mineral concretions, composed of Fe oxyhydroxide and Mn oxide. They are variable in shape and size, typically 1–12 cm in maximum dimension. They are most abundant on the ocean's abyssal plains, at water depths of 4,000–6,500 m, where they lie on or immediately below the sediment-covered seafloor (FIGS. 1, 2, 3A). Here, Fe and Mn oxide colloids slowly precipitate around a hard nucleus (FIGS. 3B, 3C) over millions of years, from ambient seawater (hydrogenetic) and sediment pore waters (diagenetic). Nodule formation is favoured by a range of environmental factors, which are also used as a basis for defining prospective areas for seafloor exploration (FIG. 2). There are five main environmental factors for nodule formation: 1) slow sedimentation rates and bioturbation, which keeps the nodules close to the surface of the seafloor; 2) bottom currents that remove fine sediments and oxygenate the abyssal plain; 3) moderate levels of primary productivity in the surface waters that supply sediment-dwelling bacteria with sufficient organic matter for use in diagenetic reactions that release metals to the pore fluids; 4) semi-liquid sediments that enhance the amount of pore water and diagenetic input to nodule

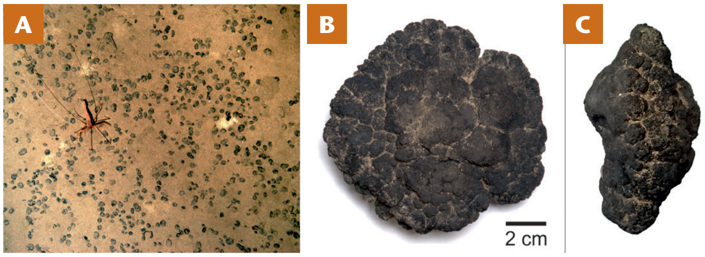

FIGURE 3 Ferromanganese nodules from the Clarion–Clipperton Zone (CCZ) in the Pacific Ocean. (**A**) Nodules on the sediment-covered abysall plain in the northeastern 'Area of Particular Environmental Interest' encountered on the RRS *James Cook* cruise JC120 using the autonomous underwater vehicle *Autosub6000*. (**B**) Upper surface of a large, 11 cm wide nodule. The rough botryoidal surface results from hydrogenetic growth. (**C**) Side view of the same nodule, showing the flattened shape and smoother base produced by diagenetic growth. COPYRIGHT BRITISH GEOLOGICAL SURVEY, NATIONAL OCEANOGRAPHY CENTRE ©UKRI 2018.

growth; and 5) location close to and below the calcite compensation depth (the depth at which calcite dissolves quicker than it can accumulate) (Hein and Koschinsky 2014). The physicochemical properties of the Fe and Mn colloids under oxic conditions make them excellent at scavenging dissolved metals from seawater. Through these processes, nodules are strongly enriched in Ni, Cu, Co, Mo, Zr, Li, Y and rare-earth elements (REEs) relative to the Earth's crust (Hein et al. 2013).

Ferromanganese Crusts

In contrast to Fe–Mn nodules, ferromanganese (Fe-Mn) crusts precipitate on hard surfaces in the ocean, where they are also termed 'cobalt crusts', 'cobalt-rich crusts' and 'manganese crusts' (Fig. 4). They are mineralogically similar to hydrogenetic Fe–Mn nodules and, until the late 1970s, little distinction was made between the two deposit types (Hein and Koschinsky 2014). Their similar physicochemical properties to nodules and their hydrogenetic mechanism of formation means that they also sequester large quantities of metals from ambient seawater. Genetic models for the formation of these deposits are reviewed by Lusty et al. (2018 this issue) who illustrate the importance of local-scale oceanographic processes on crust formation. In addition to their extreme metal enrichments, and therefore, mineral resource potential, they are also important because their stratigraphic layers preserve the isotope composition of seawater at the time of their deposition. This can provide a record of ocean and climatic evolution that might span thousands to tens of millions of years (Koschinsky and Hein 2017). Ferromanganese crusts also influence the concentration of some elements and their redox state in the marine environment (Hein and Koschinsky 2014). A novel example of their scientific application is the use of isotope stratigraphy to date Fe–Mn crusts that coat fossil whale bone: this technique can estimate the time since the whale carcass was deposited and provide temporal constraints on the evolution of the seafloor biotic communities that these carcasses support (Nozaki et al. 2017).

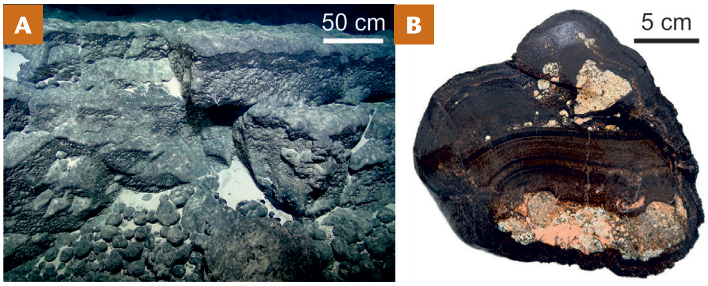

Figure 4 Ferromanganese crusts from Tropic Seamount in the northeast Atlantic Ocean encountered during the RSS *James Cook* cruise JC142. (**A**) Crusts on the flank of the seamount, photographed from the remotely operated vehicle (ROV) *Isis*. (**B**) Section through a crust sample that shows a complex history of development on fragments of phosphatized sedimentary substrate rock, collected using ROV *Isis*. Copyright British Geological Survey, National Oceanography Centre ©UKRI 2018.

Seafloor Massive Sulfides

Hydrothermal venting of metal-rich fluids is associated with magmatic activity, typically at the boundaries of tectonic plates. It occurs in all the oceans at depths down to 5,000 m (Beaulieu et al. 2013) (Figs. 1, 2). This phenomenon is one of the most spectacular examples of geology in action (Fig. 5A). The discovery of hydrothermal vents, including the dense, faunal communities that these sites support (discussed by Jones et al. 2018 this issue), is considered among the most remarkable scientific finds of the 20th century. Many scientists think this is where some of the earliest life on Earth may have originated (Dodd et al. 2017). Seafloor hydrothermal processes are estimated to circulate the entire volume of the global oceans through the oceanic crust over timescales of about 200,000 years (Johnson and Pruis 2003). The immense scale of this process means it plays a critical role in removing heat from the Earth's crust and controlling the metal budgets of seawater. The characteristics and importance of the related base- and precious metal-rich seafloor massive sulfide deposits (Figs. 5B, 5C) are explored by Petersen et al. (2018 this issue).

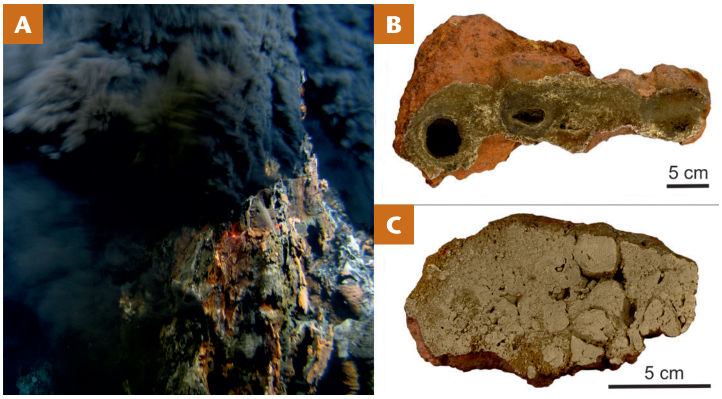

Figure 5 Submarine hydrothermal activity and seafloor massive sulfide (SMS) mineralization. (**A**) The top of vent chimney 'Balor', located at a depth of 3,000 m in the 'Moytirra Vent Field' at 45°N on the Mid-Atlantic Ridge, photographed from the remotely operated vehicle (ROV) *Holland* 1; courtesy of A. Wheeler, B. Murton and the VENTURE cruise participants, and the Marine Institute, Ireland. (**B**) Cut section of sulfide chimney from the Trans-Atlantic Geotraverse (TAG) area of the Mid-Atlantic Ridge. (**C**) Pyrite-rich SMS mineralization from the TAG Field. Samples shown in (B) and (C) were collected using the ROV *HyBis*, during *James Cook* cruise JC138. Copyright British Geological Survey, National Oceanography Centre ©UKRI 2018.

DEEP-OCEAN EXPLORATION AND MINING

Despite the major technological advances in nodule recovery and the successful pre–pilot mining and metallurgical testing at the Atlantis II Deep site (central Red Sea) during the 1970s and early 1980s when there was great optimism and a widely held belief that deep-ocean mining would commence by the late 20th century, subsequent progress has been slow and unsteady. This was due to adequate supply of metals from land-based mines; to unfavourable economic conditions, including rising energy costs and stable or declining metal prices; to technological challenges; to a growing environmental awareness; and to obligations arising from the United Nations Convention on the Law of the Sea (described by Lodge and Verlaan 2018 this issue). However, with many of these obstacles receding, there is renewed interest in the exploitation of deep-ocean mineral deposits from the private sector, governments, policy makers, regulators, researchers, and non-governmental organizations.

Drivers for Deep-Ocean Minerals Extraction: Why Now?

The mining industry is fond of saying, "If it can't be grown, it has to be mined." The Earth's crust provides almost all of society's minerals and metals, the vast majority of which are currently derived from mining on land. Global metal demand is increasing, primarily linked to population growth and urbanization, and there are concerns about the security of supply of raw materials due to uneven resource distribution and geopolitics. In recent years, certain metals have been designated as 'critical', primarily owing to their economic importance and likelihood of supply shortage.

These factors coupled with the increasing challenges of land-based mining (Calas 2017) are motivating the search for alternative sources of mineral raw materials. Whilst there are many land-based options that can contribute to future mineral supplies, for an industry that accepts significant risk and that has flourished by expanding into new and extreme environments, the deep ocean represents just another frontier.

Present Activity

No commercial-scale deep-ocean mining has yet taken place, but the following developments point to current significant global activity:

- As of February 2018, the International Seabed Authority (ISA) had approved 26 contracts for exploration on the international seabed. The role and activity of the ISA is described by Lodge and Verlaan (2018) in this issue.
- Mineral exploration is also occurring in seabed areas that fall within the jurisdiction of coastal states. For example, the Solwara 1 seafloor massive sulfide project in the Bismarck Sea of Papua New Guinea is at the forefront of the race to become the world's first commercial deep-ocean mine, having already been granted an environmental permit and seabed mining lease.
- There is an increase in government-funded research and resource evaluation programs in numerous countries, including Brazil, China, France, Germany, India, Japan, Korea and Russia. Relevant national legislation is also being updated, which is rapidly enabling a deep-ocean minerals industry, for example the UK Deep Sea Mining Act (2014).
- There is a proliferation of academic research, peer-review publications (e.g. Hein et al. 2013; Petersen et al. 2016) and both popular media and non-governmental organization coverage on the topic.

TECHNICAL CHALLENGES

Determining the Magnitude of the Resource: What We Do and Don't Know

Beyond the first-order assumption that deep-ocean mineral resources are likely to be proportionate to the area of the seafloor (Hannington et al. 2011), we know that specific geodynamic and oceanographic settings control the types of mineral deposits that form and that they influence deposit spatial density, size, form and geochemistry (Figs. 1, 2). Although current estimates of seafloor mineral resources contain significant uncertainties (e.g. Petersen et al. 2018 this issue), recent studies conclude that the deep seabed hosts large quantities of metals, sometimes exceeding land-based mineral 'reserves' i.e. resources that are currently economic to extract (Hein et al. 2013; Cathles 2015).

The composition of Fe–Mn nodules varies at regional to intra-nodule scales (Hein and Koschinsky 2014), but estimates suggest that they may represent one of the most abundant mineral resources on Earth. The metals of greatest economic interest in Fe–Mn nodules are Ni and Co and, to a lesser extent, Cu and Mn. The greatest known concentration of Ni and Cu-rich Fe–Mn nodules occur in the so-called Clarion–Clipperton Zone in the eastern equatorial Pacific Ocean where nodule density can reach a wet weight of 75 kg·m^2 of seabed (Hein and Koschinsky 2014; Petersen et al. 2016). Additional, important, occurrences are found in the Peru Basin off South America and in the Central Indian Ocean Basin. The most prospective area for cobalt-rich Fe–Mn nodules is the Penrhyn Basin, close to the Cook Islands in the South Pacific (Fig. 2). The Clarion–Clipperton Zone alone is predicted to contain 21 billion tonnes of nodules, hosting about 280 Mt of Ni (i.e. 3.5 times greater than the total land-based 'reserves'), 220 Mt of Cu, and 40 Mt of Co (i.e. 5.5 times the land-based 'reserves') (Hein and Koschinsky 2014). Although the Clarion–Clipperton Zone is approximately the size of Europe, it only represents a small proportion of the total seafloor that is currently considered prospective for Fe–Mn nodules, which exceeds 51 million km^2 (i.e. larger than the land area of Asia). There are still vast swathes of the ocean floor yet to be explored and whose mineral potential remains unknown (Petersen et al. 2016). Despite the remarkable concentration of some critical metals in Fe–Mn crusts, Lusty et al. (2018 this issue) urge caution over the reliability of existing resource estimates because of the sampling methods typically employed.

Technology-Driven Science: Drones and Robots

Without a step change in surveying technology, high-resolution mapping of the entire deep-ocean floor is not realistic. Yet, predicting and exploring the most prospective zones is surely a priority. Even this is fraught with uncertainty because current activity naturally focusses on the areas of highest perceived prospectivity based upon historical exploration and existing mineral-deposit models drawn from relatively restricted geographic areas. It can be argued that the deep ocean is so poorly explored that we may not currently even be targeting the optimum zones.

Deep-ocean mineral exploration employs a range of techniques that include ship-based swath sonar bathymetric mapping, geophysical surveying, and the use of autonomous underwater vehicles and remotely operated vehicles to carry a range of sensors (Fig. 6A). Developments in autonomous underwater vehicle technology, including increased autonomy, longer range, improved hovering capabilities and new geophysical and geochemical sensing tools, are key to more efficient seafloor mapping (Wynn et al. 2014). Increased use of swarms of autonomous underwater vehicles that can synchronously map parallel tracts of the seafloor is required. The efficient and rapid interrogation of the huge volume of new data generated will rely on developments in automated image analysis and artificial intelligence. Petersen et al. (2018 this issue) emphasize the importance of seafloor drilling for accurate resource evaluations (Fig. 6B). However, for this to become routine, the technology will have to become more efficient and reliable to reduce the cost of obtaining drill core.

Mining Technology Development and Economics

Technology readiness needs to be considered across the entire lifecycle of operations, from exploration and resource assessment through to mining (Fig. 6C), ore transport, environmental monitoring and management, mineral processing, and metal recovery (Fig. 7).

Ferromanganese crusts are the most technically challenging deep-ocean mineral deposits to recover because they are firmly attached to often steep and uneven rock surfaces (Fig. 4A). Test mining of Fe–Mn nodules and seafloor massive sulfides has already been undertaken. However, full-scale deep-ocean mining systems, including ship-to-ship ore transfer and equipment reliability in ~5,000 m water depths, still require field testing (Fig. 7). Deposit-specific, integrated field tests and pilot mining projects are required to prove the technical feasibility, to assess environmental impacts of mining and to help establish reliable financial and risk models. The costs involved may necessitate a consortium approach, like that successfully employed to reduce risk in the hydrocarbon sector. Another possibility

Figure 6 Deep-ocean exploration and mining equipment. (**A**) The UK marine research vessel RRS *Discovery* and an array of equipment, including autonomous underwater vehicles, used for surveying and monitoring the marine environment. (**B**) Deployment of the British Geological Survey remotely operated sub-sea rock drill (RD2) to acquire drill core from seafloor massive sulfide deposits on the Mid-Atlantic Ridge (RRS *James Cook* cruise JC138). Copyright British Geological Survey, National Oceanography Centre ©UKRI 2018. (**C**) Deep-sea mining machines manufactured by the UK-based engineering firm SMD (Soil Machine Dynamics Ltd) for Canada-based Nautilus Minerals Inc. Photo: SMD, www.smd.co.uk.

is that national strategic interests and the pursuit of stable supplies of raw materials, with government backing, could result in fast-tracked deep-ocean mining operations. For example, in 2017, Japan, a country heavily dependent on mineral imports, excavated seafloor massive sulfide ore and transported it to the surface in their waters off the coast of Okinawa. However, the long-term development of these resources will be principally based on economic criteria and their ability to compete with land-based mines.

Uncertainties at each stage of the deep-ocean mining value chain, coupled with the potential for future metal price volatility, limit confidence in the profitability of deep-ocean mining. However, the European Commission indicates that marine seabed mining activities could potentially contribute to sustainable economic growth. They estimate that by 2030 as much as 10% of the worlds minerals could be derived from the ocean floor (European Commission 2012). Preliminary assessments, based upon numerous assumptions, suggest that the mining of seafloor massive sulfide deposits and nodules could be economically competitive compared with mining some large, low-grade deposits on land (Cathles 2015). The International Seabed Authority consider that deep-ocean mining "appears to be feasible" under certain conditions, namely, deposits having high-grade ores, being proximal to land and occurring in relatively shallow water depths. However, very few sites are currently considered to have sufficient size and grade for potential future mining (International Seabed Authority 2002). The Solwara 1 seafloor massive sulfide deposit (off Papua New Guinea) is relatively small, with an inferred total mineral resource of ~1.4 million tonnes at a grade of ~8% Cu and ~6 g/t Au. By comparison, ancient volcanogenic massive sulfide deposits on land can contain resources of >150 million tonnes. However, Solwara 1 is one of only a few deep-ocean deposits with a mineral resource estimate that is compliant with international reporting standards. It is high-grade compared to many comparable land-based deposits, lies at a water depth of about 1,600 m, is about 50 km from land and is considered "potentially economically viable" to extract (AMC Consultants 2018).

Extracting ore from the seabed and transporting it to the surface or to land is only the first stage in recovering metals from deep-ocean mineral deposits (Fig. 7). Uncertainty also surrounds the processing of the mined ores and the number of metals that can be economically recovered. The potential for improving the efficiency and reducing the environmental impact of metal extraction from deep-ocean mineral deposits is explored by Zubkov et al. (2018 this issue).

ENVIRONMENTAL IMPACTS AND REGULATORY CHALLENGES

One of the greatest challenges facing the development of deep-ocean mining is gaining the social license to operate: the perception that the potential risks and environmental impacts are too great needs to be overcome. Addressing this will require education, engagement, transparency and, crucially, confidence in the governance framework. Jones et al. (2018 this issue) examine the environmental risks posed by deep-ocean mining, highlighting the need for a first-order understanding of many deep-sea ecosystems that may be affected. This fundamental knowledge is essential to inform development of an evidence-based, robust and socially acceptable regulatory framework for deep-ocean mineral extraction, a complex and emotive topic that is explored by Lodge and Verlaan (2018 this issue). These latter authors provide an overview of the role of the International Seabed Authority in deep-ocean mineral stewardship and the challenges faced in establishing a comprehensive and dynamic regulatory regime for these unique natural resources, which protects the interests of numerous stakeholders.

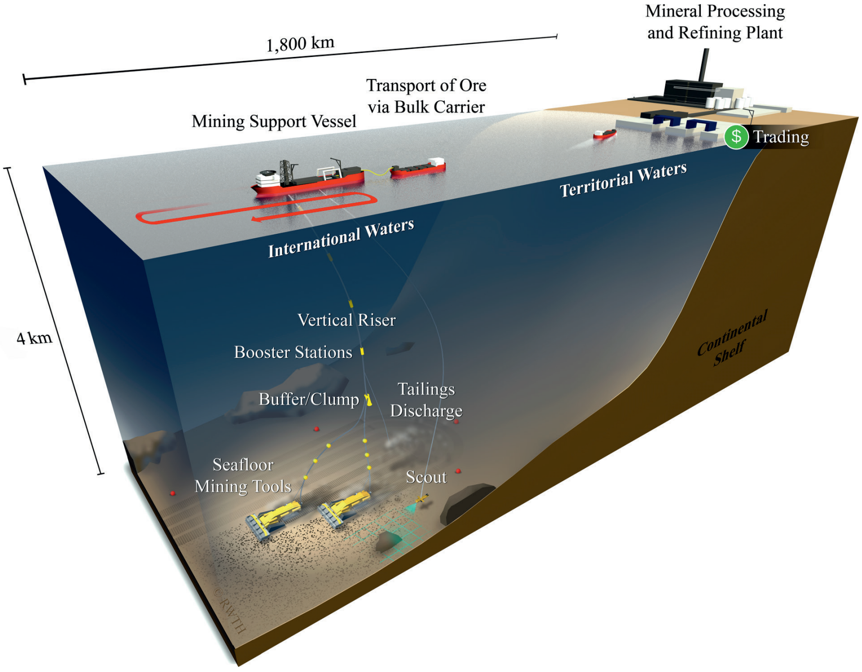

Figure 7 Concept for a deep-ocean ferromanganese nodule mining operation. Image: Volkmann and Lehnen (2017). Published with license by Taylor & Francis © 2017.

OUTLOOK

We have sufficient metal resources on land for decades to come. However, as demand grows, the combination of high base- and precious metal grades, and the extreme enrichment of some critical metals in deep-ocean mineral deposits, is likely to result in their eventual extraction. How quickly this happens is highly uncertain, as the development of deep-ocean mining will be influenced by a number of factors that are diverse, dynamic and often interrelated (spanning economics, geopolitics, technology, environment, regulation and societal acceptance).

Extracting these resources will present something of a societal conundrum. Mining will inevitably impact the natural environment, yet many of the metals that these resources contain are the very ones vital to technologies that are integral to society developing a low-carbon future, meeting global sustainable development goals and ensuring the long-term health of the planet. As discussed by Lodge and Verlaan (2018 this issue), automatic opposition to deep-ocean mining is not constructive when its overall environmental impact relative to land-based sources of these metals is uncertain. Currently, we lack the fundamental knowledge about the deep-ocean biosphere to make objective, evidence-based decisions on how best to regulate the sustainable and equitable extraction of these mineral deposits. Furthermore, deep-ocean mineral deposits can only be considered mineral 'resources' in the broadest sense, as whilst they have anticipated future value commercial-scale economic extraction of metals is largely unproven. It is now, therefore, time to prepare by increasing the rate of seafloor exploration and research to increase our confidence in resource assessments. By these means, we can then determine which resources are most accessible and can be mined with minimum environmental impact if required. The sheer scale of the task appears overwhelming: the exploration areas are typically intercontinental in scale, very remote and in water depths reaching several thousand metres. The key to advancing understanding, to improving the efficiency of exploration and to reducing costs will be international collaboration between different academic disciplines and industry, innovative technology and ensuring that data are openly available.

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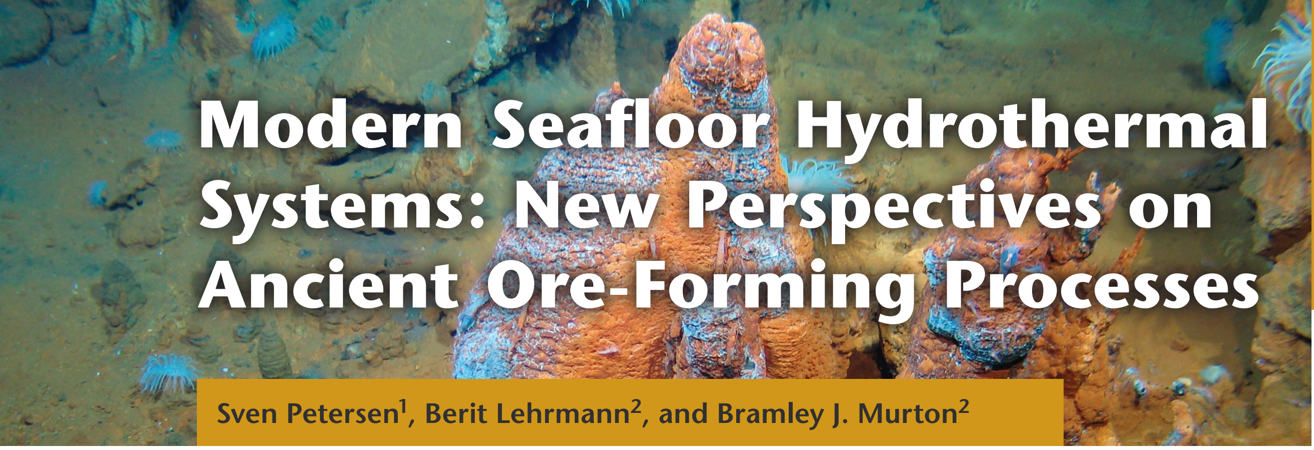

Modern Seafloor Hydrothermal Systems: New Perspectives on Ancient Ore-Forming Processes

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Seafloor massive sulfides are deposits of metal-bearing minerals that form on and below the seabed as a result of heated seawater interacting with oceanic crust. These occurrences are more variable than previously thought, and this variability is not necessarily reflected in the analogous volcanogenic massive sulfide deposits that are preserved in the ancient rock record. The geological differences affect both the geochemistry and the size of seafloor massive sulfide deposits. Current knowledge of the distribution, tonnage, and grade of seafloor massive sulfides is inadequate to rigorously assess their global resource potential due to the limitations in exploration and assessment technologies and to our current understanding of their 3-D characteristics.

Keywords: marine minerals, seafloor massive sulfides, exploration, drilling

INTRODUCTION

Modern seafloor massive sulfide deposits are widely considered as possible future metal resources, a view reflected by recent and increasing levels of exploration activity by governments and industry. This in itself is attracting concerned interest from the public. Seafloor massive sulfides form from processes that have shaped our ocean floor and planet over billions of years, as exemplified by the many deposits that once formed on the ancient ocean floor and that are now found on land as a consequence of continental collision and mountain building. Many of these so-called volcanogenic massive sulfide deposits have been mined for metals for thousands of years. In fact, volcanogenic massive sulfide deposits hosted in ancient and uplifted ocean crust on the island of Cyprus were some of the earliest deposits mined for copper. This was done on such a large scale by the ancient Phoenician civilization (fl. ~1000 B.C.) that the island of Cyprus actually derived its name from the Greek word for copper, *Kyprios*, which later became the Latin *Cyprium aes* ('Cyprian metal'), which later became *cuprum*.

It is now 40 years since modern seafloor hydrothermal systems were discovered in the Galapagos Rift and East Pacific Rise. Over those four decades we have begun to recognize the diversity and complexity of modern hydrothermal systems. As a consequence, we are starting to realize that our understanding of the more ancient massive sulfide deposits may be incomplete. The lack of understanding may be due to the long history of geological processes that have obscured the information related to their formation. Modern seafloor massive sulfides, therefore, provide the opportunity to study the ancient deposits without the subsequent overprint of deformation and metamorphism.

We know that seafloor massive sulfide deposits (also known as "black smoker" deposits) form as a consequence of seawater circulating into and out of hot oceanic crust deep beneath the seabed. This usually occurs at volcanically active tectonic plate margins that include mid-ocean spreading centers and volcanic arcs (Hannington et al. 2005) (Fig. 1). During this process, cold seawater penetrates through cracks in the seafloor to reach depths of several kilometers where it is heated to temperatures over 400 °C. The resulting chemical reactions generate a caustic fluid that is hot, slightly acidic, and chemically reduced. This fluid leaches the surrounding rocks and becomes strongly enriched in dissolved metals and sulfur. Due to its lower density, this superheated mineral-rich cocktail rises through the crust and emerges from the seafloor into the overlying water column through hydrothermal vents. These then form hydrothermal vent fields that are commonly associated with "oases of life", harboring exotic chemosynthetic faunal communities (Fisher et al. 2007). Unlike nearly all other forms of life on Earth, the animals living as hydrothermal vent communities derive their primary energy not from sunlight but from the hot (and nourishing) chemical soup that forms the vent fluid. Most of the metals dissolved in the ascending vent fluids precipitate when they mix with cold seawater, resulting in black- and white smoker chimneys and associated mounds of accumulated massive sulfide. Most of the metals carried by the rising vent fluids to the seafloor simply disperse into the overlying water column. Some of these metals precipitate as metalliferous sediments on the seafloor while the rest remain dissolved and are carried away by currents over tens to hundreds of kilometers into the deep ocean (Resing et al. 2015).

Metal-rich minerals that precipitate at the vents often form individual chimneys, ranging from a few centimeters to >40 m in height. Over time, these collapse and the resulting sulfide debris accumulates to form sulfide mounds built on top of the underlying seafloor. These mounds constitute the main mass and tonnage of seafloor massive sulfide deposits. Their growth is not restricted to chimney collapse but includes complex processes such as dissolution and replacement within and below the mounds, resulting in the formation of mixtures of sulfide and altered host rock known as stockworks. High-temperature hydrothermal

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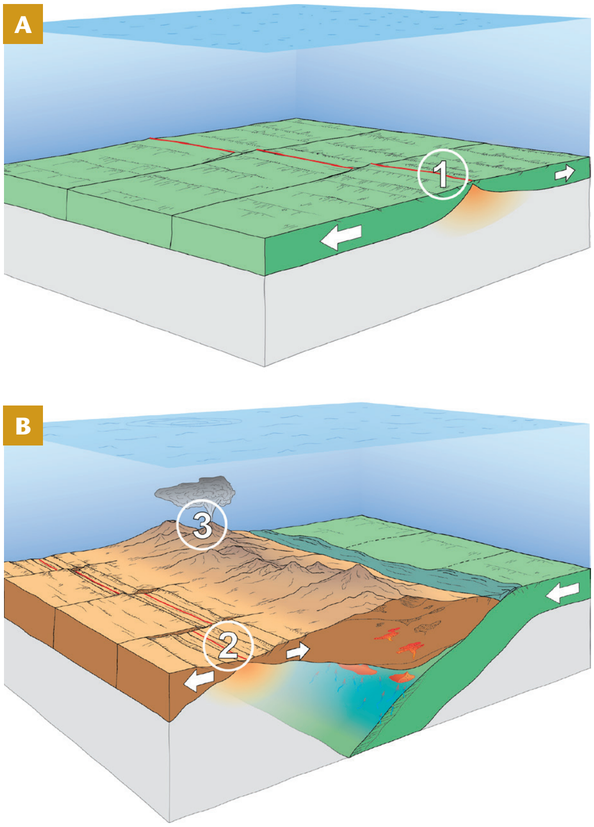

FIGURE 1 Block models of the major tectonic settings for modern seafloor hydrothermal activity. (**A**) Typical fast- to intermediate-spreading ridge where hydrothermal activity is located along the spreading axis (1 = mid-ocean ridge deposits). (**B**) Volcanic arc/back arc system with contributions of volatiles to the hydrothermal systems from the subducting slab as well as from magma chambers. (2 = back-arc basin deposits; 3 = arc volcanoes) IMAGE: M. KLISCHIES OF GEOMAR.

fluids may also dissolve early formed sulfides and reprecipitate them at the cooler outer margins of the deposit. Collapse and mass-wasting of the mound's flanks forms mineral-rich sediments that are often deposited over a kilometer or more away from the original deposit.

Over the years, variations of this simple deposit model have been described from the seafloor globally. However, some of the styles of active venting on the modern seafloor have not yet been identified in the ancient rock record on land. These include sites with pronounced contributions from magmatic volatiles and metals, those that result in seafloor lakes of liquid sulfur, and others that are characterized by venting of liquid carbon dioxide (de Ronde and Stucker 2015). In some cases, not finding ancient analogs could be related to their preservation potential. Biological processes on the seafloor may, for instance, consume native sulfur quickly, leaving no trace of it in the ancient rock record.

DISTRIBUTION OF ACTIVE AND INACTIVE VENT SITES

So far, about 380 sulfide-bearing or high-temperature hydrothermal sites have been found throughout the modern global ocean, indicating the widespread occurrence of this type of seafloor mineralization (FIG. 2). These are mainly active high-temperature hydrothermal vent fields that are restricted to the young and volcanically active parts of the ocean floor. About three quarters of the known deposits are hydrothermally active and only one quarter are inactive.

The bias towards hydrothermally active vent sites results from our current exploration technologies. These have been developed to find hydrothermally active sites by tracing their location from physical and chemical anomalies in the water column (Baker 2017). These anomaly indicators include particle-rich plumes, temperature anomalies, chemical signatures such as high concentrations of manganese and iron, changes in redox potential (Eh), and even gas bubbles. Traditional exploration methods involved laborious ship-based vertical profiling and sampling of the water column. Modern surveys now tend to use a variety of sensors mounted on autonomous (robotic) underwater vehicles (AUVs), which significantly speeds up the investigation (Connelly et al. 2012; Kawada and Kasaya 2017). The efficiency of this AUV approach has been demonstrated in the Okinawa Trough (off Japan) where AUV surveying over the past four years has doubled the number of known active vent sites from 11 (found between 1988 and 2013) to 23 in 2017. Recent estimates suggest that there are ~1,300 active high-temperature vent sites globally, of which about 1,000 remain to be found (Beaulieu et al. 2015).

Plume surveys are still the primary tool for exploring for active hydrothermal systems. However, they fail to locate older and hydrothermally extinct seafloor massive sulfide deposits (FIG. 3) due to their lack of distal water column signals. As a result, little is known about the occurrence and distribution of extinct seafloor massive sulfide deposits, including those that may be located far from zones of active venting or that might be buried by sediments or lava. These extinct seafloor massive sulfide deposits have been through the complete hydrothermal cycle and reached their maximum size, so are likely to be more abundant and larger than the hydrothermally active massive sulfide deposit sites that are still forming. As a result, extinct seafloor massive sulfide deposits are a current focus of global exploration for potential deep-sea mining sites (Petersen et al. 2016). In the past, extinct seafloor massive sulfide deposits have been detected by visual observation, and often by pure chance, in the vicinity of known active vents (Cherkashev et al. 2013). Even now, there have been few systematic regional surveys for extinct seafloor massive sulfide deposits and, as a result, only 27% of the known sulfide-bearing seafloor deposits are hydrothermally inactive. But there is compelling evidence that many more extinct seafloor massive sulfide deposits sites exist. In a recent survey at the Endeavour Segment of the Juan de Fuca Ridge, northeastern Pacific Ocean, AUV-based high-resolution bathymetry identified extinct sulfide chimneys and mounds. In only eight dives, each lasting 18 hours, the number of chimneys and mounds discovered was quadrupled (Jamieson et al. 2014). This is noteworthy because this vent field is considered to be one of the best studied submarine hydrothermal fields known, having seen well over 100 submersible and remotely operated vehicle (ROV) dives during the past 30 years. In a more recent study, an AUV-based survey in the Trans-Atlantic Geotraverse (TAG) area of the slow-spreading Mid-Atlantic Ridge indicated that about ten times more sulfide material is contained in extinct seafloor massive sulfide deposits than in the area's well-known active hydrothermal mound (Petersen et al. 2017). Taken together, these observations provide increasing evidence that extinct seafloor massive sulfide deposits are far more common than previously thought, and they almost certainly comprise the vast majority of the modern-day seafloor massive sulfide resource.

METAL CONCENTRATIONS

The resource potential of seafloor massive sulfides depends critically on their bulk chemical composition. The composition of the deposits is highly variable on a regional scale

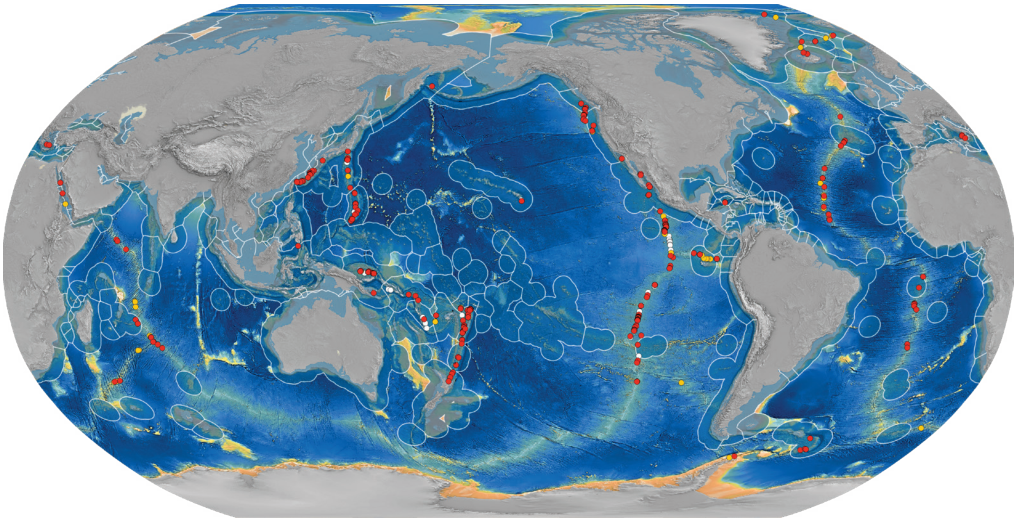

FIGURE 2 Global distribution of active (red) and inactive (yellow) seafloor massive sulfide sites. Sites where no detailed information on activity is given by white dots (N = 378). Exclusive economic zones are indicated as enclosed areas. IMAGE COURTESY OF GEOMAR.

(TABLE 1) and not all elements contained in the sulfides are of commercial interest (Hannington et al. 2005; Monecke et al. 2016). For example, compared with basalt-hosted deposits at mid-ocean ridges, seafloor massive sulfide deposits at back-arc basins and arc volcanoes often contain higher concentrations of copper and zinc, a feature that makes them economically attractive (TABLE 1). Gold and silver are also enriched in some deposits, especially back-arc basins, volcanic arcs, and ultramafic-hosted mid-ocean ridge systems, where concentrations of these precious metals can reach several tens of parts per million (ppm) for gold and hundreds of ppm for silver. Certain trace elements that are of growing importance for modern society (e.g. gallium, germanium, tellurium, selenium, indium) occur in concentrations of only a few tens of ppm, but can be significantly enriched in some occurrences (Monecke et al. 2016).

The bulk composition also varies greatly at the deposit scale, and even in hand-specimen. This is often a reflection of the temperature-controlled solubility of many metals. Copper-rich minerals (chalcopyrite and isocubanite) typically form high-temperature cores to chimneys and mounds (FIG. 4). The cooler outer parts of the deposits comprise minerals rich in iron (pyrrhotite, pyrite, marcasite) and zinc (sphalerite, wurtzite) together with various silicates and/or sulfates. These mineral assemblages are usually deposited at slightly lower temperatures due to the hydrothermal fluids starting to mix with seawater. As a result of this heterogeneity, black smoker chimneys are not representative of the bulk compositions of the deposits. There is further evidence that the chemical composition of the interior of sulfide mounds, as a whole, differs significantly from samples collected from the seafloor. Investigations from ancient deposits, as well as from modern seafloor sites where the interior of the sulfide mounds is exposed or has been accessed by drilling, indicate enrichments of copper, zinc, gold and silver are typical for grab samples taken from the surface of the mounds (Hannington et al. 2005). Published average chemical compositions of modern seafloor massive sulfides are usually based on such surface grab samples taken from high-temperature chimneys and, therefore, do not represent a reliable basis for resource estimation. This is largely a result of sampling having been driven by scientific research focused on understanding processes rather than an economic focus on resource potential. Suffice to say, the only viable economic assessment of a seafloor massive sulfide deposit has been for the Solwara 1 site off Papua New Guinea (Nautilus Minerals Inc.), which included more than 500 cores being drilled (Golder Associates 2012).

RESOURCE POTENTIAL

Estimates of the global resource potential of seafloor massive sulfides vary widely. Cathles (2011) argued that "the ocean floor is a giant volcanic massive sulfide district with metal resources more than 600 times the total known volcanogenic massive sulfide reserves on land and a copper resource which would last over 6,000 years at current production rates." In contrast, the amount of sulfide along the narrow neo-volcanic zone at ocean spreading centers, where new oceanic crust is produced, is estimated at 600 million tons globally (Hannington et al. 2011). This latter estimate was largely based on the known distribution of active hydrothermal vent sites at the time. The difference between the two estimates is huge and there is obviously a need to improve global resource estimates through a better understanding of the distribution and occurrence of hydrothermally inactive systems.

TABLE 1 THE MEAN METAL CONTENT OF SEAFLOOR MASSIVE SULFIDE OCCURRENCES WITH RESPECT TO THEIR TECTONIC SETTING. Note that the concentration of the trace metals gold and silver is given in parts per million (ppm). N = number of deposits for which there is chemical data. MOR = mid-ocean ridge. DATA FROM GEOMAR.

Setting	N	Cu wt%	Zn wt%	Pb wt%	Fe wt%	Au ppm	Ag ppm
Sediment-free MOR	60	4.2	8.2	0.2	26.0	1.2	92
Ultramafic-hosted MOR	12	13.2	7.1	<0.1	24.7	6.6	66
Sediment-hosted MOR	4	0.9	3.1	0.4	32.2	0.4	65
Intraoceanic back-arc	36	2.6	17.3	0.7	14.9	4.2	188
Transitional back-arcs	13	6.6	17.4	1.5	8.8	12.9	321
Intracontinental rifted arc	6	2.7	14.0	8.0	5.8	3.5	2,091
Volcanic arcs	17	3.9	8.9	1.8	11.0	10.0	204

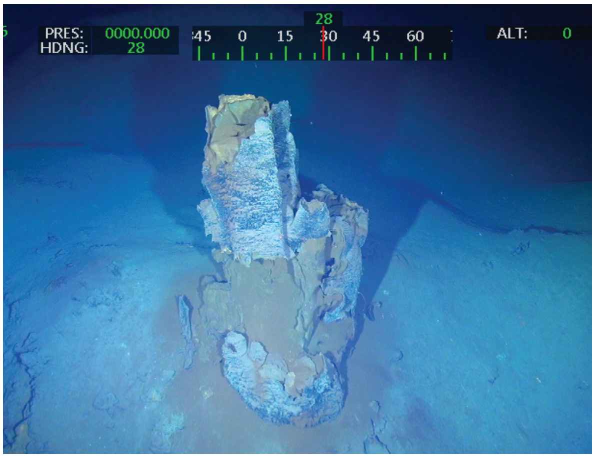

Figure 3 An inactive chimney topping an inactive mound in the Trans-Atlantic Geotraverse Hydrothermal Field (New Mound). Field of view approximately 3 m. Image: National Oceanography Centre.

Some of the uncertainty in resource estimates lies in the enormous range in size (tonnage) of many modern seafloor massive sulfides. These deposits are, of course, three-dimensional but with limited surface expression. Information from visual inspection of their surface morphology and from sampling indicates that they may reach a thickness of several tens of meters. However, most known sites have a diameter of less than a few tens of meters and, thus, contain only a small amount of sulfide material (a few thousand tons to 10,000 tons) (Hannington et al. 2011). Some occurrences on the global mid-ocean ridges, however, are known to contain between 100,000 tons and 1 million tons of massive sulfide. Very few are thought to be as large as 10 million tons. Hence, up until now, only a small number of known massive sulfide deposits are large enough to be considered as economically interesting. This contrasts with the size distribution of ancient deposits, which are generally much larger (Hannington 2014). The data for land-based deposits, however, is strongly biased towards large deposits because it includes only data for deposits that were large enough to be mined or to justify drilling. Many small sulfide occurrences are not included in resource data (Hannington et al. 2010). Additionally, current exploration technology on the modern seafloor is geared for detecting actively forming and commonly young deposits in the neovolcanic zone of mid-ocean ridges. Exploration in favorable geological settings, such as within sediment-filled basins, may show evidence for larger deposits on the modern seafloor.

It is probable that large and inactive (or extinct) sulfide deposits occur some tens to hundreds of kilometers away from a mid-ocean ridge axis, where they are now buried below a few tens of meters of sediment or lava. The potential to find such “off-axis” deposits opens up a vast area of the seafloor to future exploration. For example, extending the exploration effort to only 20 km on either side of the global spreading centers increases the prospective area to 3.2 million km^2 (Petersen et al. 2016). However, without a distal geochemical or geophysical signature that is detectable over hundreds to thousands of meters away from the deposit, and with only poorly constrained geophysical properties, such buried and inactive deposits will be difficult to locate and evaluate. The resource potential also depends on the fate of extinct seafloor massive sulfide deposits. The oldest dated sulfide deposits on the modern seafloor reach ages up to 220,000 years and are located along the Mid-Atlantic Ridge (Cherkashev et al. 2013). We do not know how long these massive sulfide deposits withstand seafloor weathering or if there are processes that protect them from oxidation. If not, they may fully oxidize, releasing their base metals back to the seawater.

Without a better understanding of their size, structure, distribution, and preservation, the global resource potential of inactive sulfide occurrences remains uncertain. Knowledge about the regional and local spatial controls of sulfide deposition are also still lacking. This is largely a reflection of the lack of high-resolution investigations away from spreading axes. Large inactive deposits have been discovered in the past few years, especially associated with major tectonic structures at slow-spreading ridges (German et al. 2016), and this opens the possibility that these off-axis deposits may be more common than we think. As a consequence of this potential, seven applications for exploration for seafloor massive sulfide deposits have been approved by the International Seabed Authority (located in Jamaica), the authority responsible for managing activities in the deep-sea beyond national jurisdiction. All of these exploration areas (10,000 km^2 each) lie along slow-spreading to intermediate-spreading ridges of the central Atlantic Ocean (for which there are three contracts) and of the central Indian Ocean (four contracts).

Our difficulty in exploring for off-axis extinct seafloor massive sulfide deposits is a reflection of our inability to identify and assess deposits buried beneath even a

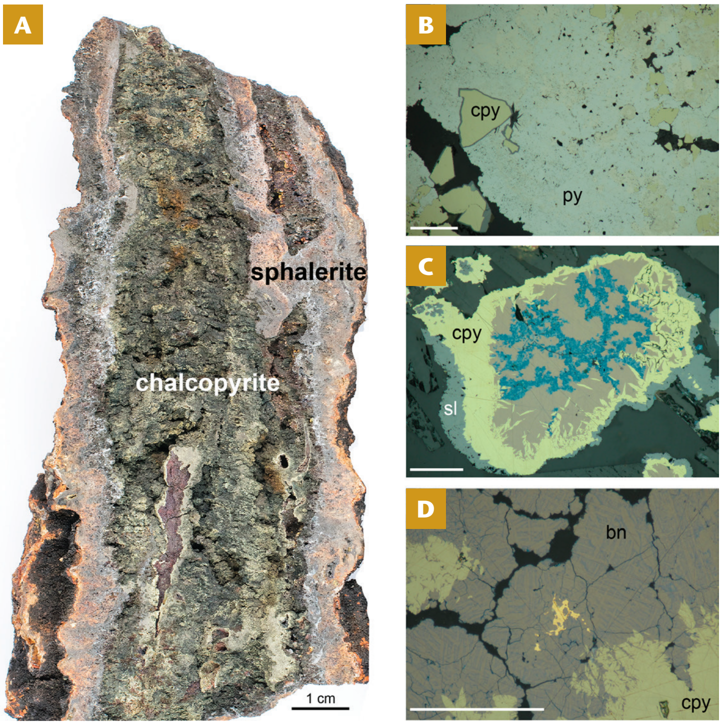

Figure 4 (**A**) Typical section through a black smoker vent showing the copper-rich interior dominated by chalcopyrite and a zinc-rich outer part with abundant sphalerite. Sample D1920-R12 collected during RV *Falkor* cruise FK160320 from the Niua South hydrothermal field in Tonga (**B**) Early chalcopyrite (cpy) is lined by grey sphalerite and overgrown by massive pyrite (py). Thin section photomicrograph of sample 53ROV-05 obtained from the Manus Basin during RV *Sonne* cruise SO216 in 2011. (**C**) Complex intergrowth of bornite (bn) overgrown by chalcopyrite (cpy) and sphalerite (sl). Bornite is oxidized to covellite (blue) along cracks. Thin section photomicrograph of sample 29ROV-16 obtained from the Manus Basin during RV *Sonne* cruise SO216 in 2011. (**D**) Native gold (bright yellow) intergrown with bornite (bn) and chalcopyrite (cpy). Scale bar in 4B, 4C, 4D is 100 µm. Thin section photomicrograph of sample 33GTV-1A obtained from the Manus Basin during RV *Sonne* cruise SO216 in 2011. Images: S. Petersen (GEOMAR).

few meters of sediment or lava. Yet there is hope. The sediments themselves may provide a far-field geochemical halo around inactive deposits at a scale comparable to that of plume mapping for black smoker vents in the water column. Although sediment geochemistry has been a standard tool in marine geology for over a century, there have been few modern advances to adapt this technique to the search for marine mineral resources (Cherkashev et al. 2013). This contrasts with the search for ore deposits on land, where exploration geochemistry has achieved a high degree of sophistication, including the application of ultrasensitive tracers such as mobile metal ions and pore-fluid gases to indicate subsurface deposits (Cohen et al. 2010). Depth profiles of metals in seafloor sediments can even be used to estimate the age of a source (based on sedimentation rates). But, as yet, there are few sensitive mineralogical, geochemical, or isotopic tracers that could be used as vectors towards metal deposits over lateral distances of 1–2 km or that lie buried at any depth below the seafloor.

THE THIRD DIMENSION

Because seafloor massive sulfide deposits are 3-D, and surface sampling is unlikely to be representative of the entire orebody, any resource estimate must incorporate depth information. As described above, tonnage calculations for most known seafloor deposits are based on surface estimates of the lateral extent of hydrothermal precipitates, morphology, and outcrop thickness. In many cases, these estimates are considered to overestimate their size and tonnage due to the incorporation of large areas that are thinly covered by hydrothermal material but that do not contain sulfides (Hannington et al. 2011). Drilling, the routine approach for mineral resource assessment on land, is currently the only technology that can provide reliable information on the subsurface composition of a mineral deposit. It has only been performed on a few seafloor massive sulfide deposits but has provided valuable insight into the interior composition.

Drilling by the Ocean Drilling Program in 1994 at the active Trans-Atlantic Geotraverse mound, which measures 200 m in diameter and 45 m in height, revealed a zoned deposit. Near-surface sulfide is enriched in copper, zinc, and gold, while lower-grades occupy the interior (Humphris et al. 1995). This further demonstrates how resource estimates might suffer from potential bias if only surfaces are sampled. Elsewhere, drilling seafloor massive sulfide sites covered with thick sediment accumulation, either close to land or near explosive volcanic activity, indicated the occurrence of subseafloor replacement of clastic sediment and infilling of pore space by sulfides. This is caused by the sediment retaining a high proportion of metals from the vent fluid rather than these metals being lost to the water column as a hydrothermal plume, which is the case at sediment-free mid-ocean ridges. This, and the impermeable nature of the sediment blanket that is focusing fluid flow upwards, may result in the formation of large deposits that are mainly subseafloor. Such a setting is exemplified by drilling of the sediment-filled Middle Valley segment of the Juan de Fuca Ridge (off the Pacific Northwest of North America). Here, drilling intersected 100 meters of massive sulfides at the Bent Hill Mound, as well as several large stacked lenses of massive sulfide buried within the sediment at the so-called ODP Mound (Zierenberg et al. 1998). A conservative estimate indicates nine million tons of sulfides are present in the Bent Hill deposit alone (Zierenberg et al. 1998).

The most comprehensive drilling of any seafloor massive sulfide deposit is the commercial drilling at the Solwara 1 deposit in the Bismarck Sea, close to Papua New Guinea's New Ireland Province. The drilling revealed a reserve of 2.5 million tons of massive sulfide (Golder Associates 2012) at a site that is planned to be the first operational commercial deep-sea mine. A few other seafloor massive sulfide deposits have been drilled by seafloor rigs and these have returned important information on the composition of the upper few meters of the deposits; however, this is insufficient for proper resource estimates (Petersen et al. 2016 and references therein). Whereas all these drill sites are in active hydrothermal systems, drilling of extinct deposits is required to better understand the fate of massive sulfides after hydrothermal activity has ceased and when mass wasting, as well as oxidation, has affected them.

It was, therefore, an important step when, in 2016, three inactive sulfide mounds located several kilometers away from the active Trans-Atlantic Geotraverse mound were drilled thanks to funding and support of the European Union's "Blue Mining" Project (Murton et al. 2017). All three sites show a similar distribution of rock types with depth that provides important information on the difference between active and inactive vent sites in this area. The extinct seafloor massive sulfide mounds are characterized by a superficial cover of pelagic calcareous sediment that overlies an unconsolidated layer of Fe-oxyhydroxides (Murton et al. 2017). These are then underlain by a coherent and dense layer of red-colored silica-rich "jasper", up to 5 meters thick, that overlays the massive sulfide. The association of thick iron–silica-rich strata overlying sulfides is well documented for ancient sulfide deposits preserved in the geological record on land, such as the "tetsusekiei" cherts from the Kuroko deposits in Japan and from hydrothermal cherts and the jaspers from the Iberian Pyrite Belt (Scott et al. 1983; Barriga and Fyfe 1988; Leistel et al. 1997). However, it has not previously been observed beneath the modern seafloor. These coherent "jasper" layers appear to be a common product, formed during the waning (cooling) stage of the hydrothermal cycle. As a result, they form an impermeable cap that protects the underlying massive sulfide ore body from oxygen-rich seawater and, thus, from subsequent dissolution. Hence, the "jasper cap" may play an important role in preserving sulfide deposits as a mineral resource once hydrothermal circulation ceases and the sulfide deposits are transported away from the ridge axes by seafloor spreading.

FUTURE EXPLORATION AND ASSESSMENT METHODOLOGY

The growing body of evidence to indicate the resource potential of extinct and off-axis seafloor massive sulfide deposits is a stimulus for the development of techniques to rapidly explore for them. Recent bathymetric mapping of 47 km^2 of the Trans-Atlantic Geotraverse Hydrothermal Field at a resolution of 2 m to 0.5 m by an AUV identified a number of inactive seafloor massive sulfide occurrences (Petersen et al. 2017). Such high-resolution AUV-based mapping of the seafloor, using coregistered acoustic backscatter imagery, magnetic-field, and self-potential data, seems to be the only way to survey larger areas of the seafloor fast, efficiently, and relatively cheaply. Yet despite covering 47 km^2 during a single cruise, this represents only a fraction of the 10,000 km^2 that a contractor to the International Seabed Authority is required to survey during the 15-year lifetime of the contract. Even if we only consider a 20 km corridor around a seafloor spreading axis, swarms of AUV working simultaneously might to be the only realistic option for achieving any sort of well-informed global resource estimate.

Once sulfide occurrences have been detected, information on their subseafloor extent needs to be acquired. Seafloor drilling is very expensive and difficult, but it is mandatory for reporting mineral resources and reserves to internationally recognized standards. Hence, there is an urgent need to develop geophysical tools to help us estimate the thickness of sulfide deposits prior to drilling. Electromagnetic and seismic methods have recently been tested at the Trans-Atlantic Geotraverse Hydrothermal Field and are starting to provide such information (Jegen et al. 2016; Gehrmann et al. 2017; Gil et al. 2017). Future technology development is also needed to distinguish low-grade sulfides and barren rock from valuable ore during the drilling process itself, which could reduce the drilling time (Spagnoli et al. 2017).

There is lots to do and no shortage of scientific and commercial opportunity!

ACKNOWLEDGMENTS

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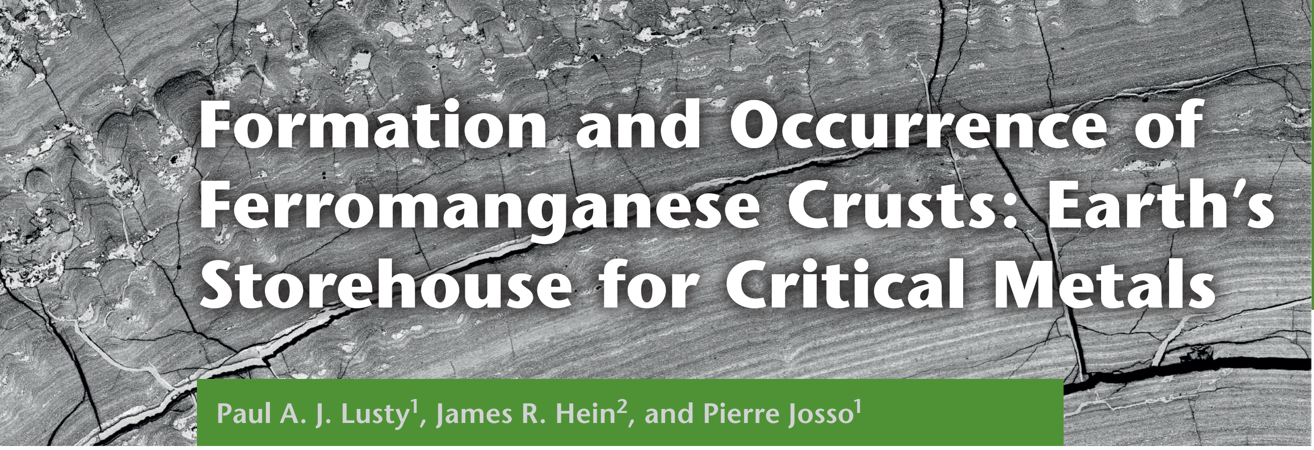

Formation and Occurrence of Ferromanganese Crusts: Earth's Storehouse for Critical Metals

Paul A. J. Lusty[1], James R. Hein[2], and Pierre Josso[1]

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Marine ferromanganese oxide crusts (Fe–Mn crusts) are potentially important metal resources formed on the seafloor by precipitation of dissolved and colloidal components from ambient seawater onto rocky surfaces. The unique properties and slow growth rates of the crusts promote adsorption of numerous elements from seawater: some, such as Te and Co, reach concentrations rarely encountered elsewhere in nature. Consequently, Fe–Mn crusts are potential sources of metals used in technologies considered essential for the transition to a low-carbon economy. However, the precise distributions and metal concentrations of Fe–Mn crusts at regional and local scales are poorly constrained because of the diversity of geological, oceanographic and chemical processes involved in their formation.

Keywords: ferromanganese, Fe–Mn crust, critical metal, resources, paleoceanography, seamount, cobalt, tellurium

INTRODUCTION

Iron and manganese oxide precipitates, commonly in the form of ferromanganese (Fe–Mn) crusts and nodules, are a ubiquitous feature of the deep ocean floor. Iron and manganese deposits form in a range of geological settings, and a continuum exists from hydrothermal to seawater-derived (hydrogenetic) end-members. Diagenetic processes operating within seafloor sediments result in chemically reducing conditions that liberate Mn and other elements to pore waters, which then diffuse upward and may reach the seafloor where they become available for oxidation and precipitation, forming Mn nodules. These local-scale processes and geochemical inputs result in deposits with distinct characteristics and compositions that influence their mineral resource potential. It is the hydrogenetic crusts and hydrogenetic–diagenetic nodules that are currently of greatest economic and scientific interest. The scientific value of Fe–Mn crusts, as archives of Earth processes, is introduced by Lusty and Murton (2018 this issue) and detailed by Koschinsky and Hein (2017).

FORMATION AND OCCURRENCE OF FERROMANGANESE CRUSTS

Generalized Model of Formation

Ferromanganese crusts are layered, metal-rich chemical deposits formed by accretion of colloids of hydrated Mn and Fe oxides onto virtually any indurated substrate in the deep ocean (Fig. 1). These crusts accrete at water depths between 400 m and 7,000 m (Hein and Koschinsky 2014), on sediment-free areas of ridges, seamounts (active or extinct undersea volcanoes), and plateaus in the global ocean. The crusts range in thickness from a patina to 250 mm thick pavements (Hein et al. 2000). Bathymetric features promote upwelling, causing turbulent mixing of water masses, which both help to sweep away sediments and enhance the interaction between deep oxygenated waters and nutrient-rich waters of the oxygen-minimum zone (the depth zone in which the oxygen saturation of the water column is at its lowest). Accumulation of Fe oxyhydroxides and Mn oxides occur at all water depths but may be enhanced if an oxygen-minimum zone is present, which acts as a reservoir for dissolved Mn and other metals (Fig. 2). Colloids of Fe and Mn oxides are highly reactive, having high specific surface areas (mean 325 m²/g) (Hein et al. 2000) and opposite surface charge (Fe weakly positive; Mn strongly negative), which make them effective at scavenging dissolved cations and anions via sorption driven by weak coulombic interaction. Subsequent oxidation at Mn and Fe oxide surfaces promotes enrichment and retention of redox-sensitive elements (e.g. Co, Ce, Pt, Te, Tl) (Koschinsky and Hein 2003).

Ferromanganese crust growth is one of the slowest natural processes on Earth, with average growth rates of 1–10 mm per million years. Slow growth combined with low bulk density (mean 1.3 g/cm^3 dry bulk) and high porosity (mean 60%) provides extensive opportunity for the sequestration of metals from seawater (Hein et al. 2000). These processes and properties mean that concentrations of many metals, most notably Pb, Co, Mn, some rare-earth elements, Te, and Pt, in crusts reach up to nine orders of magnitude above their concentrations in seawater (Hein and Koschinsky 2014).

Global Deposit Distribution

The general understanding of the geological and oceanographic processes controlling Fe–Mn crust formation and metal sequestration has been used to predict where crust deposits are likely to form (Hein et al. 2013). Seamounts, the most prospective environments for potentially exploitable deposits, are common seafloor features that vary in height from hundreds to thousands of metres above the seafloor. They are some of the largest volcanic structures on Earth (Sager et al. 2013). Satellite-derived gravity data

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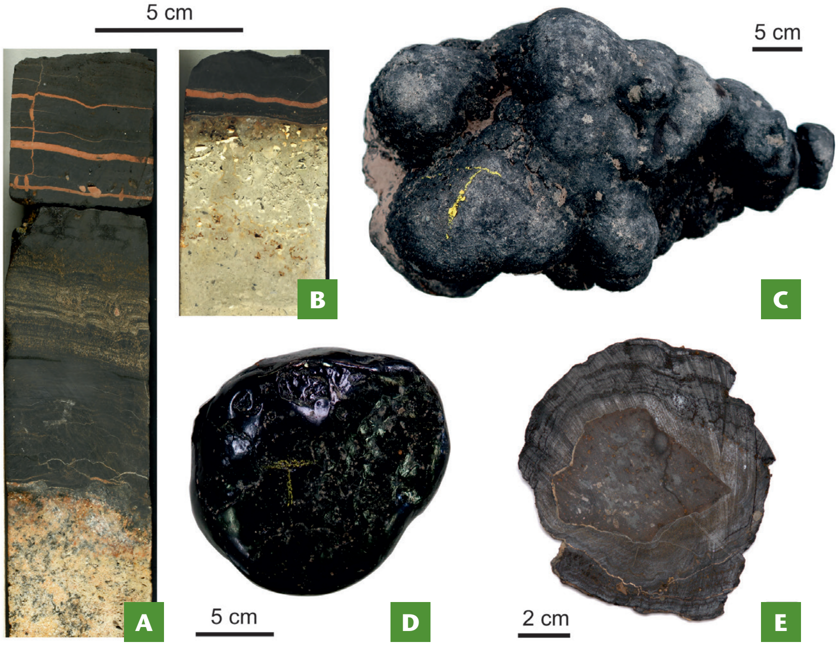

FIGURE 1 Samples of Fe–Mn crust taken from Tropic Seamount (Atlantic Ocean) during RRS *James Cook* cruise JC142, using remotely operated vehicle *Isis*. (**A**) Cut section of a drill core showing layers in a thick Fe–Mn crust and reddish-brown carbonate-rich laminae in the upper part of the deposit. (**B**) Cut section of a drill core showing a relatively thin layer of Fe–Mn crust. (**C**) Knobbly surface of a block of Fe–Mn crust collected at a water depth of 3,403 m. (**D**) Polished surface of a cobble coated in an Fe–Mn crust. (**E**) Cut cross-section of an Fe–Mn crust that grew around a basalt cobble. COPYRIGHT BRITISH GEOLOGICAL SURVEY ©UKRI 2018

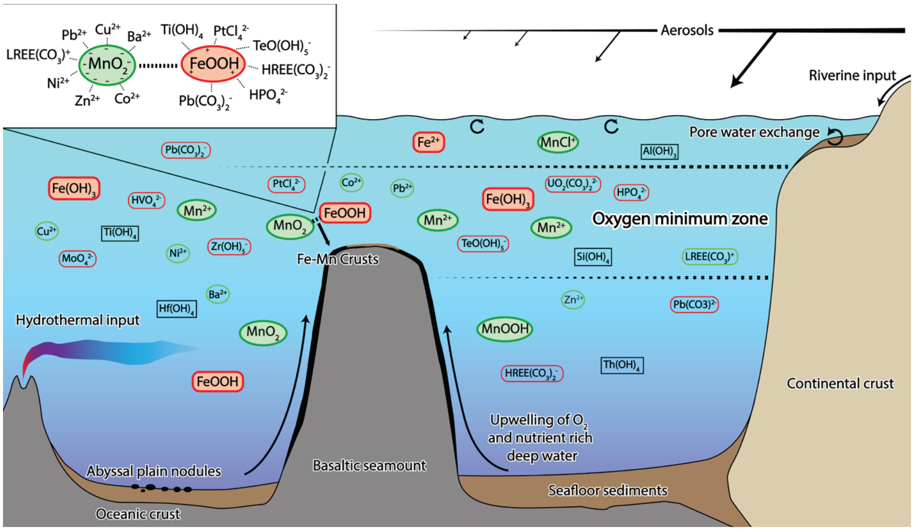

FIGURE 2 Genetic model showing the many sources that contribute to the seawater trace-element budget (e.g. aerosols, rivers, hydrothermal, sedimentary inputs). Formation of Fe–Mn crusts occur at all water depths but may be enhanced if an oxygen-minimum zone is present. INSET (TOP LEFT): A simplified electrochemical model for the sorption of trace elements on the charged surfaces of Fe oxyhydroxides and Mn oxides accumulating on hard substrates to form Fe–Mn crusts. MODIFIED FROM KOSCHINSKY AND HALBACH (1995) AND CONRAD ET AL. (2017).

predicts that thousands of seamounts occur worldwide, the vast majority of which remain uncharted (Wessel et al. 2010). Collectively they form one of the largest biomes on Earth, with upper estimates suggesting they cover an aggregated area larger than South America. The largest cluster of seamounts occurs in the central Pacific Ocean where flat-topped seamounts (termed 'guyots') have a mean surface area of about 3,400 km^2, with individual edifices reaching about 11,000 km^2 (Hein et al. 2009) – this is comparable to the land surface area of Jamaica.

It can take up to 70 million years to develop the thickest Fe–Mn crusts (Hein et al. 2000, 2009), and the most extensive resources, therefore, occur on the oldest edifices. The northwest equatorial Pacific Ocean has the oldest known oceanic lithosphere and the greatest number of large seamounts and, therefore, hosts the most abundant Fe–Mn crusts (Hein and Koschinsky 2014). The Prime Crust Zone in the central and western Equatorial Pacific is currently of greatest economic interest (Hein et al. 2009, 2013). The Fe–Mn crust potential of the Atlantic Ocean has been less thoroughly investigated than the Pacific Ocean, although Fe–Mn crusts are known to be widespread (e.g. Muiños et al. 2013; Halbach et al. 2017; Marino et al. 2017). The Fe–Mn crust potential of the polar oceans has also recently become apparent (Hein et al. 2017; Konstantinova et al. 2017) (FIG. 3).

ECONOMIC IMPORTANCE

Metal Concentration and Tonnage

The economic importance of Fe–Mn crusts was initially studied in the early 1980s (Halbach et al. 1982). Current interest arises from their polymetallic nature, high concentrations of critical metals (introduced by Lusty and Murton 2018 this issue), and huge estimated global metal resources (FIG. 3). Cobalt, a metal of low abundance in the continental crust, is classified as critical by the European Union. It is currently the metal of greatest economic importance in Fe–Mn crusts because of its abundance, relatively high-value and increasing demand, particularly for the manufacture of lithium-ion rechargeable batteries used in consumer electronic devices and electric vehicles. Significantly, Fe–Mn crusts contain Co contents of up to ~2.0 wt% and mean concentrations for large areas of the global ocean range from 0.30–0.67 wt% (Hein et al. 2000, 2013). Hein et al. (2013) reported mean Co concentrations of 0.66 wt% for Fe–Mn crusts from the Prime Crust Zone and estimated a total cobalt resource of 50 million tonnes for this area alone (FIG. 3). To put this in perspective, total terrestrial cobalt 'reserves' (resources that are currently economic to extract) are estimated to be 7.1 million tonnes (U.S. Geological Survey 2018). Deposits in the Central African Copperbelt, the greatest known terrestrial repository of cobalt, typically have Co concentrations in the range of 0.1–0.5 wt% (Cailteux et al. 2005). Aside from the huge tonnage of cobalt, Fe–Mn crusts effectively sequester certain metals that rarely attain economic concentrations in other geological environments. Tellurium, one of the scarcest elements in the Earth's crust (~1–5 ppb) (Belzile and Chen 2015) is of growing economic importance due to its use in thin-film, high-efficiency photovoltaic energy generation. It is enriched by a factor of 10^4 relative to the Earth's crustal mean, more than any other element in Fe–Mn crusts (Hein et al. 2003): maximum values in Fe–Mn crusts of ~200 ppm, and global average concentration of

~50 ppm. Ferromanganese crusts in the Prime Crust Zone are estimated to contain 450,000 tonnes of Te (Hein et al. 2013), far exceeding the total estimated land-based tellurium 'reserves' of 31,000 tonnes (U.S. Geological Survey 2018).

Resource Assessment and Mining

Estimates of the total amount of metal contained in Fe–Mn crusts globally are enormous (Hein et al. 2013) (Fig. 3). Their basin-scale geological and geomorphological exploration criteria are well established (Hein et al. 2000; Hein and Koschinsky 2014), and the key mine-site characteristics at a seamount-scale have been identified (e.g. surface area, slope angles, sediment cover) (Hein et al. 2009). However, a major challenge for resource assessment and mine-site delineation is that Fe–Mn crust thickness and composition varies significantly at regional and local scales (Hein and Koschinsky 2014). The processes affecting the distribution of Fe–Mn crusts on individual seamounts are also still poorly known (Hein et al. 2000). The International Seabed Authority's regulations on prospecting and exploration for Fe–Mn crusts allocate up to 3,000 km^2 for exploration and a maximum area of 1,000 km^2 will be approved for exploitation, and we suggest that about 500 km^2 will be required for a 20-year mine site. An area of this size, particularly if it extends across multiple seamounts, will inevitably incorporate variability in geomorphological, geological and oceanographic conditions, all of which could significantly affect Fe–Mn crust thickness and metal grade. Greater knowledge of the local-scale processes that create the optimum conditions for the formation of thick [a mean thickness of >40 mm is desirable for a mine site (Hein et al. 2009)] and high-grade Fe–Mn crusts is fundamental to developing improved seamount-scale exploration models. The fact that it takes tens of millions of years to accumulate thick Fe–Mn crusts means that understanding how paleoceanographic conditions have changed with time is essential.

HOLISTIC SEAMOUNT-SCALE GENETIC STUDIES

The Seamount Environment

Seamounts are complex and dynamic marine environments with interacting geological, biological, chemical and oceanographic controls that influence small-scale (metre to kilometre) variability in Fe–Mn crusts. Accordingly, high-resolution, integrated multidisciplinary studies on individual seamounts are the next essential stage in Fe–Mn crust exploration and resource assessment (e.g. Hein et al. 2000). Yet studies at this scale remain limited (e.g. Usui et al. 2017 undertook chemical analysis on 60 samples from a single seamount in the Pacific), leaving our knowledge of the detailed distribution of Fe–Mn crusts in most oceans unclear. For example, the resource potential of Fe–Mn crusts on ten Atlantic seamounts has been evaluated based on only 18 grab and dredge samples (Muiños et al. 2013).

To understand better the local-scale controls on Fe–Mn crust formation and composition requires a holistic study of oceanography, morphology, geology and tectonic history of the host edifice. This, in turn, requires autonomous underwater vehicles and remotely operated vehicles to enable methodical geological mapping, and a need for comprehensive and systematic sampling of Fe–Mn crusts across an entire edifice at all depths. Videography provides the essential spatial control and context necessary to interpret local-scale genetic controls on Fe–Mn crust distribution. Combined with hydrographic monitoring and numerical modelling, this type of integrated research can reveal the complexity and dynamism of seamount environments. Such studies are likely to change our understanding of Fe–Mn crust deposition and considerations for resource assessment.

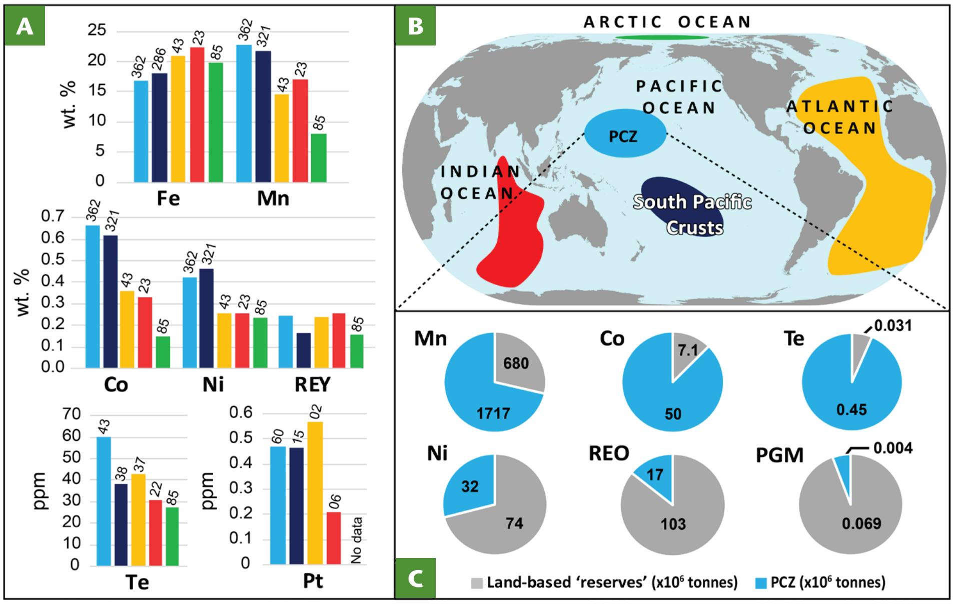

Figure 3 Metal grade, global resource distribution and estimated metal tonnages for Fe–Mn crusts and land-based 'reserves'. (**A**) Mean metal grade for Fe–Mn crusts from different oceans (for legend, see colours on 3B). The numbers at the end of each coloured bar indicate the quantity of samples on which the mean grade is based. With the exception of the Arctic Ocean, the number of samples is not shown for rare-earth elements and yttrium (REY) because the quantity of samples analysed varies between the different elements. Data from Hein et al. (2013) and Konstantinova et al. (2017). (**B**) Approximate distribution of the most extensive Fe–Mn crust deposits identified to date. PCZ = Prime Crust Zone; Created using ArcGIS. Copyright © Esri. All rights reserved (ESRI 2018). (**C**) Estimated in-place metal tonnages for Fe–Mn crusts in the PCZ compared to total land-based 'reserves'. PGM = platinum-group metals; REO = rare-earth oxide. Data from Hein et al. (2013) and U.S. Geological Survey (2018). Copyright British Geological Survey ©UKRI 2018

Tropic Seamount (Atlantic Ocean): A Case Study

Let us take the case of an isolated Cretaceous seamount, Tropic Seamount, located in the northeast tropical Atlantic Ocean (Marino et al. 2017). This 50 km wide, flat-topped seamount rises steeply over a distance of ~10 km from the flat abyssal plain at 4,400 m water depth to a relatively flat summit at about 1,000 m depth. A protracted geological history over ~120 My (van den Bogaard 2013), plus a distinctive morphology dominated by a flat plateau with a spur at each of the four corners and depths spanning several thousand metres (Fig. 4A), result in a diverse range of geomorphological environments, hydrographic regimes and varied ecosystems.

Crust Characteristics and Depth and Lateral Variability

In common with seamounts globally, the Fe–Mn crusts on Tropic Seamount have a variety of morphologies and surface expressions (Fig. 5). On the summit plateau and side terraces, Fe–Mn crusts typically form relatively flat

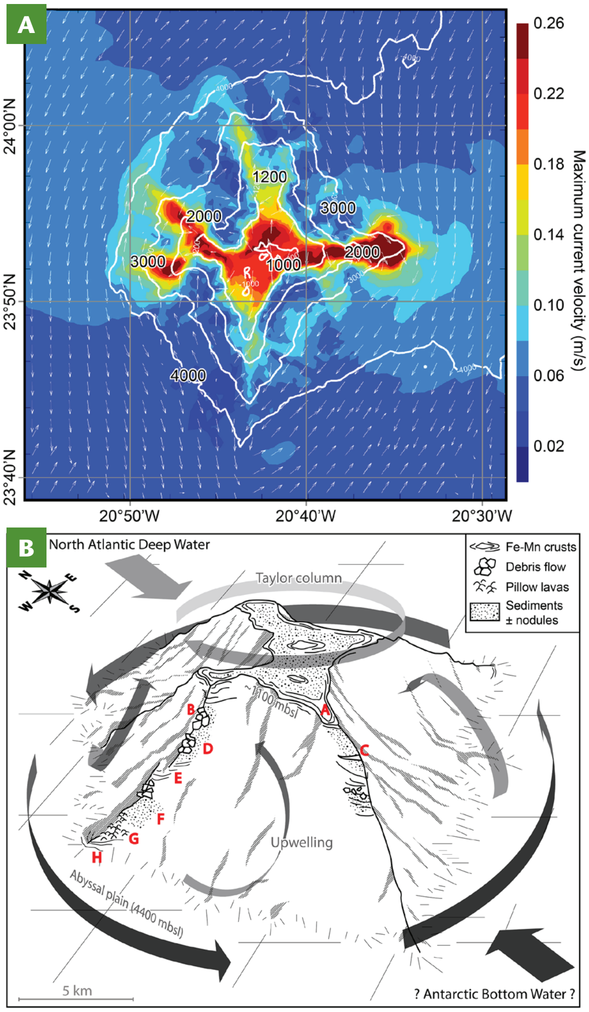

Figure 4 Tropic Seamount (Atlantic Ocean) illustrates the dynamism and heterogeneity of seamount environments. (**A**) Modelling of maximum current velocity 20 m above the seabed of Tropic Seamount over a five-tide period. Arrows indicate current direction, not intensity. The interplay among oceanic currents, internal tides and seamount topography results in areas of contrasting energy levels: stronger currents are on the summit and spurs. Image ©HR Wallingford www.hrwallingford.com. (**B**) Schematic diagram illustrating the range of environments encountered on Tropic Seamount based on remotely operated vehicle camera observations. The variation in Fe–Mn crust outcrop styles reflects topography, substrate diversity and varying sediment inputs as a function of the complex hydrographic regime. Swirling upwards currents form a weak Taylor column. Red letters A–H refer to the outcrop images illustrated in Figure 5. Copyright British Geological Survey ©UKRI 2018

pavements extending over several hundreds of metres with channels, depressions and pot holes filled by sediment (Fig. 5A). The Fe–Mn crusts locally have a knobbly or botryoidal surface (Figs. 1C, 5D), and where sediment obscures the complete crust, it deceptively gives the appearance of discrete, sub-rounded, partially buried nodules. Botryoidal surfaces are interpreted to reflect directed growth that is controlled by the accumulation of debris in irregular surface depressions that, under persistent conditions, develop into columnar textures (Hein et al. 2000). In common with other seamounts, discrete, typically sub-rounded to tabular Fe–Mn nodules, up to 20 cm in diameter, are also abundant on Tropic Seamount (Figs. 1D, 1E, 5F). In contrast to abyssal plain–type nodules (discussed by Lusty and Murton 2018 this issue), these seamount nodules are Fe–Mn-encrusted rock pebbles and cobbles (e.g. Hein et al. 2000). Their concentric layering (Fig. 1E) suggests that they grew from multiple directions, either as a result of frequent rotation during high-energy events or from growth in seawater and sediment pore waters of the same composition.

On the summit of Tropic Seamount, the Fe–Mn crust pavements are frequently undercut by currents exposing a softer substrate (Fig. 5A) and permitting the crusts to grow in multiple directions. This, and the polished rock surfaces and sub-rounded cobbles, indicate mechanical abrasion by detritus-laden bottom currents (Figs 1D, 5G) and are testament to local high-energy, erosive forces that influence Fe–Mn crust morphology and development.

Existing models based on seamounts in the Prime Crust Zone in the Pacific predict that the thickest Fe–Mn crusts occur around the summit terrace area at water depths of 1,500–2,000 m (e.g. Hein et al. 2000). At Tropic Seamount, Fe–Mn crusts of varying thickness (mm to >140 mm) and morphology occur over the entire depth range of the seamount (Figs. 1A, 1B, 4B, 5) with no obvious correlation with water depth or the oxygen-minimum zone: in the northeast Atlantic Ocean, the oxygen-minimum zone is typically between 800 m and 1,200 m (Muiños et al. 2013). In fact, substantial Fe–Mn crust pavements are encountered at depths of >3,500 m (Fig. 5H). This is consistent with the findings of Usui et al. (2017), who mapped thick Fe–Mn crusts over a wide range of water depths on a northwest Pacific Ocean seamount. More than 360 precisely located rock samples were collected during RRS *James Cook* cruise JC142 to Tropic Seamount. The samples contain an average of about 0.54 wt% Co, 82 ppm Te and 0.27 ppm Pt, which compares favourably with metal grades reported for other ocean basins (Fig. 3A).

Our understanding of the controls on small-scale lateral variation in Fe–Mn crust thickness and grade, and the extent of stratigraphic continuity, also remain rudimentary. Compositional boundaries and growth hiatuses (Fig. 1A) are common features in Fe–Mn crusts and may result from changes in the vertical extent and intensity of the oxygen-minimum zone, seawater chemistry, diagenetic processes, dissolution and mechanical erosion. The relationships among these processes and Fe–Mn crust formation and modification have direct implications for paleoceanographic interpretation and resource assessment (Koschinsky and Hein 2017). Unique, remotely operated vehicle–based core-drilling (Figs 1A, 1B) conducted at Tropic Seamount provides the essential spatial and temporal control necessary to study lateral variations in Fe–Mn crusts at the centimetre to metre scale, and, when combined with high-resolution textural, geochemical and isotopic studies, also provides new insights into the localized stratigraphic continuity and growth rates of these deposits.

Influence of Oceanic Regime

Ocean currents interact with seamounts to create their own local-scale dynamics (Boehlert 1988). This results in seamount-specific oceanic phenomena (e.g. Taylor columns, breaking internal waves) creating multiple sources of turbulence and water-mass mixing (Fig. 4B). Understanding this meso- to local-scale variability in physical oceanography and how it is influenced by topography (e.g. seamount height, morphology, symmetry), current strength and direction is key to improving our understanding of Fe–Mn crust formation and distribution. Measurements and modelling of the water column at Tropic Seamount (Fig. 4A) show the strong influence of tides on bottom-currents – a feature observed around other seamounts (Noble et al. 1988) – and the contrasting energy regimes across the edifice. Sedimentation, erosional features and the broad distribution of Fe–Mn crusts and fauna (e.g. corals and

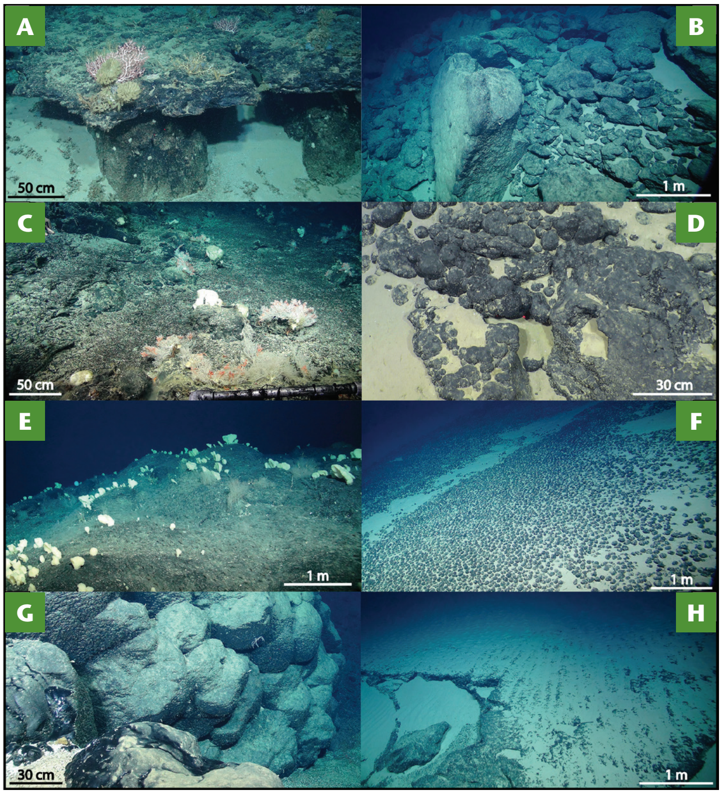

Figure 5 Photographs of Fe–Mn crusts on Tropic Seamount (Atlantic Ocean). Locations of each letter-labelled image corresponds to the red letters in Figure 4. (**A**) Ferromanganese crust pavement on undercut phosphorite basement at the edge of the summit plateau (depth: 1,150 m). (**B**) Encrusted debris flow cobbles on the steep flanks of the seamount (depth: 1,450 m). (**C**) Ferromanganese crust pavement covered by biological debris on a gentle slope on the seamount flank (depth: 1,600 m). (**D**) Knobbly Fe–Mn crust partially covered in sediment (depth: 3,772 m). (**E**) Ferromanganese crust pavement formed on a ridge on the western spur of Tropic Seamount. The high energy currents associated with the spur favours sponge growth (depth: 3,330 m). (**F**) A nodule field in a sediment-rich area on the flank of the seamount (depth: 3,640 m). (**G**) Ferromanganese crust developed on pillow lavas. Note the polished rock surfaces in the foreground (depth: 3,200 m). (**H**) Thick Fe–Mn crust pavement encountered at a depth of >3,800 m that progressively disappears under a sediment veil (depth: 3,870 m). Copyright British Geological Survey ©UKRI 2018

sponges) (Figs. 5A, 5C, 5E) reflect this energy distribution, with the thickest Fe–Mn crust deposits and highest density biological communities generally occurring in the high-energy areas.

FUTURE EXPLORATION, RESOURCE ASSESSMENT AND ECOLOGICAL RISKS

Ferromanganese crusts are the most difficult deep-ocean mineral deposit to explore and extract. Significant work is still required to determine the best exploration strategies for resource assessment and mine planning in order to recover crusts, which contain the highest concentration of key critical metals.

As mentioned by Lusty and Murton (2018 this issue), advances in automated data collection and remote sensing will be essential to effectively handle the sheer size of some seamounts and to improve the efficiency of exploration. However, seeing through sediment cover and being able to differentiate Fe–Mn crusts from the wide variety of substrate rocks on which they grow will pose a major challenge for remote sensing exploration tools. Sediment on the summit plateau of Tropic Seamount covers about 50% of the seafloor. Interpretation of autonomous underwater vehicle–acquired seafloor imagery and multibeam sonar acoustic backscatter data in isolation would give a significant underestimate of lateral Fe–Mn crust distribution: well-developed pavements are frequently covered by a centimetre-scale veil of sediment (Fig. 5H). Detecting natural gamma radiation, which is much higher over Fe–Mn crusts than any of their substrates, seems to be a promising direction for locating crusts under sediment cover and measuring crust thickness. Multifrequency sub-bottom acoustic profiling techniques (in MHz) also offer a possible way to distinguish substrate from Fe–Mn crust and, thus, provide continuous in situ measurements of Fe–Mn crust thickness.

Ground-truthing AUV data and mapping metal concentrations will require the acquisition of rock samples. In contrast to most Fe–Mn crust samples collected globally (principally by dredge or grab), remotely operated vehicle studies provide excellent spatial and depth constraints, as well as information on the local setting of the samples. While remotely operated vehicle–based sampling and mapping is time consuming and expensive, we suggest that the existing body of samples and data for Fe–Mn crusts is likely biased by the bulk sampling methods traditionally employed. For example, dredge sampling is unlikely to collect representative samples or to acquire Fe–Mn crusts where conditions are difficult, such as flat areas and where high-strength substrate rocks are encountered, as on the deeper parts of Tropic Seamount (e.g. Fig. 5G). The distribution of Fe–Mn crusts and the varied nature of the outcrops observed at Tropic Seamount (Figs. 4B, 5), emphasise the importance of conducting detailed depth-sampling transects across seamounts. Furthermore, the challenges faced acquiring representative sample material highlight the need for new Fe–Mn crust-sampling techniques that use drilling and rotary cutting tools deployed from a range of platforms.

Reliable mineral resource estimates and reserve calculations, which can inform investment decisions, require detailed information on the potential ore tonnage, metal grade, the level of sediment cover that may need to be stripped prior to extraction, and the amount of substrate that is likely to be recovered that will dilute the ore grade. The accuracy of these assessments is dependent on the availability of statistically valid and spatially constrained datasets, which have been interpreted in the context of geological models. Spatial interpolation, which is the technique of predicting the values of unsampled points using existing observations, is fundamental to mineral resource estimation and reserve calculation. The spatial distribution of Fe–Mn crusts on seamounts, as a function of variables such as water depth, means that conventional land-based spatial interpolation methods for resource estimation are inapplicable. However, preliminary studies suggest that new 3-D models may permit reliable estimates of the spatial thickness distribution of Fe–Mn crusts on a seamount surface (Du et al. 2017).

As discussed by Jones et al. (2018 this issue), Fe–Mn crusts provide habitats for a range of fauna (Figs. 5A, 5C, 5E) sustained by nutrients supplied by upwelling (Figs. 2, 4B). This results in a potential acute conflict between future Fe–Mn crust extraction and ecosystem protection. Combined mineral resource and habitat mapping studies are essential to determine the scale of this issue and whether resource areas can be identified that balance economic tonnage and grade requirements with environmental protection. Some of the potentially vulnerable marine organisms are considered resources in their own right due to the compounds (marine genetic resources) that can be derived from them (Leary et al. 2009).

CONCLUSIONS

Ferromanganese crusts represent one of the most significant repositories of critical metals on Earth. We are only beginning to appreciate the small-scale variations in Fe–Mn crust composition, thickness and morphology at the scale of individual seamounts. Seamounts are heterogeneous and dynamic mineral-forming environments, as a result of their variable geology, and changes in geomorphology and interaction with ocean currents that takes place over tens of millions of years. Ferromanganese crust growth is a function of many interacting environmental factors that vary in time and space. However, this complexity, the lack of high-resolution Fe–Mn crust mapping and sampling, and complimentary paleoceanographic research means that our understanding of the importance of the role of individual processes in Fe–Mn crust formation remains rudimentary.

Much of our present knowledge on Fe–Mn crust formation is based on the Pacific. Studies elsewhere are beginning to identify controls on Fe–Mn crust formation specific to individual ocean basins or regions and that may influence the concentration of certain elements of increasing economic importance (e.g. platinum and scandium). Greater appreciation of these inter-oceanic differences will be important for global resource assessments and could contribute to sustainable resource development that more closely reflects market demand for specific metals. While economic considerations (including the technical challenges of mining them) and warnings about environmental protection should be carefully weighed, the importance of Fe–Mn crusts as a major and secure future source of certain critical metals should not be overlooked.

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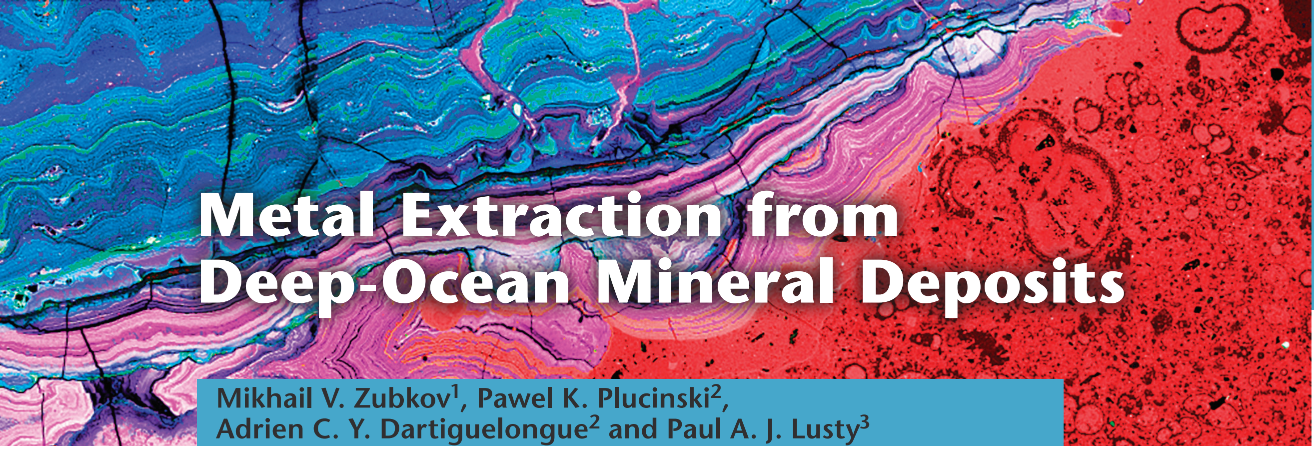

Metal Extraction from Deep-Ocean Mineral Deposits

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The future extraction of deep-ocean mineral deposits depends on being able to recover the metals in an economic and environmentally sensitive way. Metal production is one of the most energy intensive industrial sectors. The characteristics of some deep-ocean mineral deposits permit them to be readily dissolved and to release their contained metals into solution. Current innovations in hydrometallurgy, including metal leaching with ionic liquids and solvent extraction in non-dispersive phase contactors, demonstrate how metals could potentially be extracted from Fe–Mn deposits with increased energy efficiency and a reduced environmental footprint compared with traditional processing techniques. The importance of biological processes in the formation of deep-ocean Fe–Mn deposits is poorly understood. However, understanding how microorganisms select and deposit metal ions could further enhance targeted extraction of 'critical' metals.

Keywords: chelated metal ions, microbial ligand consumption, hyphal bacteria, leaching, solvent extraction

INTRODUCTION

Metal Production and Energy Consumption

Reducing energy consumption and breaking the current link between metal production and greenhouse gas emissions are among the greatest challenges to ensuring a secure and sustainable mineral supply (Lusty and Gunn 2015). Primary metal production presently accounts for 7%–8% of global energy consumption (UNEP 2013) and has many adverse environmental and health impacts. The levels of energy required in primary metal production and the associated environmental impacts of that production are likely to increase as metal demand continues to grow, as the rate of discovery of accessible land-based metal deposits containing high metal concentrations declines, and as mankind digs ever deeper below Earth's surface to recover metals. The average copper-ore grade being mined globally is now about 0.6%, a decline of 25% in ten years (Calvo et al. 2016). As ore grades decline, more waste is generated and must be treated in order to produce the same amount of metal: this, in turn, has an associated rise in energy demand and greenhouse gas emissions.

Mineral Processing, Metal Extraction and Refining

Once ore is mined, it generally undergoes several processing stages to remove non-metallic waste rock. A significant amount of energy is used for crushing and grinding the mined ore into smaller pieces from which the valuable minerals can be more easily liberated. Some metal ores need to be concentrated through a process called flotation, in which non-metallic grains are separated by settling and the metallic phases are concentrated using special flotation agents. Following suitable ore processing, the remaining minerals are physically or chemically treated to extract their metals.

Two established technologies for metal extraction exist: pyrometallurgy and hydrometallurgy. Which of the two is appropriate to use depends on the ore mineralogy, metal grade, economic considerations and the final desired products.

Pyrometallurgy involves heating metal-bearing mineral concentrates to a high temperature, to bring about physical and chemical changes that liberate metals from the individual mineral phases. It has been employed for millennia to extract metals from ore minerals. The energy required to sustain high-temperature pyrometallurgical processes may be derived entirely from the exothermic nature of the chemical reactions taking place. However, it is frequently necessary to add energy to the process through combustion of fossil fuels for heating furnaces or, in the case of some smelting processes, by the direct application of electrical energy.

Hydrometallurgy involves treating the ore or mineral concentrate with solutions to dissolve the metals from their host mineral phases. Hydrometallurgy generally uses leaching, in which the ore is piled up into mounds or placed in tanks and mixed with strongly reactive solutions such as cyanide, ammonia or sulfuric acid. Hydrometallurgy generally operates at ambient temperatures, occasionally in the open air, but it is sometimes necessary to use higher pressures and temperatures, which requires energy.

Following smelting or leaching, the metal may need to be further refined, depending on the purity of the final commodity required. Many refining techniques use electrochemistry and are, therefore, inherently energy intensive.

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The Goal: To Reduce the Environmental Footprint of Metal Production

The huge metal resources contained in deep-ocean mineral deposits are introduced by Lusty and Murton (2018 this issue), and the likely key stages in the mining process are outlined by Jones et al. (2018 this issue). Here, we focus on the final stage in the deep-ocean mining value chain: the extraction of metals from the mined ores. It is generally agreed that this process will happen onshore in similar industrial facilities to those that currently exist for processing minerals extracted from land-based mining operations.

Some of the environmental advantages of seabed mining compared with land-based mineral extraction are outlined by Lodge and Verlaan (2018 this issue). In contrast to many deposits on land, the deep-ocean mineral deposits currently being targeted for extraction are generally exposed on the seabed. Therefore, significant initial energy savings will be associated with not having to remove and handle large volumes of worthless waste rock. Furthermore, the smaller quantities of waste rock recovered with the ore should mean that less processing or concentration of the minerals is required before metal extraction can commence.

Due to their very similar characteristics and mineralogy, the sulfide-rich deep-ocean minerals deposits, termed seafloor massive sulfides, are likely to be processed in a similar way to comparable ores currently mined on land. For example, it has already been agreed that the ore from the Solwara 1 deposit off Papua New Guinea (introduced by Lusty and Murton 2018 this issue) will go to a China-based smelting company. Whilst seafloor massive sulfide deposits may not share the economies of scale with much larger land-based mining operations, the reported metal grades (see Lusty and Murton 2018 this issue), can be significantly higher, thereby potentially offsetting this disadvantage and meaning that less ore has to be mined and transported to produce an equivalent amount of metal. Although some of the technologies covered in the following discussion are relevant to processing sulfide ores, the fairly conventional nature of the mineral processing that is envisaged means they will be not discussed further here.

METAL RECOVERY FROM FERROMANGANESE DEPOSITS

Instead, we focus on the opportunities for reducing the environmental effects of extracting and recovering metals from the ferromanganese (Fe–Mn)-rich deep-ocean mineral deposits (nodules and crusts), as introduced by Lusty and Murton (2018 this issue). These authors emphasize the vast untapped repository of ‘critical metals’ (e.g. rare-earth elements, cobalt and tellurium) contained in deep-ocean Fe–Mn deposits. However, converting Fe–Mn nodules and crusts into economic resources that can compete with a land-based metal supply relies on being able to efficiently recover the metals they contain and minimizing the environmental impact of their extraction. Specifically, we review the application of hydrometallurgical techniques, such as leaching and solvent extraction, to these nodule and crust deposits, assess the use of ionic liquids, and examine the novel use of membrane contractors for metal extraction following leaching. Looking to the future, we consider how an improved understanding of the role of microbes in the formation of Fe–Mn deposits could be harnessed for metal recovery.

Hydrometallurgical Processing

Hydrometallurgical methods are generally preferable to pyrometallurgy for processing Fe–Mn deposits for the following three reasons: (1) the oxide raw material does not require a flotation stage for pre-concentration because of its high ore-to-waste rock ratio; (2) the nodules and crusts are polymetallic materials that have a relatively high metal content for which each target metal requires a different extraction method; (3) the nodules and crusts have a high porosity and a seawater content of 10%–60% by volume (Koschinsky and Hein 2017). Furthermore, hydrometallurgy has a lower energy consumption, particularly for the recovery of trace metals (e.g. the rare-earth elements, which occur in relatively low concentrations): this is attractive because it has a smaller carbon footprint (Table 1).

Despite these advantages, an initial pyrometallurgical processing of Fe–Mn ores has been considered for separating manganese and iron because both metals occur at much higher concentrations than the non-ferrous metals. The non-ferrous metal separate could then be independently processed using hydrometallurgy (Thornton 1992), adapting existing processing routes that have been established for the production of Ni, Cu, Co, Mo and Zn from nodules (Gajda and Bogacki 2010).

Key Stages in Metal Recovery

A generalized three-stage hydrometallurgical processing route could be applied to Fe–Mn ores: this is shown schematically in Figure 1. Following initial mechanical crushing and grinding to reduce particle size and increase surface area, the first stage is leaching, in which the ore feedstock is subjected to an aqueous lixiviant (i.e. liquids designed to selectively extract the desired metal from the ore). To eliminate the energy expenditure associated with pre-drying, processing of wet Fe–Mn crust could be achieved using water-compatible lixiviants. Leaching transfers soluble components from the ore into a solvent, producing solutions that contain metal(s) as hydrated

Table 1 SUITABILITY COMPARISON OF THE KEY CHARACTERISTICS BETWEEN PYROMETALLURGICAL AND HYDROMETALLURGICAL METAL EXTRACTION TECHNIQUES. Modified from Havlík (2008).

	Technology	
Terms of Reference	**Pyrometallurgy**	**Hydrometallurgy**
Treatment of low-grade ores	Unsuitable; large amount of energy necessary	Suitable, providing a selective leachant can be used
Treatment of complex ores	Unsuitable; separation is difficult	Flexible; permits production of a variety of products
Process economics	Best suited for large-scale operations; significant capital costs	Can be used for small-scale operations; moderate capital investments required
Separation of chemically similar metals	Not possible	Possible
Environmental pollution	Waste gas; noise; large amounts of dust	Less atmospheric pollution; reduced dust; reduced wastewater
Operational feature	Engineering is not considered complex	Sophisticated equipment; plant engineering is more complex

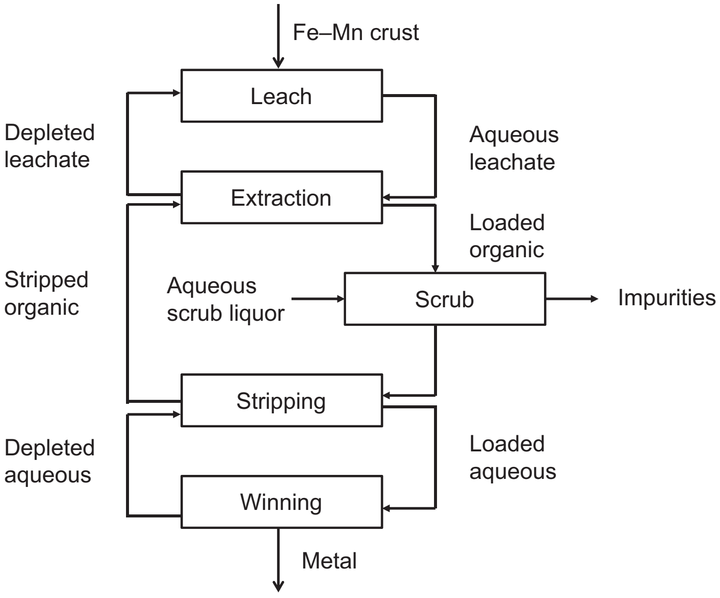


FIGURE 1 Typical leaching/solvent extraction flowsheet for the recovery of metals from Fe–Mn ores. ADAPTED FROM THORNTON (1992).

cations. The second stage is solvent extraction (employing a liquid ion-exchanger) to transfer the target element into an immiscible organic phase. The organic phase can then be contacted (mixed) with a series of aqueous solutions designed to strip out any impurities co-extracted with the target element (a process known as scrubbing). During the third, and final, stage the purified organic phase is contacted with an appropriate stripping solution of mineral acids to return the chosen element to the aqueous phase, from which it can then be recovered, thereby regenerating the organic solution for re-use.

Leaching Metals from Ores

The solvent used in chemical leaching is usually an aqueous solution containing either an acid, a base, or a complexing agent. The formation of chemical complexes facilitates the dissolution of mineral components in the aqueous solution. A key consideration in extractive metallurgy is choosing between two overall extraction strategies: (1) to leach all metallic species, with subsequent isolation of desired components, versus; (2) to selectively leach only the component of interest. Hindustan Zinc Limited (India) designed and established a 500 kg per day processing plant for Fe–Mn nodules. Their process was based on reductive pressure leaching of the nodules, using sulfur dioxide as a reducing agent in the presence of ammonia. Ammonia permits the selective dissolution of non-ferrous metals in the form of amino complexes, leaving the Fe and Mn to remain in the solid phase. After six months of pilot plant operation, the average recovery of Cu was 85%, that of Ni was 90%, and Co was 80% – very impressive results (Mittal and Sen 2003).

An alternative to chemical leaching – a process that can produce negative environmental impacts because of the use of, for example, hydrochloric acid, sulfuric acid, and ammonia – is bioleaching of metals. Bioleaching employs biological systems (chiefly prokaryotic micro-organisms) to facilitate the extraction and recovery of metals from ores. Bioleaching operates at atmospheric pressure and at relatively low temperatures, and some of the organisms can even fix carbon dioxide. This process does not require strong chemicals, which makes it relatively low-cost, low-energy and a more environmentally benign technology. It is now a well-established technique for extracting metals from low-grade reduced, sulfidic minerals and from polymetallic base-metal ores (Johnson 2014).

However, compared with reduced sulfidic ores, which are currently bioleached by bacteria that obtain their energy from the oxidation of the reduced sulfur and iron in the ore itself, deep-ocean Fe–Mn deposits are fully oxidised. Therefore, bioleaching these materials will require a radically different approach, potentially in anoxic conditions. To mobilize trace elements from Fe–Mn ores, Fe(III) and Mn(IV) hydroxides need to be reduced. Whereas there are bacteria that can reduce iron and manganese, they will require an added energy source in the form of simple organic molecules, possibly also reduced forms of sulfur, or light, all of which will increase the cost and complexity of the bioleaching process. Adding large amounts (up to 2.5 kg per kg of ore) of organic matter has, to date, only resulted in relatively poor bioleaching yields of about 12% (Zhang, et al. 2016). By contrast, the addition of metal catalysts (e.g. Ag^+, Hg^{2+}, Bi^{3+}, Cu^{2+}, Co^{2+}) has had demonstrably excellent improvements in metal extraction efficiency (Niu et al. 2015). Whilst much progress has been made in recent years on bioprocessing via a better understanding of microbial interactions, adapting bioleaching technology for processing deep-ocean Fe–Mn ores will require a greater knowledge of mineral–microbe interactions in these environments and more advanced technological developments. Therefore, bioleaching is unlikely to compete with chemical leaching, at least in the near future.

Extraction of Leached Metals

Following leaching, the metals exist in an aqueous solution as hydrated ions (FIG. 1). The conventional approach for extraction of these metals involves the use of complexing agents dissolved in solvents. Before the metal can be extracted into a non-polar organic phase, any ionic charge must be reduced or removed, or the solvating water molecules must be replaced. This can be achieved using solutions called extractants, of which there are three types: acidic, basic, and solvating.

Acidic extractants include simple reagents such as carboxylic acids and organophosphorus acids, as well as chelating acids such as β-diketones, 8-hydroxyquinoline and hydroxyoximes (Thornton 1992). The equilibrium of acidic metal extraction can be easily shifted by adjusting the pH of the leached aqueous phase and the stripping solution. Higher pH (low H^+ concentration) favours metal extraction; lower pH (high H^+ concentration) favours metal stripping from an organic extract.

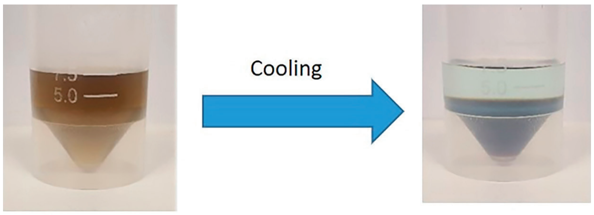
Basic extractants generally consist of amines or quaternary ammonium salts. The magnitude of extraction follows the order $R_4N > R_3NH > R_2NH_2 > RNH_3$, with the size of the alkyl group (R) generally between 8 and 12 carbon atoms, to secure the exclusive solubility in the organic phase (extracting agents are practically insoluble in the aqueous phase).

Solvating extractants operate by replacing the solvating water molecules around the aqueous metal complex, making the resulting species more lipophilic (i.e. soluble in the organic solvents). The types of organic compounds used include alcohols, ethers, esters, ketones and sulfides. Amides have also been proposed for specialized applications, such as the extraction of lanthanides and actinides, as well as precious metals.

The environmental sustainability of metal extraction using solvents has been improved by using thermally stable and less toxic ionic liquids for both leaching and solvent extraction of various metallic species (e.g. rare-earth elements, transition metals) (Chen 2016). Ionic liquids are a family of molten organic salts that have a low, or negligible, vapour pressure and that form below 100 °C. Their ionic structure makes them thermodynamically favourable for the extraction of metallic ions. Properties such as low toxicity, chemical and thermal stability, and biodegradability suggest that ionic liquids are relatively benign to the environment and to humans (Park et al. 2014). Aside from the environmental advantages, several ionic liquids have a higher partitioning for metals than conventional solvents and they have better metal selectivity. The dual role of ionic liquids as extractants and solvents makes their application beneficial compared to standard extraction systems that use large volumes of organic diluents (which are often flammable and volatile).

Several ionic liquids suitable for metal extraction have gained attention because they exhibit temperature-dependent properties. These so-called 'thermomorphic' ionic liquids, which include betainium *bis*(trifluoromethylsulfonyl) imide {abbreviated to [Hbet][Tf_2N]} (Nockemann et al. 2006), have already been successfully tested and have a low environmental impact. Above a certain temperature, thermomorphic ionic liquids become water-miscible and so act like aqueous solvating and/or complexing reagents with some metal species. During the cooling phase of the ionic liquid/water mixture, a spontaneous phase separation occurs where the metals mostly enter the ionic liquid phase. Metals can then be recovered and concentrated using small amounts of mineral acid, and the ionic liquid itself can be re-used for subsequent extraction or leaching cycles. An example of the thermomorphic behaviour of mixture of water and [Hbet][Tf_2N] is shown in Figure 2.

Following metal leaching using ionic liquids, the extraction of the metal(s) of interest can be undertaken using existing hydrometallurgical facilities. However, low phase ratios (i.e. o/w for extraction and w/o for stripping; where o = organic extracting phase, w = aqueous phase) are required to accommodate the high concentration of metals during the extraction–stripping cycle (Fig. 1). Such phase ratios cannot easily be achieved in mixer–settlers (a mixing vessel or stirred tank connected to a phase separator) or in traditional extraction columns (a contacting device where, normally, the aqueous phase flows as a continuous phase and the organic phase as a dispersed one). Centrifugal extractors are very expensive and would not be economic to bulk process Fe–Mn ore. As an alternative, non-dispersive phase contacting in synthetic hollow-fiber membranes has been proposed. The basic principle of the non-dispersive extraction process is the immobilization of the liquid/liquid interface (between the organic extracting phase and the aqueous metal-rich phase), within the pores of hydrophobic membranes (membranes not wetted by water).



Homogeneous leachate (temperature > 55°C)

Two-phase leachate (ambient temperature)

Figure 2 Thermomorphic behaviour of a mixture of water and [Hbet][Tf_2N] during the cooling phase of rare-earth element leaching. [Hbet][Tf_2N] = (trimethylammonio)acetate *bis*-(trifluoromethylsulfonyl)imide.

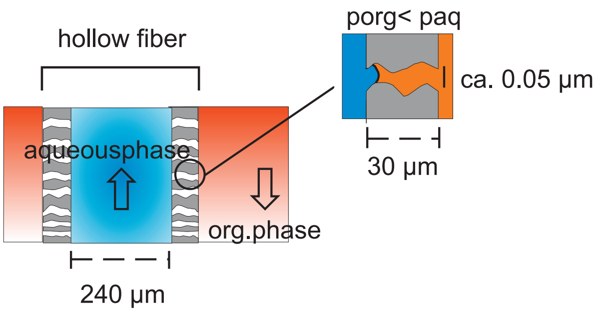


Figure 3 Schematic diagram illustrating the principle of non-dispersive phase contacting in hollow fiber membranes. Abbreviations: P_{org} = Pressure of organic phase; P_{aq} = pressure of aqueous phase.

The position of the interface is controlled by wetting, which can be thought of as the ability of a liquid to maintain contact with a solid surface, and the appropriate application of static pressure (Fig. 3).

The key to the hollow-fiber membrane process is the independent flow of the two phases either side of the membrane. This method of fluid-phase contact has the following advantages over conventional extraction equipment (e.g. columns or mixer settlers): (1) a high specific-area for mass transfer (~ > 5,000 m^2/m^3 compared to 10–100 m^2/m^3 in conventional industrial equipment); (2) the prevention of flooding (liquid accumulation); (3) an independence of phase densities and interfacial tension; (4) the ease with which it is possible to create extreme phase ratios (enrichment effect); and (5) a non-dispersive phase contact that avoids entrainment (the incorporation of small organic droplets in the aqueous phase) (Gabelman and Hwang 1999).

One hollow-fiber membrane process module that is 54 cm in length and that contains 9,000 hollow fibres (or one that is 25 cm in length containing 31,000 fibres) can replace an extraction column 6 m in length and requiring between two to four extraction stages (Daiminger et al. 1996). Considering that current Vietnamese and Chinese technologies for lanthanide separation involve between 100 and 200 mixer–settler extraction stages, the application of hollow-fiber membrane–based extraction, without the necessity for phase separation, would significantly decrease the energy consumption and the environmental footprint of the metal extraction process.

AN ALTERNATIVE FUTURE: BIOLOGICAL APPROACHES FOR RECOVERING METALS FROM THE MARINE ENVIRONMENT

The development of biological techniques for recovering metals from Fe–Mn deposits is dependent on an improved understanding of the role of microbes in the formation of those deposits. It is possible that microbes are involved either in sequestration of the major metals (Fe–Mn) and/or aid in the selective enrichment of trace metals. In terms of the latter, this process could potentially be harnessed in biotechnological methods of trace-metal extraction.

The Potential Role of Biogenic Processes in the Formation of Fe–Mn Crusts

Genetic models for the formation of deep-ocean Fe–Mn deposits are still being refined. The role of micro-organisms in their formation remains uncertain. The popular abiotic hypothesis (Goldberg and Arrhenius 1958) did explain the slow accretion rate of these crusts by suggesting there was a prolonged opportunity for abiotic scavenging of the metals from seawater (Koschinsky and Hein 2017). However, this hypothesis overlooked the potential for biogenic (biologically induced) contributions (Graham and Cooper 1959; Ehrlich 2000). Although environments rich in both Fe and Mn host diverse and numerous microbes (Graham and Cooper 1959; Ehrlich 2000), direct microbial involvement in the formation of Fe–Mn crusts remains unproven (Koschinsky and Hein 2017). Nevertheless, there is compelling indirect evidence that micro-organisms are involved in the formation of these deposits and that they may even influence growth rate, composition and, therefore, resource potential.

The biogenic origin of ancient sedimentary marine ferromanganese deposits, now preserved in the geological record on land, is widely accepted. The currently accepted model for the genesis of the 3.8 Ga banded-iron formations involves micro-organisms in the form of purple bacteria (Widdel et al. 1993) that could oxidise Fe(II) to Fe(III) in the absence of free oxygen by using the energy of sunlight. During the last 2.7 billion years, photosynthetic organisms have produced a waste product, oxygen, which oxidises Fe and Mn. In the modern oceans, this biogenically derived free oxygen continues to oxidise the terragenic reduced Fe(II) and Mn(II) cations, thereby enabling the formation of Fe–Mn deposits. Hence, even if this oxidation process is purely physicochemical, it is ultimately the result of a biogenic process.

Deep-ocean Fe–Mn crusts are rich in biological and biogenic material (Fig. 4). However, the direct involvement of microbes in precipitating redox-reactive metals remains uncertain. In Fe(II)-rich waters, for example, close to hydrothermal vent sites, bacteria living in seeps or springs compete with the chemical oxidation of Fe(II). Because only a small amount of energy can be derived from the oxidation of Fe(II) to Fe(III) to sustain their growth, iron-oxidizing bacteria need to precipitate copious amounts of iron hydroxides, and this will reduce the pH in locations where Fe(II)-rich water flows from anoxic to oxic environments. In oxygenated oceanic waters, where iron concentrations are typically in the nanomolar range, all Fe(II) is chemically oxidized to Fe(III), which has no energetic value for iron-oxidizing bacteria. In contrast to Fe(II) to Fe(III) oxidation, the chemical oxidation of Mn(II) in oxygenated waters is up to five orders of magnitude slower than biogenic oxidation (Tebo et al. 2004); Mn(II)-oxidizing bacteria, as well as fungi, are widespread and phylogenetically diverse. Although definitive proof of microbial growth using Mn(II) oxidation as the sole source of energy remains elusive, oxidation of soluble Mn(II) to insoluble Mn(IV) oxides results in an energy gain, and some evidence suggests microbes could use that energy. To oxidise Mn(II) directly, both fungi and bacteria preferentially use multicopper oxidase enzymes in a one-electron step transfer reaction that oxidizes Mn(II) to Mn(III) (Tebo et al. 2004). The resulting Mn(III) could compete with Fe(III) for siderophore ligands (organic molecules produced by microbes to scavenge iron from seawater and deliver it to the cell surface) at cell surfaces in order to facilitate microbial Fe(III) uptake. Organic acids could potentially complex Mn(III) which, in turn, could act as an oxidant on these acids and so precipitate insoluble Mn(IV) in the immediate vicinity of the microbes' cells.

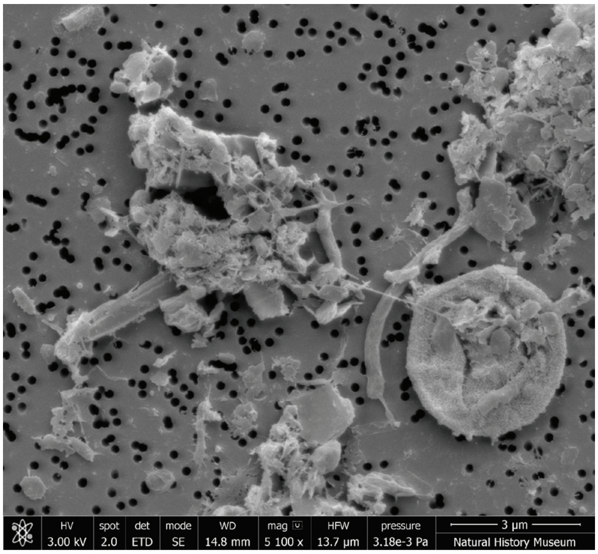


Figure 4 A scanning electron micrograph of material scraped off the surface of an Fe–Mn crust, showing the morphologically diverse microbiological and biogenic particles. The material was collected on a filter with pores 0.2 µm in diameter (black dots). Image: M. Zubkov.

Microbes can also indirectly oxidise Mn(II) by changing redox and pH conditions in the vicinity of the cell. A plethora of physiological benefits of Mn(II) oxidation for micro-organisms have been proposed, including the following: (1) the breakdown of refractory organic matter into palatable portions using the Mn(III) oxidant; (2) the scavenging of metal micro-nutrients, such as Fe, Mn, Cu, Co and Mo; (3) the storage of an electron acceptor, like Mn(III), for later use in anaerobic respiration; and (4) protection from toxic heavy metals, reactive oxygen species, radicals, predation and viruses. However, none of these benefits appear to outweigh the principal danger of extensive Mn(II) oxidation in the immediate cell vicinity, i.e. the entombment of the cell in a shell of insoluble Mn(IV) hydroxides. An exception might be the necessity to procure food for cell growth, which could override the risk of 'Mn entombment'.

Cations of Fe, Mn and other trace metals when chelated with organic ligands are both soluble and stable in seawater. Bacteria could specifically harvest such complexed cations and consume organic ligands (Spring 2006). Such bacteria would dispose of the redox cations by oxidizing Mn(II) to Mn(IV), and depositing insoluble hydroxides of Mn(IV) and Fe(III), and other trace element cations in the vicinity of the cell, to attract more complexed cations and/or free ligands. This would explain how Fe–Mn hydroxides, enriched in trace metals, can co-precipitate and form Fe–Mn deposits around microbial cells.

There are a diverse range of bacteria that are capable of depositing insoluble Fe and Mn hydroxides (Tebo et al. 2004; Koschinsky and Hein 2017). One group are the hyphal budding bacteria, which are distinct because they can use their thin long hypha to escape entombment in Fe–Mn crusts by budding daughter cells at hyphal tips (Aristovskaya 1961; Gebers 1981). These morphologically distinctive bacteria have been isolated from various Fe–Mn-enriched soils and from freshwater and marine sediments worldwide. In support of the organic-ligand consumption hypothesis, outlined above, hyphal budding bacteria can grow using simple organic acids as their only food source (Gebers 1981). They also use extracellularly bound, Cu-dependent enzymes to oxidise Mn(II) (Tebo et al. 2004). The distinct morphology of hyphal bacteria should assist in their identification on Fe–Mn deposits. However, microscopic examination of Fe–Mn crusts to date do not support an abundance of hyphal bacteria (Fig. 4). This is potentially explained by the removal of microbial biofilms during sample collection and/or sample preparation, because the presence of hyphal bacteria is indicated by qualitative molecular bioinformatic analyses of microbial communities associated with oceanic Fe–Mn crusts (Sujith et al. 2017).

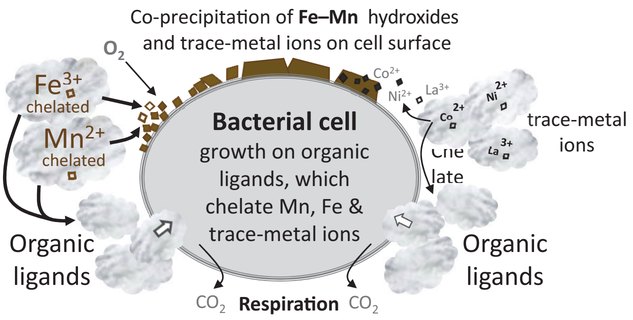


FIGURE 5 Schematic illustration of the microbial ligand consumption hypothesis for the formation of Fe–Mn encrustations. DIAGRAM: NINA KAMENNAYA

If the microbial ligand consumption hypothesis is correct, then microbial involvement in the formation of Fe–Mn crusts would be an indirect consequence (FIG. 5). Analogous to the situation where oxygen is produced by photosynthetic microbes, then Fe, Mn and trace-metal cations could be the waste products of microbes feeding on organic ligands. Thus, while metal hydroxides, rejected by microbes, chemically rearrange into Fe–Mn deposits, the bivalent trace-metal cations become entrained into, or between, the resulting molecular-scale mineral sheets (Saratovsky et al. 2006).

If the role of microbes in forming Fe–Mn deposits is indirect, then in order to develop novel bioprocessing techniques for selective recovery of specific trace metals, future research should focus on assessing how microbes selectively extract, directly from seawater, the trace metals that are essential for their growth. Seawater itself is considered a major and largely unexploited reservoir of metals (Diallo et al. 2015) that could potentially be tapped using high-selectivity biological techniques.

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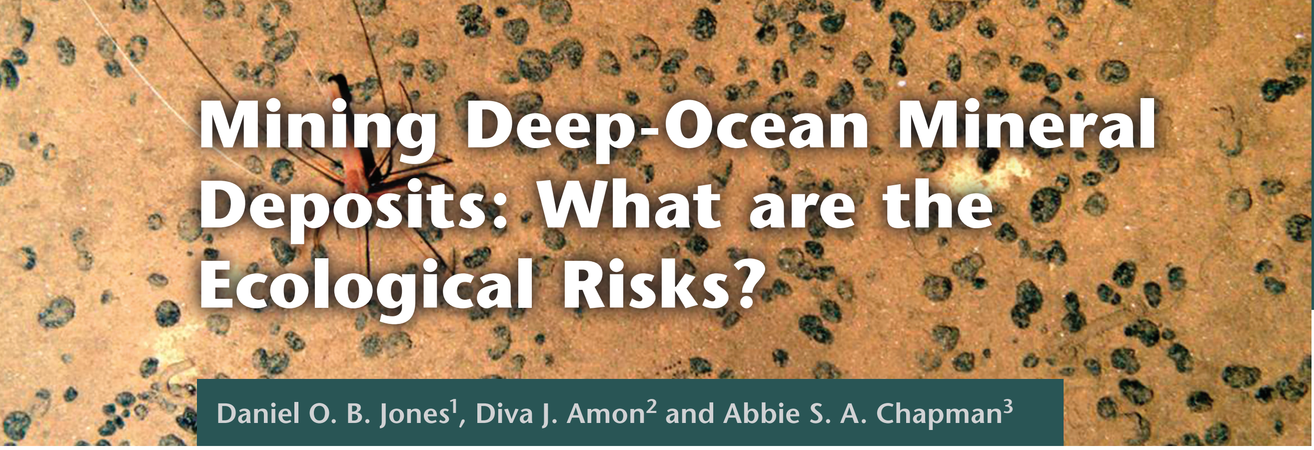

Mining Deep-Ocean Mineral Deposits: What are the Ecological Risks?

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A key question for the future management of the oceans is whether the mineral deposits that exist on the seafloor of the deep ocean can be extracted without significant adverse effects to the environment. The potential impacts of mining are wide-ranging and will vary depending on the type of metal-rich mineral deposit being mined. There is, currently, a significant lack of information about deep-ocean ecosystems and about potential mining technologies: thus, there could be many unforeseen impacts. Here, we discuss the potential ecological impacts of deep-ocean mining and identify the key knowledge gaps to be addressed. Baseline studies must be undertaken, as well as regular monitoring of a mine area, before, during, and after mineral extraction.

Keywords: deep-sea mining, environmental impact, sustainability, ecology

INTRODUCTION

Here, we consider the ecological risks associated with the extraction of seafloor massive sulfide deposits, ferromanganese (Fe–Mn) nodules and Fe–Mn crusts. Each deposit typically occurs in a different geological and oceanographic environment (Gollner et al. 2017). The deposits differ in mineralogy, metal composition, surface expression, morphology and spatial extent, resulting in different ecosystem structures and functions and different disturbance risks.

Individual seafloor massive sulfide deposits typically cover a relatively small area of the seabed (mounds may have diametres of ~100–200 m^2) compared with Fe–Mn nodules and crusts (extending over 10s–1000s km^2). In contrast to nodules that lie in or on the sediment of the lower energy abyssal plains, seafloor massive sulfide deposits may represent relatively dynamic environments (affected by active volcanism, plume fall out and slumping), and are three dimensionally extensive structures with rugged surface topography (as discussed by Petersen et al. 2018 this issue) (Fig. 1). Seafloor massive sulfide deposits can also represent environments that are stable over long timescales (e.g. Copley et al. 2007). Deposits at different water depths can be at varying stages of development: from very active, high temperature (typically 250–400 °C) vent sites, to lower temperature (20–50 °C) systems, characterized by 'shimmering' diffuse flow, to extinct seafloor massive sulfide deposits at ambient temperatures. Thus, there are a spectrum of environments, each with their own different temperature regimes, chemical fluxes and stability.

Seafloor massive sulfide deposits found in areas of hydrothermal venting support variable, but typically dense, faunal communities that have a much greater biomass and productivity than those found in other parts of the deep ocean (Fig. 1). Despite the high local abundances of fauna, the species present are often rare, with limited distributions. Active vent communities vary dramatically within regions and across the globe; generally, these have tubeworm-dominated assemblages in the East Pacific, snail and barnacle dominance in the West Pacific and Indian Oceans, shrimp dominance in the Atlantic Ocean, and crab dominance in the Southern Ocean (Van Dover et al. 2018). Massive sulfide deposits at inactive vent sites appear to have lower density but higher diversity faunal communities than active vent sites (Levin et al. 2016). Inactive vent sites offer a long-lasting substratum in ambient conditions by which sponges, corals, and echinoderm assemblages can become established, each assemblage having different sensitivities to a given mining process (Levin et al. 2016). Given the species density, biodiversity, and biomass found at active and inactive vent sites, improved understanding of these ecosystems and the risks of anthropogenic disruption is urgently required, not least because mining of these deposits appears to be imminent, as described by Lusty and Murton (2018 this issue). Some of the mining impacts at a specific site will likely differ as a result of the variable ecology.

The deep-water abyssal plains contain abundant Fe–Mn nodules and cover a huge area. They are one of the world's most pristine environments (Fig. 2). These areas are not homogeneous but vary in topography, environmental conditions and biology. Apart from the nodules, the sediments are typically very fine, although bedrock is locally exposed. Samples of the fauna of this area show extremely high biodiversity for many groups, but regional diversity is poorly characterized and the connectivity between areas is unknown for most species. The visible fauna are primarily xenophyophores (giant single-celled organisms), cnidarians (e.g. corals and anemones) and sponges, but include large crustaceans, echinoderms (e.g. sea cucumbers) and fishes (Amon et al. 2016). Many

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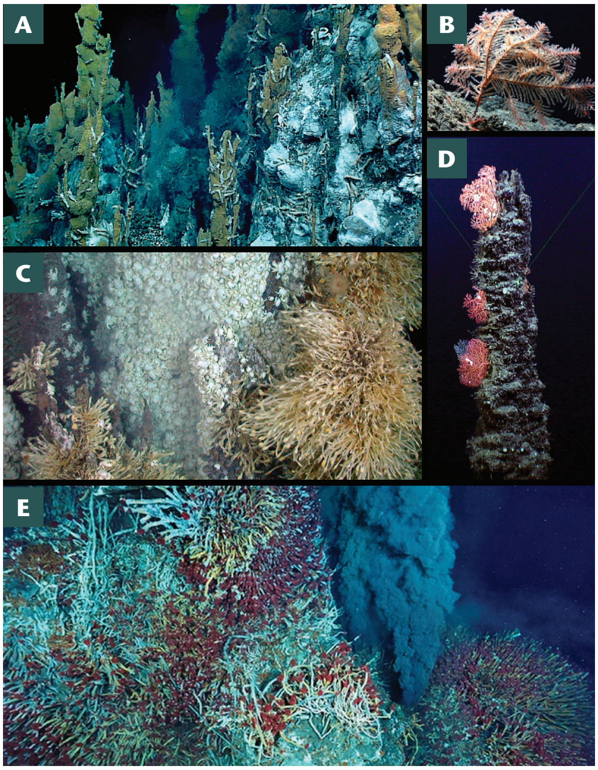


Figure 1 Examples of hydrothermal vent communities. (**A**) Seafloor massive sulfides with associated communities of shrimps, crabs and snails discovered in 2016 at 3,863 m in the Mariana back-arc axis (west Pacific Ocean). Image: NOAA’s Office of Ocean Exploration and Research. (**B**) A black coral observed at 2,227 m in the Endeavour Rift Valley (northeast Pacific Ocean). Image: Ocean Networks Canada. (**C**) Squat lobsters and stalked barnacles dominate this chimney, attaining high biomass, in the E9 vent field of the East Scotia Ridge (Southern Ocean). Image: NERC ChEsSo Consortium. (**D**) Corals living on an extinct chimney at 2,203 m in the Mothra vent field (northeast Pacific Ocean). Image: Ocean Networks Canada. (**E**) *Ridgeia piscesae* tubeworm communities, likely hosting paralvinellid worms, scaleworms, limpets, and many other faunae in their bush-like structures. Near a black smoker at 2,133 m at the Endeavour segment of the Juan de Fuca Ridge (northeast Pacific Ocean). Image: Ocean Networks Canada.

organisms, large and small, live on the nodules themselves. Sediment-dwelling fauna are primarily nematodes, foraminiferans, polychaete worms and crustaceans. The density of fauna is generally low relative to the communities found on Fe–Mn crusts and hydrothermal vents.

The ferromanganese crusts that accumulate on seamounts and ridges represent hard, stable habitats over a range of water depths in the open ocean. Some seamounts are flat-topped, with extensive summit plateaus, but their topography can also be very rugged, including steep slopes and cliffs. Ocean currents can be highly variable, as described by Lusty et al. (2018 this issue). As a result, ferromanganese crusts tend to be exposed, thereby providing habitats for attached suspension feeders, such as cnidarians (e.g. corals) and sponges (Fig. 3). In some cases, individual corals and sponges can be very large and old. Dense forests of these fauna (Fig. 3) can support a wide variety of associated fauna, such as crustaceans, echinoderms and molluscs. The majority of communities inhabiting Fe–Mn-encrusted seamounts and ridges have not been well explored or characterized.

IMPACTS OF DEEP-OCEAN MINING

Mining Equipment and Techniques

The major metal-rich deep-ocean deposits each have distinct characteristics, but the mining approaches being envisioned will have some common key stages (Fig. 4). Some types of deep-ocean mining, such as the extraction of seafloor massive sulfide deposits, may be comparable to that currently conducted on land and use similar equipment. In the early stages of development of the industry, it is likely that equipment design will be an extension of existing land-based mining techniques and subsea trenching and dredging equipment, integrated with remote system technology. All deposits types will require a seafloor collector device to gather the mineral deposit from the seafloor. The minerals will then be transferred via a vertical transport system (a riser pipe) to a surface vessel, where they will be de-watered and transferred to transport barges. The processed water, containing suspended sediment and mineral particulates, will either be discharged from the vessel at the sea surface or carried via another vertical transport system to be discharged at depth (Weaver et al. 2018).

Despite some general similarities, the seabed mining equipment that will be used to extract each of the three deposit types will be different. The equipment produced for the Solwara 1 seafloor massive sulfide project (off Papua New Guinea) (see Lusty et al. 2018 this issue), provides the best current indication of what seafloor production tools will be used and the way they will operate. In the Solwara 1 case, three track-mounted robotic tools will be used to extract the deposits. One cutting machine will prepare the ground for subsequent mining by flattening rough topography and creating benches for the other machines to operate on. A second cutter will mine along the benches. Both cutters will excavate rock by a continuous cutting process, comparable to continuous mining machines used on land. A collecting machine will then suck the disaggregated rock, generated by the cutters, off the seafloor as a slurry and pump it into the riser system.

Ferromanganese crust extraction is likely to employ similar cutting and collection machines to those used for seafloor massive sulfide deposits. In contrast, mining Fe–Mn nodules will require seabed mining equipment most likely consisting of a vehicle carrying a collector, possibly on sled runners, which may be self-propelled at a speed of about 0.5 metres per second, using tank-like tracks or with Archimedes screws (Oebius et al. 2001; Jones et al. 2017). A mining operation may employ one or multiple collectors that are each likely to be over 10 metres wide. The collector would recover nodules in surface sediments (<50 cm deep) by mechanical means or by separating them from the sediment using water jets. The seabed collecting devices will be connected with systems that pump the nodules from the seabed to the surface through a riser.

During mining operations, some of the flocculent surficial sediment would be re-suspended by movement of the collector vehicle and hydraulic jets. Deeper sediment layers could be broken up into lumps that then might partly enter the collection system. Such residual sediment would be carried to the sea surface with the nodules and would likely be separated from the nodules and discharged back near the seabed.

General Environmental Impacts of Mining Operations

The mining of deep-ocean minerals, like any form of human industrial development, will impact the surrounding environment and biological communities, including community structure and functioning. The mining vehicle is likely to disturb the sediment in wide tracks, compacting the sediment in its path and moving sediment to the edge of the track areas. The organisms near the mining operation that cannot escape will be crushed and probably killed by the machines. Noise and light pollution from the mining machinery and support vessels will impact biological communities from the sea surface to the deep-ocean floor.

Sediment plumes created by the seabed mining operation will spread in the water column and eventually settle on the seafloor, smothering any fauna in the directly disturbed area and the immediate surroundings. Sediment plumes may also arise from the surface de-watering operation. It is likely that surface discharge of particulates, although technically more straightforward, would be more harmful than discharges at depth, increasing the potential ecosystem effects by interacting with euphotic (photosynthesis possible) upper ocean systems, with organisms (e.g. plankton, marine mammals and turtles) and by enhancing the risks to humans by contaminating or otherwise impacting on commercial fishing stocks. Releasing sediment-laden water at depth could also have far-reaching impacts. For example, seabed communities may be smothered, nutrients could be introduced to otherwise nutrient-poor systems, toxic metals could be mobilized, and deep-water fisheries may be contaminated in a similar way to those at shallower depths. Models suggest that large sediment plumes will be created that spread over extensive areas, particularly in the case of Fe–Mn nodule mining, because the sediment grain size of the abyssal seafloor is so small. A sediment plume could cover at least twice the area of the operation, and likely more (Gjerde et al. 2016).

Mining Seafloor Massive Sulfide Deposits

The 'footprint' on the seafloor from extracting a single seafloor massive sulfide deposit will be smaller than for the other deposit types. However, seafloor massive sulfide mining will cause a range of impacts unique to these deposits, which will vary depending on the type of deposit being targeted (Van Dover 2014). The chemical composition of seafloor massive sulfides is distinct from Fe–Mn crusts and nodules: they potentially contain a wide range of trace metals (discussed by Peterson et al. 2018 this issue) that vary between deposit types. However, considerable efforts are being made to protect active vent sites from any mining activity because they harbour high-density, endemic faunal communities for an estimated deposit yield that is relatively small (Van Dover et al. 2018) (Fig. 1). Hydrothermally inactive vent sites are, therefore, more attractive for mining, though they should not be considered barren of life (Van Dover 2011). The impacts of mining seafloor massive sulfide deposits will be similar to those of extracting other deposit types: animals destroyed by the mining activity, removal of the primary substratum used by fauna, and the generation of sediment plumes. However, mining seafloor massive sulfide deposits will likely result in greater levels of chemical pollution than for the other deposit types, primarily resulting from the oxidation of newly exposed sulfides and the subsequent release of heavy metals into the water column. These metals are toxic and will likely have a negative impact on the species inhabiting the area surrounding the mine site – either directly, or via secondary effects such as reducing levels of available oxygen in the water. Non-vent organisms may also use vent sites for aspects of their lives: for example, some skates incubate their egg cases at active hydrothermal vent sites. The effects of mining on these organisms will be difficult to quantify and monitor.

Mining Fe–Mn Nodules

Once considered to be a near-barren landscape, the Fe–Mn nodule field in the Clarion–Clipperton Zone is now known to host high biodiversity (Amon et al. 2016) (Fig. 2). As a result, Fe-Mn-nodule mining is expected to have a number of specific impacts on seafloor and water-column communities. Most obviously, the Fe–Mn nodules themselves provide a hard surface that is home to a wide variety of life, including sponges, corals, anemones, worms, foraminifera, nematodes and microbes. In turn, many of these larger organisms provide a substratum, or foundation, for other animals to inhabit (e.g. sea stars and small crustacea on corals) (Mullineaux 1987; Gooday et al. 2015; Amon et al. 2016). Ferromanganese nodules are not a renewable resource because they take millions of years to form. Removing the Fe–Mn nodules will, thus, have major impacts on the associated fauna, particularly as it has been suggested that half of megafaunal species in the Clarion–Clipperton Zone directly depend on the Fe–Mn nodules (Amon et al. 2016; Vanreusel et al. 2016). A recently discovered example of this is the white "Casper" octopus that lays its eggs on sponge stalks growing on Fe–Mn nodules and crusts.

Ferromanganese nodules are found in very stable environments on soft sediments with strong vertical stratification and low concentrations of organic matter (Mewes et al. 2014). Disturbance of sedimentary environments like these will lead to the disruption of the surface sediment (5–20 cm deep) and cause exposure of deeper sediment layers and compaction. These changes will impact the sediment geochemistry, which will likely kill the fauna living within the sediments and impair ecosystem recovery processes. In addition, the scale of Fe–Mn nodule mining will be particularly large, with the potential for areas of several hundred square kilometres to be disturbed each year by a single operation (Smith et al. 2008). Impacts on this scale are rare in deep-ocean environments and may lead to effects that can be seen at regional scales, such as population reductions or even species extinctions.

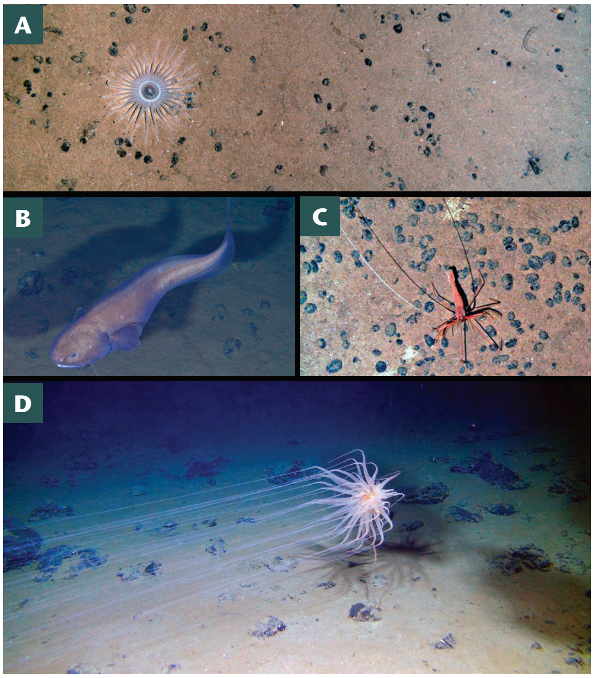


Figure 2 Fauna from the Fe–Mn nodule fields in the Clarion–Clipperton Zone (Pacific Ocean). (**A**) An anemone (left) and small coral (right). Image: National Environment Research Council, RRS *James Cook* cruise leg JC120. (**B**) Abyssal fish of *Bassozetus* species. Image: Diva Amon and Craig Smith (University of Hawaii at Manoa, USA). (**C**) Decapod crustacean *Bathystylodactylus* species. Image: National Environment Research Council, RRS *James Cook* cruise leg JC120. (**D**) Cnidarian *Relicanthus* species with very long tentacles streaming out into the seabed current. Image: Diva Amon and Craig Smith, (University of Hawaii at Manoa, USA).

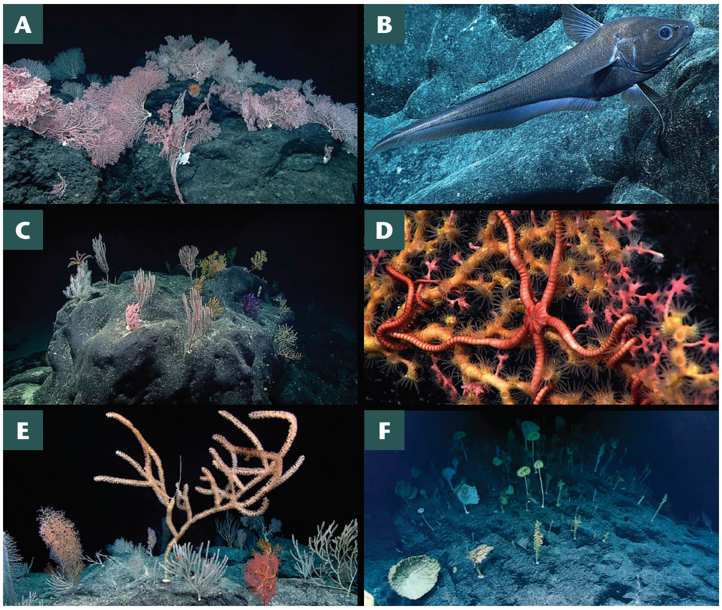


Figure 3 Faunal communities from Fe–Mn-encrusted seamounts in the Pacific Ocean. (**A**) An abundant community of large corals with anemones, crinoids and ophiuroids. (**B**) A rattail fish (*Coryphaenoides* species). (**C**) A diverse community of corals with associated crinoids and ophiuroids. (**D**) An ophiuroid living in a commensal relationship on a coral that is overgrown in some places by zoanthids. (**E**) A diverse and abundant coral and sponge community. (**F**) A community dominated by sponges. All images: NOAA Office of Ocean Exploration and Research.

Mining Fe–Mn Crusts

The mining of Fe–Mn crusts will also have a variety of environmental impacts (Schlacher et al. 2014). The extraction process will entirely remove the mineral-rich surfaces of the seamounts, which are inhabited by benthic fauna that include corals, sponges, echinoderms, and other invertebrates, sometimes in very dense populations. Many of these animals are not yet known to science, they may be long-lived (hundreds to thousands of years old for some corals and possibly sponges), be fragile, and larger individuals may be responsible for much of the reproductive output, which is needed to safeguard future populations. Isolated seamounts may host endemic species that could be more prone to extinction from mining because they are well adapted to a specific habitat and set of environmental conditions. Ferromanganese crusts are also the most likely resource to be found in areas affected by other human activities, particularly deep-sea fishing, and that could result in cumulative negative impacts (Morato et al. 2010). The sediment plumes generated by mining operations may directly impact the fish and other pelagic organisms that tend to congregate on and above seamounts. Additionally, many commercially exploited fish species depend on the rich invertebrate assemblages that are found on seamounts as nursery grounds and as hiding places to avoid predators. Thus, mining may also have secondary impacts on fish communities and the ecosystem services they provide.

Ecosystem Degradation and Recovery

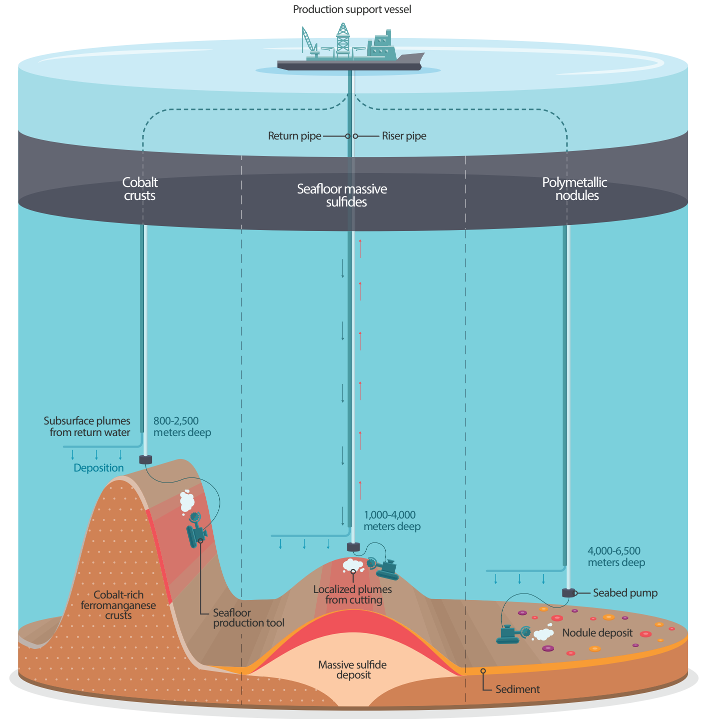
All deep-ocean mining operations will result in the degradation and loss of habitats, potentially resulting in extinctions of endemic and/or rare taxa and decreased species diversity of all size classes. Other deep-sea mining impacts include modified trophic interactions, a risk of transplanting organisms from one mining site to another, and lost opportunities to gain knowledge about what is currently unknown (Boschen et al. 2013). For both Fe–Mn crusts and nodules, the ecosystems found where mining is planned to take place tend to be slow-paced and are not usually subjected to the type of disturbances expected from mining. Even for seafloor massive sulfide deposits at hydrothermal vents, which are often considered a relatively dynamic habitat, remarkable decadal stability has been observed (Copley et al. 2007; Du Preez and Fisher 2018). As a result, it is expected that recovery from any mining disturbances will be extremely slow, particularly when important structuring habitats (e.g. nodules, vent chimneys and corals) are removed by the mining activities.

In summary, there is great uncertainty surrounding the natural environment in and around the deep-ocean mineral deposits currently being considered for extraction, as well as about the full impact of mining and the resilience of associated ecosystems and their potential for recovery.

Existing information on the ecological effects of mining and potential recovery times is limited, despite deep-ocean mining-related research having been conducted since the 1970s (Jones et al. 2017). The most intensive assessment has been the disturbance and recolonization experiment (DISCOL) that was carried out in an area of Fe–Mn nodules off Peru at a water depth of 4,150 metres in 1989. This experiment disturbed the seafloor across several kilometres with nearly 80 plough tracks. The experimental site and other similar seafloor areas were re-investigated in 2015 through the European Union-based intergovernmental Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI-Oceans) Programme. Even after 26 years, there was little change to the disturbed tracks: they looked much the same as when they were first made. Detailed biological studies showed that while some mobile species moved back into the tracks, there was very little recolonization of disturbed areas. Even microbial communities struggled to recover (Gjerde et al. 2016). Recovery from commercial-scale mining is likely to be even slower, as both the temporal and spatial scales of disturbance will be much larger than those of the experiments. These regional-scale impacts could result in local extinctions and population declines, reducing biological connectivity and reproductive success, as larval supply decreases with distance from unaffected populations.

Deep-Sea Ecosystem Knowledge Gaps

A fundamental problem for predicting the impacts of deep-ocean mining is our limited knowledge about deep-sea ecosystems in general. The animals inhabiting Fe–Mn nodules, Fe–Mn crusts and seafloor massive sulfides are poorly known: many are expected to be new to science. There is also a lack of basic ecological information; for example, on the species present and their population sizes, behaviours, distributions, life histories, growth rates, reproductive patterns and dispersal potential. We don't know, for the vast majority of organisms, how and if populations are connected, and what is needed for the maintenance of viable communities. Some species that have been evaluated show wide distributions and connectivity between populations on scales of hundreds of kilometres, but assessments of Fe–Mn nodule systems show that there are also a large number of rare species, which tend to occupy a smaller geographic range (Glover et al. 2002). These patterns may be an artefact of limited sampling, but many species are known from only a few individuals that have poorly understood ecological roles, particularly for the smaller animals. Typical conservation measures on land tend to focus on rare species for inherent value, or the ecosystem functions they support. The presence of rare species may also be used as an indicator of ecosystem health and high biodiversity although common species also play key roles in seafloor massive sulfide deposit–hosting ecosystems. Identifying 'indicator' species in the deep-sea is, therefore, currently difficult, and this in turn prevents specific species-based conservation actions and inhibits our efforts to improve management actions.



Source: New Zealand Environment Guide

FIGURE 4 Potential types of deep-sea mining operation. Image shows production support vessel on sea surface, with generalized subsurface mining equipment for the three main mining deposits shown below (**left**: Fe–Mn-encrusted seamounts; **middle**: seafloor massive sulfides; **right:** Fe–Mn nodules). IMAGE: THE PEW CHARITABLE TRUSTS.

ENVIRONMENTAL MANAGEMENT: REDUCING THE IMPACT OF DEEP-OCEAN MINING

Whilst deep-sea mining is destructive and generally regarded as inherently unsustainable, there are many opportunities to reduce the impacts through good management practices (Durden et al. 2017). First, extensive fundamental research needs to be done in each area planned for mining to ascertain baseline conditions. This research should incorporate high-resolution mapping and assessments of both the spatial and temporal patterns in physical and chemical conditions and of the faunal communities that inhabit the area. Ecosystem functioning (the combination of biological and physical interactions) should also be studied, to prevent mining-related ecosystem collapse and to ensure that the ecosystem services that we rely on will be provided during and after mining. Overall, this information will result in a better understanding of the communities that are at risk and can be incorporated into environmental management plans.

The next stage is to evaluate the potential impacts of the mining operation by undertaking environmental impact assessments. A typical environmental impact assessment will assess the risks of the project in question and sensitivities of the environment. It should also identify alternative project plans that may reduce or mitigate the impacts of mining, helping to preserve unique and vulnerable communities (Durden et al. 2018). The negative impacts on an ecosystem are typically reduced by applying a four-stage mitigation hierarchy during mining operations. This hierarchy comprises four steps that are designed to be implemented sequentially: 1) avoid (e.g. move the project away from a vulnerable habitat); 2) minimize (e.g. introduce new technology to model and reduce the sediment plume generated by a mining vehicle); 3) remediate (e.g. restore biodiversity to mined areas); and 4) offset (e.g. restore biodiversity in an equivalent area to that lost from mining). The last two options – restoration and offsetting – are considered impractical for deep-sea mining at present as a result of a range of biological, technical, financial and legal issues (Van Dover et al. 2017). Once a project's risks have been reduced as much as is practical, a decision can be made as to whether the economic, social, and political benefits of the project outweigh the costs, be they environmental or otherwise. If the project is approved, then plans can be made for ongoing environmental monitoring to identify and measure the impacts of the project. If any negative effects become too severe, the project can be curtailed. These management strategies should be continued throughout the life of the project and after it has been decommissioned.

The mining company primarily carries out the environmental management of individual mining projects. However, additional regional management is necessary for sustainable mining on broader scales to achieve wider conservation objectives. Decisions about mine-site placement, the number of active mines, and the designation of marine protected areas, are best made by the agency responsible for the regulation of mining within a region. In the case of deep-sea mining, this is principally the International Seabed Authority (based in Kingston, Jamaica), the role of which is reviewed by Lodge and Verlaan (2018 this issue). To date, the spatial allocation of exploration areas has been driven by contractor applications to the International Seabed Authority in areas of interest in the world's oceans. However, a regional management plan has been made for the Clarion–Clipperton Zone (Wedding et al. 2013), which currently includes nine areas known as the 'Areas of Particular Environmental Interest', where mining cannot currently occur. These Areas of Particular Environmental Interest are peripheral to the central section of the Clarion–Clipperton Zone, which holds the highest Fe–Mn nodule densities, and they each consist of a 200 × 200 km^2 protected zone, surrounded by a 100 kilometre buffer. The Areas of Particular Environmental Interest are designed to be geographically close enough to allow for biological connectivity with the proposed mining areas, so allowing re-colonization to occur after mining has ceased.

Further spatial management includes 'Preservation Reference Zones', which are areas established to monitor the effects of individual mining projects. Such zones are representative areas where mining cannot occur, may also act as protected areas. Many areas of mining interest do not have a regional environmental management plan. These plans need to be developed prior to mining and should take into account a range of factors, including the mining type, potential impacts, specific ecosystems, connectivity, vulnerability and the optimal approaches for management.

Management of deep-ocean mining is made more complex by the high uncertainty associated with the impacts of mining, the environments and ecosystems affected, and how they will respond to disturbance. This uncertainty can be addressed in part by further research targeted at the areas and regions of exploitation interest. To better protect large and/or connected areas, precaution and the ability to adapt management approaches as more information becomes available will also be important.

CONCLUSION

Current interest in deep-sea mining is focused on three habitats for which we are lacking fundamental baseline knowledge about species composition, ecology, and natural environmental conditions. It is, however, without doubt that deep-sea mining has the potential to have far-reaching impacts on our oceans. While some impacts will be resource-specific, mineral deposit extraction will broadly affect local and regional marine communities by removing suitable habitats, creating far-reaching sediment plumes and reducing population sizes (or, in the case of rare or specialist species, causing extinctions). Deep-sea mining will impact habitats, which will take, at a minimum, decades to recover. The need for baseline information about reproduction, growth, population sizes, diversity, distributions and more is essential for successful environmental impact assessments and sustainable management of these habitats during mineral extraction.

Exploitation on such a large scale has never occurred before in the deep ocean; its environmental management is a nascent endeavour. For the impacts of deep-sea mining to be minimized, there is a requirement for cooperation between all stakeholders on a national and international level: industry, policymakers, scientists, non-governmental organisations, and members of the public whose livelihoods depend on ocean resources. Most importantly, the International Seabed Authority will need to continue to enforce coherent strategic planning and management. This needs to take place on both local and regional scales for all areas in which there is interest in mining, and the International Seabed Authority needs to stand by its commitment to ensure that the harmful effects from deep-ocean mining are minimized and that the deep-sea mining industry proceeds in an informed and careful manner in the future.

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Deep-Sea Mining: International Regulatory Challenges and Responses

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Deep-sea mining presents complex regulatory challenges due to its multi-faceted political, economic, technological, scientific, environmental, social, industrial and legal aspects. **These must all be sensitively addressed to achieve a commercially viable and socially responsible industry. Furthermore, these aspects are either governed by, or must take into account, the burgeoning regulatory regime promulgated by the International Seabed Authority. This paper addresses the regulatory challenges associated with the three types of deep-ocean mineral deposits of greatest interest to the deep-sea mining industry: polymetallic nodules, ferromanganese crusts, and polymetallic sulfides. We review current resource interest, the international regulatory context, selected regulatory challenges, and the International Seabed Authority's innovative responses to selected issues.**

Keywords: deep-sea mining, exploration, exploitation, regulatory, environment, sustainability

INTRODUCTION

There are three main types of deep-sea mineral resources, introduced by Lusty and Murton (2018 this issue), that are currently attracting most interest. Each represent distinct classes of metal-bearing mineral deposits which occur in distinctive biogeophysical deep-sea environments. The three types of deep-sea mineral resources under discussion are polymetallic nodules ('Fe–Mn' nodules), ferromanganese crusts and polymetallic sulfides (i.e. seafloor massive sulfides). Each type of deposit presents individual technical, environmental, and regulatory challenges at every stage of the exploration and exploitation cycle. These challenges derive from the following factors:

1) the physical nature and expression of the deposit itself (considered by Jones et al. (2018 this issue));

2) the biogeophysical environment of each deposit type: abyssal plain sediments for nodules; rocky seamounts and ridges for crusts; and hydrothermal vent systems for seafloor massive sulfides;

3) the geographic location of the deposit.

ENVIRONMENTAL ASPECTS

The most significant environmental challenges and impacts of deep-sea mining as summarized by Jones et al. (2018 this issue) are briefly reiterated here because they form one of the principal regulatory challenges facing the International Seabed Authority. These environmental challenges, and the International Seabed Authority's response, also present technical challenges (not addressed here) for the deep-sea mining industry.

An extensive and rapidly growing body of scholarly literature addresses the potential effects on the marine environment of deep-sea mining. These effects are usually addressed in one or more of three contexts common to the three mineral resources under discussion: the surface, in the water column, and at and below the seafloor. The surface and the water-column effects are likely to be similar for all three resource types. The most extensive effects, i.e. those with the most potentially long-term consequences, are likely to occur at the seafloor.

The principal environmental impacts and the main environmental advantages of deep-sea mining are summarized in Table 1. It must be emphasized that deep-sea mining, considered both on its own and in the context of the overall global stressors on the health of this planet, has much to offer that is environmentally constructive.

INTERNATIONAL LEGAL AND REGULATORY CONTEXT

One regulatory challenge shared by all three deposit types is their location on and below the seabed, far offshore: at least 25 nautical miles from land (i.e. outside the 12 nautical mile territorial sea) and usually much further out to sea (i.e. beyond 100 nautical miles in the Exclusive Economic Zone). The Exclusive Economic Zone extends 200 nautical miles from a fixed baseline, which under international law is usually the low-water line along the coast (as marked on official charts of the relevant coastal state) and on the (outer) continental shelf (which may, under certain circumstances not addressed here, extend out to 350 nautical miles or to 100 nautical miles from the 2,500 m isobath), and includes sea areas beyond any national jurisdiction (i.e. the so-called 'high seas') (Fig. 1). The deposits of greatest commercial interest are found in the Pacific, Indian, and Atlantic Oceans, listed here in order of geological prospectivity (mineral potential) and associated economic interest based on current knowledge. To date, the most commercially significant resources have primarily been found outside national jurisdiction, which under international law triggers application of an international regulatory regime, of which a brief overview follows.

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TABLE 1 PRINCIPAL ENVIRONMENTAL IMPACTS AND ADVANTAGES OF SEABED MINING

Environmental Impacts of Seabed Mining

- permanent removal of hard substrate required by certain organisms/faunal communities
- effects of sediments, wastes, and other effluents (at bottom, mid-water and surface)
- noise
- vibration
- light
- leaks, spills, the effects of infrastructure corrosion
- operational discharges from the surface vessels*
- slow and different biological regeneration (especially of sessile communities)
- uncertain remediation potential
- vessel traffic for ore transport to shore* for land-based processing
- vessel-source air pollution*
- surface and mid-water marine community disturbance, especially if mining vessels remain on location for many months

Environmental Advantages of Seabed Mining (Contrasted with Terrestrial Mining)

- little or no overburden to remove (e.g. overlying rock, soil, vegetation cover)
- ore grades can be significantly higher than on land, meaning that less ore is required to provide the same amount of metal
- multiple metals can be obtained from a single site due to polymetallic nature of deposits
- no local human populations to be disrupted
- no permanent infrastructure

* governed by International Maritime Organization treaties and regulations, which are not addressed in this article

The United Nations Law of the Sea Convention

The United Nations Law of the Sea Convention (LOSC) is our world's "Constitution for the Oceans" (Koh 1983). Negotiated over nearly ten years, it entered into force on 16 November 1994; as of 1 February 2018, it has 168 parties. Comprised of 320 Articles and 9 Annexes, it is one of the longest and most complex multi-lateral treaties concluded to date. Furthermore, it is, as of 2018, the most powerful and comprehensive treaty governing human activities on this planet. No terrestrial (land-based) equivalent exists. The Law of the Sea Convention aims to have an all-inclusive scope with regard to law of the sea issues (see Preamble, first paragraph). Because it applies also to land-based and atmospheric activities when the marine environment is or may be adversely affected, its remit in this context spans the planet.

Of particular note is the profound concern of the drafters of the Law of the Sea Convention for the marine environment (BOX 1). In addition to an entire chapter (Part XII) (see below) being dedicated to this subject, the first Article addresses the marine environment by setting out an all-encompassing definition of 'pollution of the marine environment'. Note that this definition applies to anthropogenic CO_2 emissions, regardless of their source. In the environmental context, there is also extensive use of the precautionary words 'may' [e.g. LOSC Articles 119 1.(b); 145; 196; 206] and 'likely' [e.g. LOSC Articles 1 1.(1)(4); 198; 204(2)] in provisions designed to establish circumstances under which action to protect and preserve the marine environment is required.

An essential source of the Law of the Sea Convention's power is that its provisions are usually mandatory, unqualified, and without exceptions. The unqualified nature of the provisions is illustrated by the virtual absence of phrases such as 'in accordance with capabilities', 'as appropriate', 'as far as possible', 'as far as practicable,' whose use in treaties, even when coupled with 'shall', unfortunately tend to negate in practice these treaties' obligatory intentions. For example, Article 309 explicitly prohibits reservations or exceptions and Article 310 reinforces this prohibition for states becoming parties to the Law of the Sea Convention. Finally, many of its provisions are now considered to have codified, or become part of, customary international law, thereby making it exceedingly difficult under international law for non-parties to act inconsistently with those provisions.

The Law of the Sea Convention and Deep-Sea Mining

We address here the Law of the Sea Convention provisions applicable to the mineral resources found in areas beyond national jurisdiction. Of these, the most important are LOSC Part XI, LOSC Annexes III and IV, and the 1994 Agreement Relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea. Note the Law of the Sea Convention's definitions of the 'Area', 'activities in the Area', 'resources of the Area': these definitions

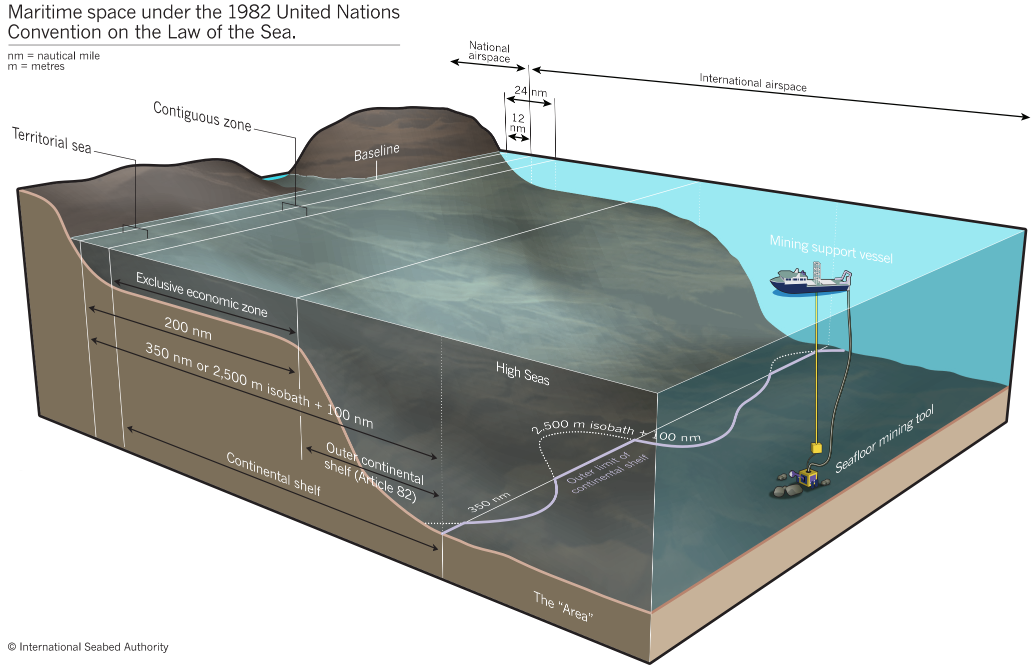

FIGURE 1 Maritime space as defined under the 1982 United Nations Convention on the Law of the Sea. IMAGE: INTERNATIONAL SEABED AUTHORITY.

Box 1 SELECTED LAW OF THE SEA CONVENTION PROVISIONS RELEVANT TO ENVIRONMENTAL ASPECTS OF DEEP-SEA MINING

Part XI (Area); Annex III (Basic Conditions of Prospecting, Exploration and Exploitation); Part XI (Implementing Agreement)

- Part XI (Article 145): Prevent/reduce/control pollution and other hazards to and interference with ecological balance of the marine environment; protect and conserve *natural* resources of the Area and prevent damage to flora and fauna of the marine environment
- Part XI (Article 147(1) and (3)): Conduct other activities in the Area *and in the marine environment* with reasonable regard for mineral activities and *vice-versa*
- Annex III Article 17 – sets out what the International Seabed Authority must regulate: Marine environment: (1)(b)(xii) and 2(f)
- Annex III Article 14(2): Marine environmental data are not proprietary
- Implementing Agreement: Preamble; Section 1(g), (h), (i), (k)

Part XII (Protection and Preservation of the Marine Environment)

- Article 192: "States have the obligation to protect and preserve the marine environment."
- Article 194(5): measures required to protect and preserve rare or fragile ecosystems [and] depleted, threatened or endangered species and other forms of marine life
- Articles 204 and 206: require both environmental impact assessment and monitoring
- Article 209: marine environmental protection requirements specifically for the Area; includes flag states
- Article 215: enforcement of marine environmental protection rules in the Area (see also Article 153(5) Part XI)

Part XIII (Marine Scientific Research)

- Article 240(d): Marine scientific research is subject to Part XII (marine environmental protection) rules (see also Article 87(1): on 'high seas' freedoms, which include marine scientific research; their exercise is not unrestricted; all 'high seas' freedoms must be exercised with due regard for activities in the Area (Article 87(2)).
- Article 256: Marine scientific research may be conducted in the Area (see also Article 87(2) and Part XI Article 143) by the International Seabed Authority, state parties and other competent international organizations
- Articles 242 and 243: International cooperation in general and between the International Seabed Authority, state parties and contractors in particular on marine scientific research is encouraged, especially on the marine environment and related research (see also Article 143 on marine scientific research in the Area). This cooperation is essential for developing and implementing *cumulative* environmental impact management systems.

all relate only to the seabed/subsoil and solid, liquid, or gaseous minerals found in areas beyond national jurisdiction, and thereby set the jurisdiction of the International Seabed Authority, the body set up under the Law of the Sea Convention (Part XI Section 4), to administer activities in and the resources of the Area.

Legal Status of the Area and its Resources

Both the Area and its resources are designated by LOSC Article 136 as "the common heritage of mankind", a sui generis legal status which entails that no state may exercise sovereignty or sovereign rights over the Area or its resources and that rights in the resources of the Area (i.e. minerals) are "vested in mankind as a whole", on whose behalf the International Seabed Authority acts (LOSC Article 137(2)), but only for those specific rights. It is important to note that in the context of the Law of the Sea Convention the "common heritage of mankind" denotes only a specific and limited legal status and does not imply any moral or philosophical concept.

International Tribunal for the Law of the Sea (ITLOS)

Established pursuant to LOSC Article 287(1)(a) and operating according to its statute under LOSC Annex VI, the International Tribunal for the Law of the Sea (ITLOS; www.itlos.org), is an essential part of the comprehensive scope of the Law of the Sea Convention. Under LOSC Article 186, the Seabed Disputes Chamber, a chamber of 11 judges, exists as a 'court within a court' with specialized jurisdiction over matters relating to deep-sea mining under Part XI of the Law of the Sea Convention. On 1 February 2011, the Chamber issued a pioneering advisory opinion (pursuant to LOSC Article 191) on responsibilities and liabilities of states engaging in or sponsoring marine mining (LOSC Article 139), especially with regard to the marine environment, holding that all states, regardless of their developmental status and financial and technical capabilities, must comply with the Law of the Sea Convention and with the International Seabed Authority's mining regulations (ITLOS 2011) (Freestone 2011).

International Seabed Authority

The International Seabed Authority implements the Law of the Sea Convention on deep-sea mining. It is headquartered in Kingston, Jamaica (www.isa.org.jm). All Law of the Sea Convention parties are members of the International Seabed Authority. The International Seabed Authority has the exclusive mandate to manage seabed minerals in the Area on behalf of 'mankind as a whole', and the exclusive right to issue exploration and exploitation contracts for minerals in the Area. It is not empowered to exclude other (non-mineral) activities in the Area, such as marine scientific research, even in areas for which it has issued an exploration contract. It is not empowered to issue contracts for activities related to other (non-mineral) resources in the Area.

Under the Law of the Sea Convention, exploration for and exploitation of seabed minerals in the Area may only be carried out under a contract with the International Seabed Authority and subject to its rules, regulations and procedures. Contracts may be issued to both public and private mining enterprises provided they are sponsored by a state party to the Law of the Sea Convention and meet certain standards of technological and financial capacity. Ultimately, the economic benefits from deep-sea mining, most likely in the form of royalties paid to the International Seabed Authority, are to be shared for the 'benefit of mankind as a whole', with particular emphasis on the developing countries that lack the technology and capital to carry out seabed mining for themselves.

The International Seabed Authority develops internationally legally binding regulations. So far, it has issued regulations governing exploration for nodules, crusts and seabed massive sulfide deposits. The exploitation regulations are now being developed. The International Seabed Authority is using an innovative international consultation process to assist it in the development of these regulations. The mineral resources of the Area are the common heritage of mankind, and the International Seabed Authority is consulting mankind on how these resources are to be exploited and how the proceeds are to be allocated. All the responses to International Seabed Authority consultations are available on the International Seabed Authority's website. Pursuant to LOSC Articles 208 and 209, International Seabed Authority regulations also operate to set minimum environmental standards for national regulation of deep-sea mining on the "legal" continental shelf (i.e. within the Exclusive Economic Zone) and on the outer continental shelf where, and to the extent that, this portion of the shelf has been formally allotted to the coastal state by the Commission on the Limits of the Outer Shelf pursuant to a claim from that coastal state. The International Seabed Authority environmental regulations are already extensive (see the International Seabed Authority's website). No exploitation contracts have yet been applied for.

The International Seabed Authority sponsors research, workshops and publications. The results are freely available on the International Seabed Authority's website and associated apps. Much of this technical activity is channelled through the International Seabed Authority's Legal and Technical Commission. Composed of 30 scientific, technical and legal specialists, it has a heavy workload. For example, the Legal and Technical Commission reviews draft regulations, examines and recommends actions by the Council of the International Seabed Authority on applications for work in the Area, monitors and comments on the contractors' work in the Area through the latter's required annual reports, and deals with the implementation of the extensive marine environmental protection duties imposed by the Law of the Sea Convention for deep-sea mining activities.

The International Seabed Authority's Environmental Data Requirements

The International Seabed Authority's environmental data requirements are extensive, as can be expected from the Law of the Sea Convention's own requirements and the environmental challenges set out in Table 1. All relevant data – including oceanographic, hydrographic, geological, chemical and biological data, data standards and inventories, cruise reports, and raw environmental data – must be published in the format established by the International Seabed Authority and all data must be made freely available for scientific analysis within four years after completion of a research cruise. An inventory of the data holdings from each contractor must be accessible on the World Wide Web. Metadata describing analytical techniques, error analyses, descriptions of failures, techniques and technologies to avoid, comments on sufficiency of data, and other relevant descriptors must be included with the actual data. To answer questions on the environmental impacts of mining, specific experiments, observations and measurements must be conducted. In this context, the Law of the Sea Convention and the International Seabed Authority strongly encourage collaborative research by contractors in which the International Seabed Authority also endeavours to participate when possible. Not all contractors are required to execute the same studies, and the International Seabed Authority encourages, advises, and assists in identifying cooperative research opportunities between contractors and other research communities. Such collaborative research is needed in, for example, the following instances:

- To minimize, and possibly mitigate, the effects of the loss of hard substrate (e.g. in the Clarion–Clipperton Zone for nodules);
- To develop methods to minimize the effects of the direct disturbance of the seafloor during mining, and of the material carried in, and deposited from, the operational plume generated;
- To enhance natural recolonization of the seabed after mining has taken place.

This requires detailed, long-term (at least ten years) regional and local baseline and operational research, including experiments and modelling. Even ten years may be insufficient time to fully understand the impacts of deep-sea mining: in the deep sea, disturbed biological communities rebuild only very slowly (Jones et al. 2018 this issue). The major challenges are to first minimize and then, if possible, mitigate and remediate the effects of mining with regard to, in particular, hard substrate removal and sedimentation.

Environmental Regulatory Challenges

The International Seabed Authority needs all this environmental information because it must also engage in regional environmental management, which includes assessment and management of cumulative and local impacts of mining activities, biodiversity conservation, and facilitation of benthic recolonization. For an area the size of, for example, the Clarion–Clipperton Zone (~7 million km^2) in the northeast Pacific Ocean, and with (as of 1 February 2018) 16 different exploration contracts from 18 different state parties, this is a daunting challenge (Fig. 2). Nevertheless, the Clarion–Clipperton Zone is the area where these requirements are going to be first set out and tested. This is because the Clarion–Clipperton Zone is the only region in the deep sea that has been subject to ongoing research in all the oceanographic and many of the engineering disciplines since the 1960s, and because its nodules are the closest to exploitation of the three categories of resources located in the Area. All 18 state parties have exploration contracts for nodules in the Clarion–Clipperton Zone.

REFLECTIONS ON THE REGULATORY CHALLENGES FACING THE INTERNATIONAL SEABED AUTHORITY

Seafloor minerals are the only example of a global resource that is under international contractual management by an international organization established exclusively for that purpose. This immediately distinguishes them from other resources in frontier environments, such as those in outer space. Therefore, the International Seabed Authority represents a unique experiment in international law, international relations, and international regulatory development. For many countries, it fulfils a long-held vision that the mineral wealth of the deep seabed beyond national jurisdiction should not be appropriated by a few technologically advanced countries but should be shared between all countries, including the landlocked and disadvantaged countries, given its status under the Law of the Sea Convention as the common heritage of mankind. The task of the International Seabed Authority is to deliver on this vision and to make sure that it is done in the most responsible and sustainable way possible.

Two major challenges confront the International Seabed Authority at present. The first is to establish a workable regulatory framework for mineral exploitation that incentivizes contractors to commit significant investment and resources to develop deep-sea mining projects, but which also addresses concerns of state parties to the Law of the Sea Convention, as well as other stakeholders, such as environmental groups. These concerns range around, for example, regulatory stability and predictability, and the financial and environmental management regime.

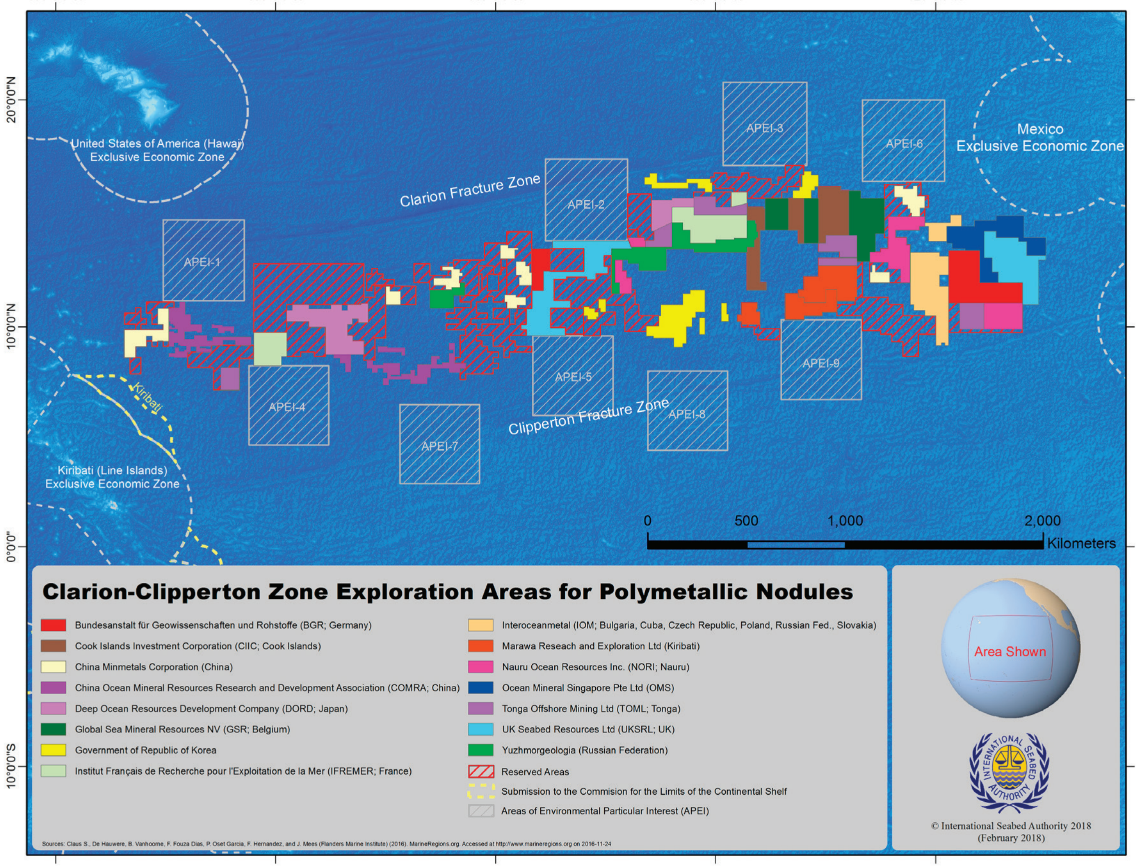

FIGURE 2 The Clarion–Clipperton Fracture Zone in the northeast Equatorial Pacific Ocean. Each coloured block represents an area under current exploration for polymetallic nodules by various contractors. The associated sponsoring states are indicated in brackets. The map also shows Areas of Particular Environmental Interest as squares with diagonal white lines. IMAGE: INTERNATIONAL SEABED AUTHORITY.

The second major challenge is environmental planning at the regional scale. As briefly described above, this is a greater, and potentially far more interesting, challenge. If project-based environmental management is primarily the function of the operator, the other major task of the International Seabed Authority is to manage it at a global and regional scale. In one critically important way, this is already the case, because the fundamental concept of the Law of the Sea Convention is that deep seabed mining is only allowed to take place under contract to the International Seabed Authority. Hence, the default position is that the seabed is off limits to mining except where expressly permitted by the International Seabed Authority following a lengthy process of approval. Everything is protected. This essential aspect immediately sets deep seabed mining apart from any other high-seas activity, including fishing. But more work is needed to effectively manage environmental planning at a regional scale.

With regard to deep seabed mining and the environment, a major challenge is addressing the persistent unease that deep seabed mining must be bad for the marine environment in some way. This unease may be in part attributable to the word ‘mining’, which conjures up images of destruction taken from controversial practices ascribed to some land-based operations. When this is juxtaposed with the popular – but alas erroneous – image of the deep seabed as a pristine wilderness, then alarm does result. In reality, seabed mining has been around for centuries. It is likely that the deep seabed mining industry will use or adapt many of the proven technologies and management techniques used successfully for many years in shallow-water mining.

As alluded to above, there is good evidence that, compared to land-based mining, seabed mining offers a more commercially and environmentally sustainable source of raw material supply far into the future. Therefore, dramatic headlines such as ‘an invisible land grab’, ‘machines the size of buildings literally destroying the systems that keep us alive’, ‘clear-cutting the ocean floor’, and so forth, are misleading, emotive and not constructive. Similarly, comparisons to disasters such as the oil spill from the *Deepwater Horizon* in the Gulf of Mexico in 2010, which involved a volatile compound totally different in character to deep-sea hard-mineral ores, are misguided.

It is necessary that, collectively, the international community ground its regulatory discussions in reality. Key points are set out in the paragraphs immediately below.

Deep seabed mining has not started yet. All activities to date are exploration, which so far have involved no significant environmental impact. Therefore, the international community has a unique opportunity to get it right. In fact, this is probably the best-regulated industry that has not happened yet!

Even when deep seabed mining does start, it will most likely be at the scale of a limited number of operations. Based on the size of investments required, no one is currently predicting more than a handful of commercial operations during the first 15 or so years. This offers ample time to monitor and assess impacts, learn from experience and to improve technology.

Existing, well-established and proven environmental management techniques are easily applicable to deep seabed mining. The international community agrees that environmental impact assessments are required and that the regulator must specify the level of permitted impacts. The standard environmental management tools that have been used in offshore industries for years – spatial management, impact assessment, prevention, and mitigation – are all applicable.

Worst-case scenarios are massively exaggerated and bear very little relation to reality. By and large, deep-sea mining involves rocks and mud, not volatile compounds under pressure. No tailings (in the land-based mining sense) result from deep seabed mining, operations can be monitored and halted very quickly, and direct impacts stopped rapidly.

It is clearly acknowledged that the international community, in the form of the International Seabed Authority, is embarking upon a new adventure, with many unknown factors to consider, and that it is confronted with real problems around a lack of detailed knowledge of deep-sea ecosystems, a lack of scientific data, and an uncertainty as to the scale and duration of impacts.

It must be stressed, however, that it is useless and counterproductive to argue that an a priori condition for deep-sea mining is an existential debate about whether it should be permitted to go ahead or not. The international community passed that point already many years ago. This is because the one factor that distinguishes deep seabed mining from any other extractive activity, or indeed any other ocean use, is the nature of the underlying legal regime established by the Law of the Sea Convention, as briefly described above.

Nevertheless, it is clear that it will be necessary to drastically improve our knowledge of the deep seabed, both inside and outside of exploration areas. This is, in fact, being done through systematic and regulated exploration, to the overall benefit of all of us. Another critical and urgent step is to design representative networks of protected areas, managed by the International Seabed Authority, where no mining should occur. So far, the only regional environmental management plan is that for the Clarion–Clipperton Zone adopted in 2012. This ground-breaking and unique plan originated in work funded by the J. M. Kaplan Fund (a New York–based foundation for social and environmental causes) and the Pew Charitable Trusts (a Philadelphia-based organization that applies research to improve aspects of public life) to develop a scientific case for identifying a biogeographically representative network of potential protected areas. The plan was subsequently developed through an expert consultative process under the auspices of the International Seabed Authority and adopted by its political organs.

The main feature of the plan is nine Areas of Particular Environmental Interest (Fig. 2). But this also highlights one of the main flaws of the plan. It is of limited value to just set aside protected areas on the basis of models. Actual data are required to obtain a better overall picture of the regional environment. The amount and quality of available data have improved tremendously over the past few years as contractors have advanced their exploration programmes and as international scientific investigations have been undertaken. Several contractors have cooperated with the International Seabed Authority to gather data on the Areas of Particular Environmental Interest. A high priority are independent scientific research cruises, preferably with the participation of the International Seabed Authority and of developing-country scientists and specifically aimed at gathering data on the Areas of Particular Environmental Interest and surrounding areas. Only then can the International Seabed Authority undertake a meaningful review of the Clarion–Clipperton Zone Regional Environmental Management Plan and make decisions for the future.

Beyond the Clarion–Clipperton Zone, singled out here as the part of the Area most likely to see deep-sea mining occur first, both the International Seabed Authority Council and the General Assembly of the United Nations recognize the urgent need to develop regional plans in other mineral provinces of the Area where exploration activities are taking place. Member states of the International Seabed Authority emphasize the need for a global, multiregional approach that would enable the production of better policy and operational frameworks for site-specific management activities. Key areas for consideration include the Mid-Atlantic Ridge, the Central Indian Ocean Triple Junction, and the northwest Pacific Ocean.

Regional environmental plans, designed to collate all relevant scientific data for each sub-region of the Area, are the best way to complement the work already undertaken by the International Seabed Authority and to give more ownership to state parties in each region, particularly developing countries. In turn, this would strongly contribute to the discussions held within the International Seabed Authority for developing the necessary frameworks and processes in order to set specific management objectives for contractors in the planning and monitoring of exploration and mining activities, particularly where multiple activities are taking place in the same maritime zone. The challenge is that scientific work on the required scale is very expensive. Even more resources are required to carry out long-term monitoring to measure and understand changes to the environment over time.

CONCLUSION

The International Seabed Authority has a unique, legally mandated opportunity to establish a comprehensive framework for commercially and environmentally responsible management of the emerging deep-sea mining industry. It hopes that others will find this vision equally compelling and will join it in this endeavour.

ACNOWLEDGMENTS

The authors are grateful for comments on a draft of this article by Professors David Freestone and Rosemary Rayfuse and by Ms. Youna Lyons. The authors are writing in their personal capacities. The views expressed in this article do not necessarily reflect the views of the International Seabed Authority or any of its member states.

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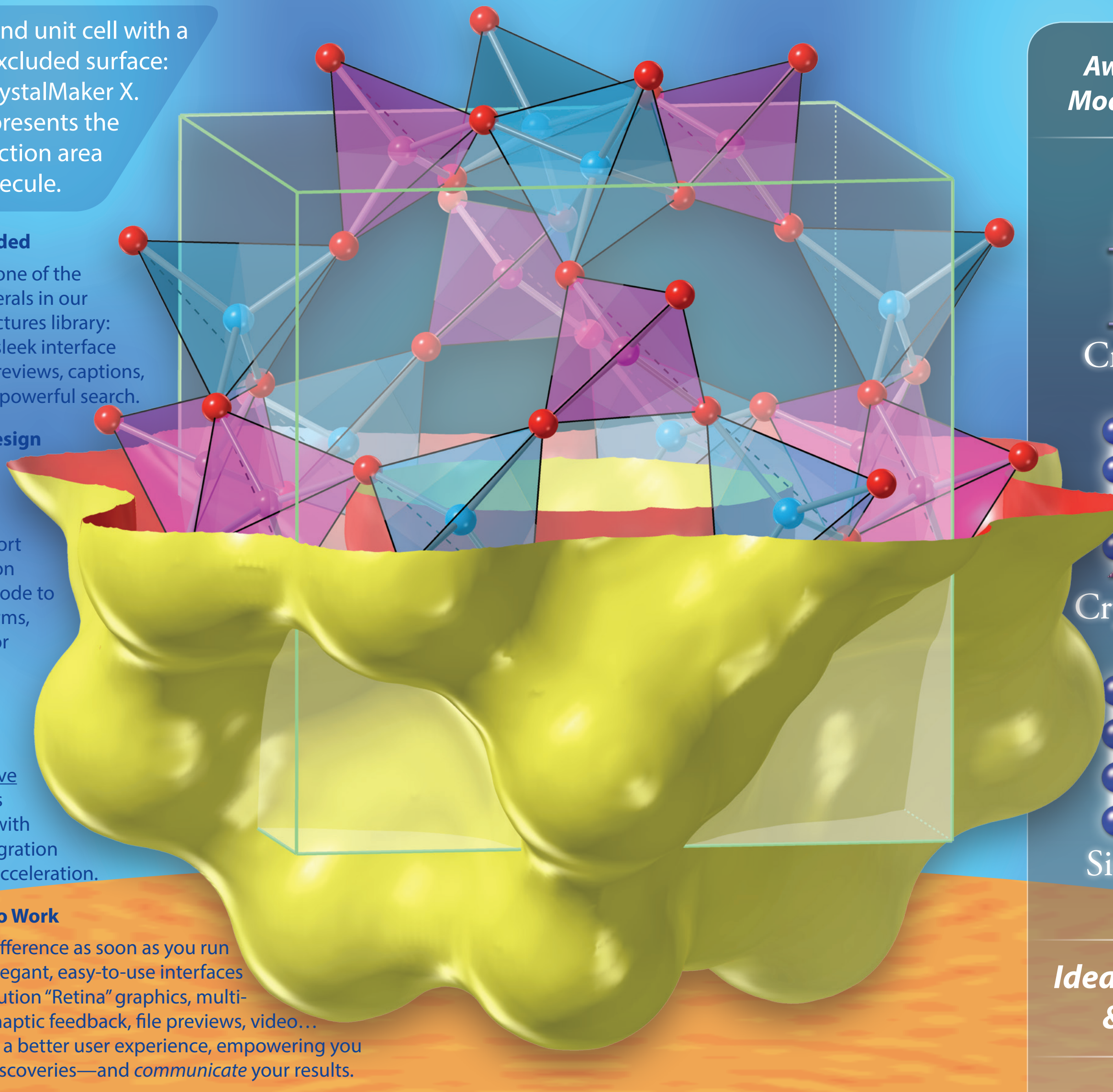

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Meteoritical Society

http://meteoriticalsociety.org

INVITATION TO THE 2019 ANNUAL MEETING OF THE METEORITICAL SOCIETY

You are cordially invited to attend the 82nd annual meeting of the Meteoritical Society (MetSoc), which will take place 7–12 July 2019 in Sapporo (Japan). The meeting is being jointly organized by Hokkaido University, National Institute of Polar Research (NIPR), and Japan Aerospace Exploration Agency (JAXA) and will be held on the Sapporo Campus of Hokkaido University. Oral sessions will take place in three meeting rooms in the Hokkaido University Conference Hall. Poster sessions will also take place at the Hokkaido University Conference Hall. Invited lectures, including the Barringer Lecture and the MetSoc Award ceremony, will take place at the conference hall in the Clark Memorial Student Center, which is a four-minute walk from the Hokkaido University Conference Hall. Yet to be finalised are the plans for a variety of special sessions and workshops on the 50th year anniversaries of the falls of Allende and Murchison meteorites, the first discovery of the Yamato Antarctic meteorites, the Apollo 11 mission, and on-going asteroid sample-return missions.

Conference registration begins on the evening of Sunday, 7 July 2019 at the Hokkaido University Conference Hall. A welcome party will be held at the University Museum. On the Wednesday afternoon of the meeting, several excursions will be offered that will allow participants to explore Sapporo and the surrounding area (including a city tour, a bus trip to Otaru harbor, a guided tour to the Kan Yasuda sculpture museum, and more). There will also be several Japanese culture experience programs for guests during the meeting. The Conference Banquet will be held at the Sapporo Park Hotel, which is inside Nakajima Park in the middle of downtown Sapporo.

Hokkaido University itself was established in 1876 as the Sapporo Agricultural College, the first modern academic institute in Japan. The Sapporo Campus of Hokkaido University, one of the largest university campuses in Japan, is located in the center of Sapporo City. Sapporo is the capital city of Hokkaido Prefecture, and the largest city on Hokkaido Island, the northernmost island of Japan. A summer in Sapporo might be described as brisk and comfortable.

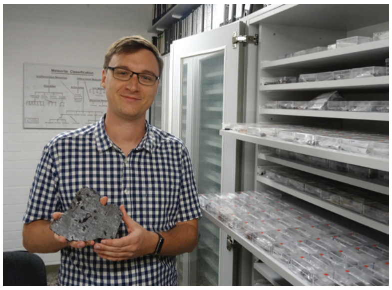
We are looking forward to welcoming you to Sapporo!

Hisayoshi Yurimoto
e-mail: yuri@ep.sci.hokudai.ac.jp

INTERNATIONAL METEORITE COLLECTORS ASSOCIATION: THE BRIAN MASON AWARD

In 1997, Joel Schiff, the first editor of the popular *Meteorite* magazine, created a travel award in honor of Brian Mason, who was born in New Zealand and spent the majority of his career as a curator at the Smithsonian Institution (Washington, USA). The award is given to a student attending the annual meeting of the MetSoc who submits an abstract that clearly explains some exciting results of particular interest to readers of *Meteorite* magazine. The recipient is required to write a popular account of their work for the magazine. Since 2008, the award has been generously funded by the International Meteorite Collectors Association.

Morgan Cox



Markus Patzek

This year the Program Committee for the Moscow (Russia) meeting selected **Morgan Cox and Markus Patzek** to win the Brian Mason Award. **Morgan Cox** is an undergraduate student at Curtin University in Perth (Australia). Her abstract was entitled “Characterisation of Shock Deformation at the Spider Impact Structure, Western Australia”, and authors were M. Cox, A. Cavosie, K. Miljkovic, P. Bland, T. Kenkmann and Z. Hoskins. **Markus Patzek** is a graduate student at Westfälische Wilhelms-Universität Münster (Germany). His abstract was entitled “O-Isotope Composition of CI- and CM-like Clasts in Ureilites, HEDs, and CR Chondrites” and the authors were M. Patzek, A. Pack, A. Bischoff, R. Visser and T. John.

CALL FOR AWARD NOMINATIONS

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

The society gives a number awards each year. The **Leonard Medal** honors outstanding contributions to the science of meteoritics and closely allied fields. The **Barringer Medal and Award** recognize outstanding work in the field of impact cratering and/or work that has led to a better understanding of impact phenomena. The **Nier Prize** recognizes outstanding research in meteoritics and closely allied fields by a young scientist. The **Service Award** honors members who have advanced the goals of the Meteoritical Society to promote research and education in meteoritics and planetary science in ways other than by conducting scientific research. The **Paul Pellas–Graham Ryder Award** is given for the best student paper in planetary science and is awarded jointly by the Meteoritical Society and the Planetary Geology Division of the Geological Society of America.

2018 ANNUAL MEETING STUDENT TRAVEL AWARDS

On behalf of the Meteoritical Society, we would like to thank the organizations whose generous sponsorship has provided student travel grants, postdoc travel grants, and travel grants for scientists from countries with limited financial resources. These sponsoring organizations, and the recipients of the travel awards themselves, are listed below.

This year, 52 travel grants were given to students and researchers who attended the annual meeting of the society in Moscow (Russia). Student travel grants and travel grants for scientists from countries with limited financial resources are generously sponsored by the Barringer Crater Company, the O. Richard Norton Fund, NASA, Elsevier publishers, the Meteoritical Society, the International Meteorite Collectors Association, the Planetary Studies Foundation, and Darryl Pitt and the Macovich Collection (Montana Meteorite Laboratory, USA).

Barringer Crater Company

Nicola Mari, University of Glasgow (UK)
Patrizia Will, ETH Zürich (Switzerland)
Aine O'Brien, University of Glasgow (UK)
Morgan Cox, Curtin University (Australia)
Takashi Yoshizaki, Tohoku University (Japan)
Stefan Farsang, University of Cambridge (UK)
Miriam Rüfenacht, ETH Zürich (Switzerland)
Jens Barosch, University of Cologne (Germany)
Nozomi Matsuda, Hokkaido University (Japan)
Daniela Weimer, ETH Zürich (Switzerland)
Runlian Pang, Friedrich-Schiller-Universität Jena (Germany)
Amanda Stadermann, University of Arizona (USA)
Brendan Haas, Washington University (USA)
Leticia De Marchi, Auburn University (USA)
Neeraja Chinchalkar, Auburn University (USA)

O. Richard Norton Award

Gerhard Schmidt, Heidelberg University (Germany)
Atsushi Takenouchi, University of Tokyo (Japan)
Haruka Ono, University of Tokyo (Japan)
Malgorzata Sliz, University of Bern (Switzerland)
Kana Amano, Tohoku University (Japan)
Wladimir Neumann, German Aerospace Center (Germany)
Runlian Pang, Friedrich-Schiller-Universität Jena (Germany)
Craig Walton, University of St Andrews (UK)
Matthew Huber, University of the Free State (South Africa)
Arindam Dutta, Geological Survey of India (India)
Amanda Stadermann, University of Arizona (USA)
Brendan Haas, Washington University (USA)
Kaitlyn McCain, University of California at Los Angeles (USA)
Evgeniya Khakhalova, University of Minnesota (USA)

Elsevier

Thomas Barrett, The Open University (UK)
Mattias Ek, ETH Zürich (Switzerland)
Atsushi Takenouchi, University of Tokyo (Japan)

International Meteorite Collectors Association, Brian Mason Award

Morgan Cox, Curtin University (Australia)
Markus Patzek, Westfälische Wilhelms-Universität Münster (Germany)

NASA Emerging Worlds

Evgeniya Khakhalova, University of Minnesota (USA)
Josiah Lewis, Washington University in St. Louis (USA)
Orion Cohen, Reed College (USA)
Leticia De Marchi, Auburn University (USA)
Neeraja Chinchalkar, Auburn University (USA)

Planetary Studies Foundation

Amanda Stadermann, University of Arizona (USA)
Kaitlyn McCain, University of California at Los Angeles (USA)

Darryl Pitt/Macovich Collection

Haruka Ono, University of Tokyo (Japan)

The Meteoritical Society Endowment Fund

Yogita Kadlag, Freie Universität Berlin (Germany)
Jane MacArthur, University of Leicester (UK)
Elizaveta Kovaleva, University of the Free State (South Africa)
Atsushi Takenouchi, University of Tokyo (Japan)
Jinia Sikdar, Freie Universität Berlin (Germany)
Wladimir Neumann, German Aerospace Center (Germany)
Josiah Lewis, Washington University in St. Louis (USA)

The Meteoritical Society Travel for International Members Fund

Dwijesh Ray, Physical Research Laboratory (India)
Taha Shisseh, Universiy of Hassan II (Morocco)
Imene Kerraouch, University of Science and Technology—Houari Boumediene (Algeria)

Mineralogical Society of America

PRESIDENT'S LETTER

Michael Brown,
MSA President

My, oh, my; how time flies!

As we age, time seems to go by more quickly. Is it really time to write my sixth and last President's Letter? It is early August, so I have three months left. My major task during this period is to complete the hire of a replacement for Alex Speer who will retire as Executive Director of the Mineralogical Society of America (MSA) at the end of 2019. At the time of writing, the search remains open and the Search and Selection Committee is working hard to identify a strong short-list of candidates. Although this task is not finished, I do want to take this last opportunity to thank Nancy Ross (Chair), David Bish, Barb Dutrow, John Ferry, John Hughes, and Rodney Ewing for serving on the Search and Selection Committee. The Executive Committee and Nancy Ross, as Chair of the Search and Selection Committee, will conduct interviews during October at the MSA offices in Chantilly, Virginia, and choose a successor to Alex before the last council meeting of 2018, which will take place in early November. Hopefully, the next MSA President, Mickey E. Gunter (Department of Geological Sciences, University of Idaho, USA) will be able to let you know the outcome of this process early in the New Year of 2019.

In this final letter, I want to promote the MSA short courses and workshops. By the time this is published, the short course entitled High Temperature Gas–Solid Reactions in Earth and Planetary Processes will have passed, but the Reviews in Mineralogy and Geochemistry (RiMG) volume will be available for purchase from the MSA web site (http://www.minsocam.org/msa/RIM/Rim84.html). If you are interested in organizing a short course, then information for prospective organizers is also available (http://www.minsocam.org/msa/SC/#organizingSC). The MSA also sponsors workshops, but these have been infrequent. I think we should offer more workshops. Maybe you are interested in organizing a workshop rather than a short course? If so, information for prospective organizers can be found at the society's web site (http://www.minsocam.org/msa/SC/#organizingWrkshp).

If you are reading this and you are not a member of MSA, please become one; if you are a member, please encourage your students and colleagues to become members! Membership is the lifeblood of any learned society. The MSA has about 2,250 members sensu lato, of whom about one-half are members sensu stricto, the other half being made up of seniors, fellows, and students. Membership fluctuates, of course, and recently our membership has varied from <2,000 in 2000 to >2,750 in 2010. It is important for the future of the MSA that students in crystallography, geochemistry, mineralogy, and petrology of Earth and planetary materials not only become members while students but also continue their membership during their professional careers. In this endeavor, we should both set an example and provide encouragement.

The end is in sight! I thank the fellows and members of the MSA for the opportunity to serve as President of the society on the eve of its centennial year. No man is an island, and I am grateful to MSA officers and councilors for their advice and support during the past year. A special thanks goes to Executive Director Alex Speer: you made my job as MSA President more effective by providing sage advice. In closing, I want to return to the theme of my first letter and thank our professional and volunteer workforce: it is through your efforts that MSA runs smoothly year in, year out. On Tuesday, 6 November 2018 I will pass the gavel to Mickey Gunter. However, I look forward to serving the MSA in different roles for many years to come.

Michael Brown, 2018 MSA President

NOTES FROM CHANTILLY

- **2018 Election Results** – The 2018 President of the society is Mickey Gunter, the Vice President is Carol D. Frost, and Past President is Michael Brown. Bryan Chakoumakos remains in office as Secretary. Thomas Duffy was re-elected Treasurer. New councilors are Mark J. Caddick and Adam C. Simon, joining continuing councilors Sarah Carmichael, Sarah C. Penniston-Dorland, Jay Ague, and Donna Whitney. The outgoing councilors are Rajdeep Dasgupta and Peter Nabelek.
- MSA 2019 membership renewals starts in September, with notices being sent electronically. This will be followed by several electronic reminders before a paper copy is sent to those who do not renew online by the end of October. Members who renew and pay online before 10/31/2018 will receive a $5 dues discount; the discount reflects cost savings to MSA from members who renew early online. There will be several electronic reminders before a paper copy is sent during November to those who do not renew online by the end of October.
- Members and Fellows who are in the senior, honorary, and life categories are sent renewal notices. They need not pay dues but are sent notices as the best way to prompt an update of membership information, particularly mail and e-mail addresses.
- MSA Council voted an increase in 2019 dues for members (from $80 to $85). Student membership remains the same (at $20), and all members will have access to the electronic versions of both the *American Mineralogist* and *Elements*. Sustaining memberships will remain at $150 + regular dues.
- Council approved, on a trial basis, a membership rate lower for early career members. Early career is here defined as three years beyond being a student; the membership rate would be $45.
- Member subscription rates to the print version of the 2019 *American Mineralogist* will increase. The print subscription price to US members will be $135 (currently $125); to foreign members it will be $145 (currently $135). The subscription price (paper and electronic) to US institutional members will increase to $1,150 (from $1,100); for foreign institutions it will be $1,175 (from $1,125). Institutional electronic-only subscription will increase to $1,050 (from $1,000). These prices represent increases of 4%–8%. Included in the institutional subscription are all current-year (2019) print issues of *American Mineralogist*, Reviews in Mineralogy and Geochemistry, *Elements*, as well as access to the electronic versions of these publications on the MSA website starting with volume 1, number 1. GeoScienceWorld institutional subscriber prices for archival print copies of *American Mineralogist* and the Reviews are $200 and $250, respectively. The MSA offers institutional subscriptions to print + electronic [$315 (US) and $335 (non-US)] or electronic-only ($275) versions of the *Reviews*.
- Council approved a 20% surcharge for institutional subscribers renewing after January 15. Such late institutional subscriptions are an extra expense that requires the purchase of extra inventory, plus the processing and packing of back issues, and needing to ship at rates higher than the usual bulk shipping for periodicals.
- If you subscribe to other journals through MSA—*Gems & Gemology*, *Journal of Petrology*, *Mineral News*, *Physics and Chemistry of Minerals*, *Mineralogy and Petrology*, or *Rocks & Minerals*—please renew early. The MSA needs to forward your renewal to those publishers before your subscription runs out.

J. Alex Speer
jaspeer@minsocam.org

AWARD NOMINATIONS

Nominations Sought for 2020-2021 Awards

NOMINATIONS MUST BE RECEIVED BY 1 JUNE 2019

The **Roebling Medal** (2020) is MSA's highest award and is given for eminence as represented by outstanding published original research in mineralogy.

The **Dana Medal** (2020) is intended to recognize continued outstanding scientific contributions through original research in the mineralogical sciences by an individual in the midst of their career.

The **Mineralogical Society of America Award** (2020) is given for outstanding published contribution(s) prior to 35th birthday or within 7 years of the PhD.

The **Distinguished Public Service Medal** (2021) is presented to an individual who has provided outstanding contributions to public policy and awareness about mineralogical topics through science.

Society **Fellowship** is the recognition of a member's significant scientific contributions. Nomination is undertaken by one member, with two members acting as cosponsors. A form is required. Please contact committee chair or MSA home page.

Mineralogical Society of America

Submission requirements and procedures are on MSA's home page:
http://www.minsocam.org/

RESEARCH GRANTS

The Mineralogical Society of America 2019 Grants for

RESEARCH IN CRYSTALLOGRAPHY

from the Edward H. Kraus Crystallographic Research Fund with contributions from MSA membership and friends

STUDENT RESEARCH IN MINERALOGY AND PETROLOGY

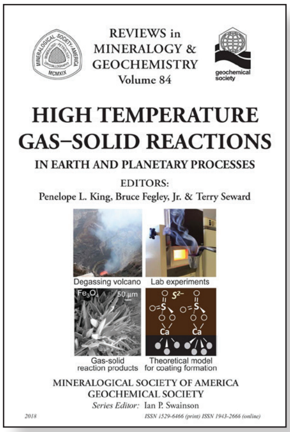
from an endowment created by MSA members

Selection is based on the qualifications of the applicant; the quality, innovativeness, and scientific significance of the research of a written proposal; and the likelihood of success of the project. There will be up to three US$5,000 grants, with the restriction that the money be used in support of research. Application instructions and online submission are available on the MSA website, http://www.minsocam.org. Completed applications must be submitted by 1 March 2019.

The 2019 16-month calendar showcases Gold, published by Lithographie, LLC, in cooperation with MSA. It is available from MSA: http://www.minsocam.org/.

NEW PUBLICATION AD

Reviews in Mineralogy and Geochemistry Volume 84: ***High Temperature Gas–Solid Reactions in Earth and Planetary Processes*** 2018. Editors: Penelope L. King, Bruce Fegley, Jr. and Terry Seward. i-xiv + 514 pages. ISBN 978-0-946850-00-3


REVIEWS in
MINERALOGY &
GEOCHEMISTRY
Volume 84

HIGH TEMPERATURE
GAS–SOLID REACTIONS
IN EARTH AND PLANETARY PROCESSES
EDITORS:
Penelope L. King, Bruce Fegley, Jr. & Terry Seward

MINERALOGICAL SOCIETY OF AMERICA
GEOCHEMICAL SOCIETY
Series Editor: Ian P. Swainson
2018 *ISSN 1529-6466 (print) ISSN 1943-2666 (online)*

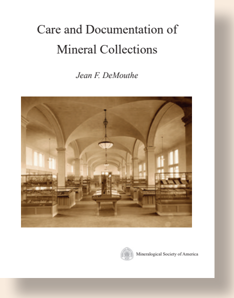
Gas mixtures play a crucial role in distributing elements between different parts of the Earth and of planet-forming systems over a range of settings and temperatures. Despite the fundamental role of gases in geochemical cycles and their prevalence both in the crust and in the early solar system, we are unaware of any reviews on this topic. This volume arose from an interest in promoting further research into the role of gases in geologic systems on Earth and beyond, with an aim of illuminating the gaps in our knowledge. The focus is on high-temperature interactions because at low temperatures, the low density, very low dielectric constant gas mixtures only rather loosely "physisorb" onto natural materials. In contrast, at higher temperatures, solids volatilize and condense, they lose/gain volatile components, and heterogeneous chemisorption reactions can occur between gases and solid surfaces. These reactions have previously been paid very little attention, but recent research has laid some foundations for understanding the processes involved and their applications to Earth and planetary environments.

The volume is divided into five main topics: (1) Experimental and analytical approaches to characterizing gas–solid reactions; (2) Modelling approaches to examining gas–solid reactions; (3) Terrestrial volcanic systems; (4) Planetary systems; (5) Industrial processes.

Description and ordering online at www.minsocam.org or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110 USA phone: +1 (703)652- 9950 fax: +1 (703) 652-9951 e-mail: business@minsocam.org. Cost is $45 ($33.75 members MSA, GS, CMS).

Care and Documentation of Mineral Collections

Jean F. DeMouthe, i-vi+ 94 pages. ISBN 978-0-939950-99-7


Care and Documentation of
Mineral Collections
Jean F. DeMouthe
Mineralogical Society of America

This work is an attempt to provide information and guidance on all aspects of caring for and documenting mineral collections. It is aimed at professionals and amateurs alike and is dedicated to everyone who shares a love of minerals and those who care for and about collections. The ten chapters are: Collection Organization; Documentation; Ancillary Collections; Preventive Conservation; Storage; Hazards, Safety, and Risks; Administrative Policies; Private Collections; and Bibliography and Resources.

Description and ordering online at www.minsocam.org or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110 USA phone: +1 (703) 652-9950 fax: +1 (703) 652-9951 e-mail: business@minsocam.org. Cost is $30 ($22.50 members MSA, GS, CMS).

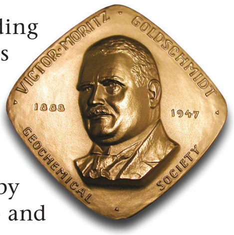
Geochemical Society

www.geochemsoc.org

WELCOME TO NEW GEOCHEMICAL SOCIETY MEMBERS

The Geochemical Society (GS) is welcoming a group of new members following this summer's Goldschmidt Conference in Boston (Massachusetts, USA). If you registered for the meeting as a nonmember, then you automatically received membership to the society through 31 December 2019. That membership includes a subscription to *Elements*, as well as the weekly *Geochemical News* e-mail and a discount to next year's Goldschmidt Conference in Barcelona (Spain). If you did not receive a welcome e-mail in August, it may be that we do not have your address on file. Please e-mail the business office at gsoffice@geochmesoc.org or call 1-202-545-6928 to make sure that we have your current contact information.

NOMINATE A COLLEAGUE FOR A GS AWARD BY 31 OCTOBER 2018



There is still time to nominate an outstanding colleague for one of the society's 2019 awards and special lectures. Information about the Goldschmidt, Clarke, Hayes, Patterson, and Treibs awards can be found at www.geochemsoc.org/awards. Details regarding the Geochemistry Fellows, jointly awarded by European Association of Geochemistry (EAG) and GS, are also available on the GS website.

We are also seeking nominations for special lectures to be presented at next year's Goldschmidt Conference. Lecture nominations require only a single nomination letter—no additional letters of support are needed.

The society seeks a broad diversity for its awards, and to achieve this goal we need high-quality nominations from all parts of the geochemical community. Nominations must be received by 31 October 2018; the winners will be announced in February 2019.

Prof. Yuichiro Ueno is recognized as the 2018 Earl Ingerson Lecturer by GS President Roberta Rudnick during the 2018 Goldschmidt Conference in Boston (Massachusetts, USA).

RENEW YOUR MEMBERSHIP FOR 2019

Geochemical Society members can renew quickly and securely on the GS website: www.geochemsoc.org. Renew by 31 December 2018 to save $5 off the regular dues and enjoy uninterrupted access to *Elements*, *Geochemical News*, and registration discounts to Goldschmidt2019 in Barcelona and to other conferences. Members also have access to the online member directory (available by signing into your profile on the website). You can also choose a two-year membership option to save time and money. If you prefer to renew by mail, please visit the website to download a form to send with your payment.

2019 GS MEMBERSHIP RATES

Category of Membership	**Rate if paid by 31 December 2018**	**Regular Rate**	**Two-Year Membership (before/after 31 December)**
Professional: High-income Countries	$35	$40	$70 / $75
Professional: Low-income Countries*	$10	$15	$20 / $25
Senior	$15	$20	$30 / $35
Student	$10	$15	$20 / $25

* See below for more information

The society also offers a Life Member option that eliminates the need to renew every year. The current life membership rate is 70 minus your current age times $35 USD, with a minimum rate of $175. Contact the business office at gsoffice@geochemsoc.org for more information on upgrading your membership to this convenient option.

REDUCED DUES FOR GS MEMBERS FROM QUALIFYING COUNTRIES

In order to make membership more affordable for scientists in every county, the GS Board of Directors recently approved a new dues structure for professional members. A reduced professional rate of $15 is now available to scientists from countries classified by the World Bank as having low-income or lower-middle-income economies. If dues are paid before 31 December, then the rate is only $10. Visit geochemsoc.org/membership/join to learn more about which countries qualify.

Students from qualifying countries may apply for free memberships through the Introductory Student Membership Program.

KEEP YOUR GS PROFILE CURRENT

Have you recently moved or changed your e-mail address? Keeping your GS member profile current allows us to send *Elements* and *Geochemical News* to the right place every time. Updating your contact information is easy: just visit www.geochemsoc.org/contact and click the link to access your online member profile. You can also e-mail the business office with updates or corrections at any time.

Geochemical Society Business Office
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USA

FIND US AT GSA AND AGU THIS FALL

The Geochemical Society will be at the Geological Society of America's Annual Meeting in November 2018 and at the American Geophysical Union's Fall Meeting in December 2018. Find us in the exhibit hall to renew or update your membership, learn about our programs, or just to say "Hello!". Thanks to partnerships with the GSA and the AGU, members of the Geochemical Society can take advantage of the discounted member registration rates for both conferences.

Société Française de Minéralogie et de Cristallographie

www.sfmc-fr.org

SFMC GENERAL ASSEMBLY REPORT

The annual General Assembly Société Française de Minéralogie et de Cristallographie's (SFMC) was held 7 June 2018 at the University Pierre et Marie Curie in Paris (France). Marc Blanchard, SFMC Secretary, summarized the activity of the society during the year 2017. The SFMC supported several scientific meetings, among them the 12th Rayons X et Matière Colloque and the short course entitled Petrochronology: Methods and Applications, for which two student grants were offered. The SFMC was also present at the Goldschmidt2017 Conference, held 13–18 August 2017 in Paris, after signing a partnership agreement with the European Association of Geochemistry, the co-organisers of the Goldschmidt conferences. Marc Blanchard also reminded those present at the SFMC General Assembly of the two distinguished winners of the 2017 Haüy–Lacroix Award, the publication of the book *Minerals with a French Connection* and the society's contributions to the *European Journal of Mineralogy* (*EJM*) and to *Elements*. Christian Chopin, SFMC Treasurer, presented the 2017 budget, which was approved.

CELEBRATION OF THE SFMC 140th ANNIVERSARY

The participants of the SFMC 140th Anniversary Meeting in front of MINES ParisTech building (Paris, France).

The SFMC was born 21 March 1878 after Alfred Des Cloizeaux gathered together a group of mineralogists at the Sorbonne (Paris) to discuss their recent scientific work. The 140th anniversary of this event took place 8 June 2018 at the Hôtel de Vendôme of MINES ParisTech in Paris. After a welcome address by MINES ParisTech's museum curator, Didier Nectoux, the current SFMC President, Bertrand Devouard, summarized some 2,500 years of the history of mineralogy. It was followed by half-hour lectures by invited keynote speakers. The scientific program went under the title of "Mineralogy of the Extremes" and covered such topics as the evolution of systematic mineralogy, characterizing crystal structures of nanomaterials using electrons, the very small-scale mechanisms in radioactive minerals, the exploration of extreme pressure and temperature conditions, the mineralogy of Mars, diamond formation and volatile flux within the Earth's mantle, natural and synthetic talc in the industry, and minerals as witnesses of extremely old terranes.

Opening of the meeting, Didier Nectoux (curator of the Mineralogy Museum MINES ParisTech).

President Bertrand Devouard giving the first lecture in the conference hall.

The participants also enjoyed the sunny garden of the Hôtel de Vendôme where they cordially interacted over the poster presentations during the coffee breaks and the buffet lunch.

Lively discussion at the poster presentation in the garden of the Hôtel de Vendôme (Paris).

Before closing the assembly, Bertrand Devouard announced the winner of the 2018 Haüy–Lacroix Award: it went to Simon Couzinié for his PhD thesis "Evolution of the Continental Crust and Significance of the Zircon Record: A Case Study from the French Massif Central", which was co-supervised by Profs. Jean-François Moyen (University of Saint-Etienne, France) and Gary Stevens (University of Stellenbosch, South Africa).

Simon Couzinié, recipient of the 2018 Haüy–Lacroix Award.

After the award presentation, the various SFMC participants ended a most enjoyable afternoon with the visit to MINES ParisTech's mineral museum, accompanied by curator Eloïse Gaillou.

This special day was a great success. The SFMC now looks forward to its 150th anniversary!

Mineralogical Society of Great Britain and Ireland

www.minersoc.org

GRANULITES AND GRANULITES 2018

The annual meeting of the Mineralogical Society of Great Britain and Ireland (MSGBI) for 2018 was held 10–13 July 2018 in Ullapool (Scotland) and had the title 'Granulites and Granulites 2018'. There was a preceding fieldtrip to the nearby classic locality of the so-called Assynt Window, and a post-meeting trip to Rogaland (southwest Norway). The meeting was convened by Tim Johnson with the support of the MSGBI staff and a team of session chairs, field trip leaders, and many others who helped out.

Four-Day Field Trip to Assynt (Scotland)

Almost 40 delegates were treated to fantastically clear and sunny weather in the Scottish Highlands for a four-day trip around the Lewisian rocks of Assynt, a classic locality for granulites. The warm weather even managed to discourage the normally "welcoming" midges, a lucky escape.

The trip was led by Simon Harley (Edinburgh School of Geosciences, Scotland), Kathryn Goodenough (British Geological Survey), George Guice (School of Earth and Ocean Sciences, Cardiff, Wales) and Tim Johnson (Curtin University, Western Australia).

The packed programme for the four days included the following visits:

Happy geologists on day 4 of the trip to Assynt (Scotland).

Dick White loving the outcrop at Tarbet (Scotland).

'Molly', Simon Harley's mobile scale provider.

Conference Reception and Presentations

The conference moved indoors on Tuesday evening with a spectacular ice-breaker reception at the Ullapool village hall. A warm welcome from a Scottish piper, followed by a wonderful selection of food from local producers, including the nearby fishing industry, was a great way to start the meeting.

Two-and-a-half days packed with oral and poster presentations followed at the wonderful Macphail Conference Centre in Ullapool. Almost 50 talks were delivered, including the following invited talks:

- "Does the Earth have a pulse? Constraints from the Geological Record and Implications for Tectonic Processes", by Peter Cawood
- "Granulites, Geodynamics and 'Accessory Terranes'", by Daniel Viete
- "Considerations on Zircon, Monazite and Garnet Geochemistry and Geochronology in High-Grade Rocks", by Daniela Rubatto
- "Recognizing Melt Pathways in the Crust: Nature and Experiments", by Sandra Piazolo
- "Progress and Pitfalls in Metamorphic Phase Petrology", by Richard White
- "Ten Years of Research on Nanogranitoids", by Bernardo Cesare
- "Overprinting Metamorphic Events during Continental Collision: Insight from Geodynamic Modelling", by Elena Sizova
- "Lewisian Crustal Evolution—Six Decades of Dating and Peering through the Metamorphic Fog", by Martin Whitehouse

The 51st Hallimond Lecture, which was supported by the MSGBI, was ably delivered by Mike Brown (University of Maryland, USA) and had the title, "Time's Arrow, Time's Cycle: Granulite Metamorphism and Geodynamics".

Mike Brown (LEFT) receiving his Hallimond Lecture Certificate from Simon Harley (RIGHT).

Simon Harley also rocked the aisles during the conference banquet by singing 'Bad Bad Michael Brown' (with acknowledgement [and some apologies!] to Jim Croce, writer of the song 'Bad Bad Leroy Brown' on which Simon's composition was based).

Mike Brown was also honoured by Wiley, publisher of *Journal of Metamorphic Geology* (edited by Prof. Brown) and supporter of supported a drinks reception before the conference banquet, for his many years of service to the journal.

Post-Conference Five-Day Field Trip to Rogaland (Norway)

Following the granulites conference, which ended at noon on Friday 13th July, some 25 delegates took a long bus drive to Aberdeen airport from where they departed to Stavanger for the post-conference trip in Rogaland (Norway).

The purpose of the five-day trip, led by Trond Slagstad (Geological Survey of Norway) and Chris Clark (Curtin University), was to study: (1) high- to ultrahigh-temperature metamorphic rocks of the ~1 Ga Sveconorwegian orogen, which records up to 150 million years of apparently continuous high-grade conditions; (2) the nature of the transition to the surrounding lower-grade rocks, which have a simpler metamorphic history; and (3) to discuss possible tectonic scenarios. The large and very international group, with participants from the USA, the UK, Australia, Italy, China, Norway, Germany, South Africa, Canada and Switzerland, seemed – and indeed, turned out – to be the perfect group for such discussions. The photo below shows the participants inspecting osumilite- and sapphirine-bearing gneisses and having discussions where geologists discuss best – on outcrop.

Osumilite locality

In addition to very high-grade rocks, we also visited rocks that preserve magmatic foliations and other features that underpin a complex, long-lived magmatic evolution that we are currently trying to combine with the observed, coeval metamorphic evolution. In the end, we hope the participants went back home with a much-improved understanding of Sveconorwegian orogenic processes. For us, having expert field-trip leaders who could to tap into a vast repository of knowledge and experience was invaluable to confirm and correct work done so far, as well as generating new ideas and locations for further study.

Copies of the field guides for both the Assynt and the Rogaland field trips are available, courtesy of the authors, from the MSGBI office. Please contact Kevin Murphy (kevin@minersoc.org).

The fifth conference in the series will be ‘Granulites and Granulites 2022’, which is scheduled to take place in China and to be organized by Yingde Zhang.

R.A. HOWIE BEST PAPER AWARD

This year’s best paper award was presented to Emma Hart for her paper “Mineral Inclusions in Rutile: A Novel Recorder of HP-UHP Metamorphism” (Hart, E., Storey, C., Braund, E., Schertl, H.-P. and Alexander, B.D., 2016. *Earth and Planetary Science Letters*, **446**, 137–148). As part of her prize, Emma opted to present a paper during the ‘Granulites and Granulites 2018’ conference.

Emma Hart (RIGHT) receiving the certificate for her ‘Best Paper Award’ for 2018 from MSGBI Executive Director, Kevin Murphy (LEFT).}

MINERALOGICAL MAGAZINE

Since our launch with Cambridge University Press, we have forged ahead with issues for 2018. By the time you read this we will have published six issues for 2018, including an extra, open-access issue on critical metals and another special June issue on platinum-group minerals. Our backlog is creeping down, our submission to publication times are reducing further, and our 2018 impact factor is 1.744, comfortably within Q2 (Clarivate) for mineralogy journals. We have also completed the transfer of our archive to the Cambridge Core host. Members can access the archive by logging on to www.minersoc.org and selecting the Cambridge service for *Mineralogical Magazine*. This is now the only source of the online archive. Non-members will no longer be able to access the journal archive. The MSGBI Council felt it was reasonable that those wishing to benefit from use of the journal’s archive should pay the very reasonable membership fee for that privilege.

Cambridge University Press also hosted a very enjoyable and successful ‘Meet the Editor’ event during the August 2018 International Mineralogical Association conference in Melbourne (Australia). This was attended by Dr. Stuart Mills, Principal Editor of the *Mineralogical Magazine*, and a large number of members of the magazine’s editorial board.

CLAY MINERALS

The June and September issues of the journal *Clay Minerals* have been published and the journal schedule is now on track.

Our impact factor has also received a boost this year, to 1.219, which is a welcome return on the investment of time and effort made by our editorial team, backed by the MSGBI Council and the European Clay Groups Association.

THIRD EUROPEAN MANTLE WORKSHOP (EMAW 2018)

The third edition of the European Mantle Workshop (EMAW) was held 26–28 June 2018 in the historical buildings of the University of Pavia (Italy). The meeting consisted of three days of oral/poster presentations and three optional field trips. Oral presentations were held in the magnificent Aula del Disegno; poster sessions took place in the Renaissance-styled Cortile Sforzesco. The EMAW workshop was organized by the Department of Earth and Environmental Sciences (University of Pavia) and the Institute of Geosciences and Earth Resources of the National Research Council of Italy (IGG-CNR, Pavia), in collaboration with the Italian Society of Mineralogy and Petrology (SIMP). A total of 131 participants from 22 countries attended and, happily, more than 40% of the attendees were PhD students and young researchers.

Participants from 22 countries attended.

The EMAW 2018 workshop comprised 53 oral and 72 poster presentations that featured cutting-edge research on the evolution of the Earth's mantle. The four main topics were as follows: (1) mineralogical, petrological and geochemical studies of mantle xenoliths, orogenic peridotites and ophiolitic mantle sections; (2) experimental studies on the production, migration and emplacement of mantle melts and fluids; (3) geophysical studies and numerical models of the deep mantle; (4) serpentinization and carbonation of peridotites, and the relationship between microscopic organisms in extreme environments. Keynote talks were given by Françoise Chalot-Prat (University of Lorraine, France), Sandro Conticelli (University of Florence, Italy), Istvan Kovacs (Hungarian Academy of Sciences, Hungary), Andreas Stracke (University of Münster, Germany) and Andrea Tommasi (University of Montpellier II, France). The poster sessions were arranged so that there would be ample time for discussion in a relaxed atmosphere, with coffee and small snacks. All participants enjoyed the evening dinner offered by EMAW 2018, which included live music and dancing.

As part of EMAW 2018, three optional field trips had been organized. There were two one-day pre-workshop excursions: first, an illustration of rifting-related structures in the mantle section from the External Ligurian ophiolites (northern Apennines), which was jointly led by Alessandra Montanini (University of Parma, Italy) and Riccardo Tribuzio (University of Pavia, Italy); second, a visit to the dunite to harzburgite melt conduits in the Lanzo Massif South mantle peridotites (western Alps), jointly led by Alessio Sanfilippo (University of Pavia) and Alberto Zanetti (IGG-CNR, Pavia). There was also a two-day post-workshop field trip aimed at visiting the mantle bodies within, and at the base of, the lower continental crust of the Ivrea–Verbano Zone, which was led by Antonio Langone (IGG-CNR, Pavia), Maurizio Mazzucchelli (University of Modena and Reggio Emilia, Italy) and Alberto Zanetti (IGG-CNR, Pavia). About half of the EMAW 2018 participants decided to join at least one of the field trips.

One of the pre-workshop field-trip leaders, Alessandra Montanini (University of Parma).

The abstract volume and field-trip guides are available at http://emaw2018iggpavia.unipv.it/. Feedback by the EMAW 2018 participants was extremely positive. The fourth edition of the European Mantle Workshop will be held in 2021 in Toulouse (France).

Riiccardo Tribuzio, University of Pavia, Italy
(tribuzio@crystal.unipv.it)

Alberto Zanetti, IGG-CNR, Pavia, Italy (zanetti@igg.cnr.it)

EGU GALILEO CONFERENCE

The European Geosciences Union's Galileo Conference "Exploring New Frontiers in Fluid Processes in Subduction Zones" was held 24–29 June 2018 in Leibnitz (Austria). It was co-organized by Carmen Sanchez-Valle (Münster, Germany), Timm John (Berlin, Germany), Nadia Malaspina (Milano Bicocca, Italy), Katharina Vogt (Münster, Germany), Simone Tumiati (Milano, Italy) and Yury Podladchikov (Lausanne, Switzerland). The conference brought together different disciplines and many of the key players in the field of fluid-mediated processes in subduction zones. The four main themes and the keynote speakers were as follows: "Experimental/Theoretical Studies of Fluid Properties – The Fluids Perspective", with Ronit Kessel (Jerusalem, Israel); "Natural Observations – The Rock Perspective", with Marco Scambelluri (Genova, Italy); "Thermodynamic Modelling of Fluid–Rock Interactions – The Equilibrium Perspective", with Dimitri Sverjensky (Johns Hopkins, USA); "Coupling Geochemistry and Geodynamics – The Dynamic Perspective", with Cian Wilson (Carnegie, USA).

The Italian Society of Mineralogy and Petrology (SIMP) offered travel grants to three PhD students, giving them the opportunity to participate in this state-of-the-art conference and hear about future perspectives in defining strategies for an efficient integration between experimental and theoretical studies of fluid–rock interactions, field observations and geodynamic models for fluid migration. The interactions between the leading researchers and the participants that arose out of the oral and poster programmes, the breakout discussion groups, and a round table were among the main highlights of the event.

Nadia Malaspina, University of Milano Bicocca, Italy
(nadia.malaspina@unimib.it)
Simone Tumiati, University of Milano, Italy
(simone.tumiati@unimi.it)

THE LINCEO AWARD FOR GEOSCIENCES

The Linceo Award for Geosciences (**Premio Linceo per le Geoscienze**) for 2018 goes to Mauro Prencipe, an associate professor at the University of Turin (Italy). Mauro has contributed to spreading the application of quantum methods to model the chemical and physical properties of minerals under non-ambient conditions. Mauro's work is essential for anyone who wishes to investigate mineral phases using computational ab initio methods.

Mauro Prencipe (on the right) with the President of the Accademia dei Lincei , Prof Alberto Quadrio Curzio.

The Accademia dei Lincei was founded in 1603 by Federico Cesi and is the oldest scientific academic organization in the world. One of its first members was Galileo Galilei (http://www.lincei.it).

Sociedad Española de Mineralogía

www.ehu.es/sem

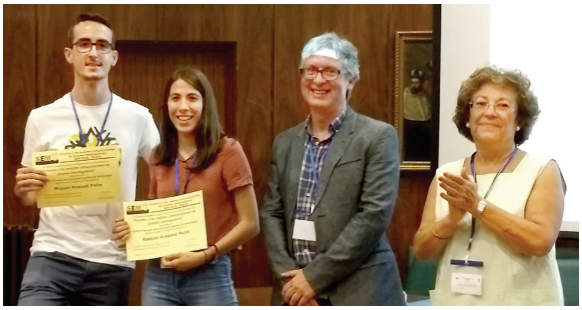
THE 37th ANNUAL MEETING OF THE SPANISH MINERALOGICAL SOCIETY

The 37th Annual Meeting of the Spanish Mineralogical Society (SEM) was held 12 July 2018 in Madrid (Spain). The meeting was devoted to recent studies on crystallography, mineralogy, geochemistry and petrology and their applications. It brought together 70 participants from a range of Spanish universities and research institutes, including some industry professionals.

Professor Francisco Velasco (LEFT) receiving his SEM Honorary Member Award from SEM President Juan Jiménez (RIGHT) during the award ceremony of the 37th Annual Meeting of the Spanish Mineralogical Society.

During the meeting, Professor Francisco Velasco (University of the Basque Country) was made an SEM Honorary Member for his outstanding contribution to the field of mineralogy, particularly on the topic of ore deposits. He is admired and respected by students and colleagues alike. The SEM thanks Francisco Velasco for his dedication to the profession and for his inspiring teaching.

The invited speaker at the meeting was Professor Joaquin Proenza (University of Barcelona, Spain). He presented the plenary conference lecture "Mineral Deposits and Energy Transition: A Perspective from Unconventional Rare-Earth Deposits".



LEFT TO RIGHT: young researcher winners Miquel Roquet Peñas and Raquel Arasanz Pujol, with Juan Jiménez (SEM President) and Emilia García Romero (organizing committee and SEM Treasurer).

As has become traditional, two awards were given for the best student presentations. This year, Raquel Arasanz Pujol and Miquel Roquet Peña (both students at the University of Barcelona,) were co-winners with their talk "Minescope: Observation of Minerals under the Microscope in the Mobile" and Pedro Granda Ibáñez (University of Oviedo) for his talk "Formation of Natrojarosite under Environmental Conditions". Also, the award for the Best Master's Thesis was given to Pablo Cayetano Forjanes Pérez (Complutense University of Madrid) for his thesis "Calcite and Anhydrite Interaction with Sr- and Ba-rich Solutions: Implications in the Genesis of Massive Deposits of Celestine".

The organizing committee would like to thank all the participants for this fruitful and excellent meeting. We are already looking forward to the 38th Annual Meeting of the Spanish Mineralogical Society, which will be held in the beautiful city of Ronda (Málaga, Spain) in 2019.

EAG SUPPORTS JUNIOR SCIENTISTS AROUND THE WORLD

Making up over a third of our member base, students, as well as postdocs and other recent graduates, form an integral and very active part of the European Association of Geochemistry (EAG). Furthering opportunities and career prospects for early career scientists remains one of our core activities, and several dedicated initiatives and resource banks have been developed over the years. The PhD and postdoc positions listed on our job opportunities webpage are frequently the most clicked links in our monthly newsletter and are among the most popular posts on our social media channels. Our conference announcements are, likewise, of high interest to those in the early stages of their careers. We also maintain a database of undergraduate and postgraduate programs and bursaries on the EAG website. The complete range of EAG resources and programs for early career scientists can be viewed on our dedicated page at www.eag.eu.com/early-career/.

Good to know: *Early Career Councillor Sami Mikhail, a lecturer at the University of St. Andrews (UK), is the voice of early career scientists within the EAG Council. You can contact him at sm342@st-andrews.ac.uk.*

Supporting Participation at International Conferences and Workshops

EAG Ambassadors at the AGU Fall Meeting in New Orleans (Louisiana, USA), December 2017.

Four initiatives developed by the EAG are aimed directly at helping junior geochemists to attend and participate in conferences, short-courses and workshops around the globe. The **Student Sponsorship Program** provides travel grants of up to €500 for students to attend events in Europe. The **Early Career Ambassador Program** offers financial support (50% of expenses, up to €1,500) for Europe-based PhD students and postdocs to travel to international conferences held outside Europe. The **Goldschmidt Conference Grants Program**, organised in alternating years by the EAG or by the Geochemical Society (GS), provides support for early career scientists from low-income countries to attend one of the largest geochemistry conferences in the world. The EAG also provides **sponsorship for member-led short-courses and conferences** in Europe, allowing reduced rates to be offered to student members who wish to participate. Thirteen events have received EAG sponsorship to date, enabling almost 100 students to benefit from the opportunity to gain more specialized training in their fields.

Outreach Activities that Benefit Junior Scientists

Now in its eighth year, the **Distinguished Lecture Program** (DLP) was established with the aim of introducing and motivating scientists and students from under-represented regions of the world to emerging areas of research in geochemistry. The program currently focuses on Central and Eastern Europe, and lectures have been held in universities and institutes across Poland, the Czech Republic, Croatia, Hungary, Bulgaria, Romania, Slovakia, Slovenia, and the Ukraine.

Each year's distinguished lecturer is selected on the basis of a combination of their outstanding research contributions to geochemistry and their ability to communicate their ideas to a broad audience. Previous lecturers have given talks on subjects as diverse as geomicrobiology, mantle evolution, paleoclimate, biogeochemical cycling of trace elements, speleothems, and the cryospheric sciences, to name just a few. The 2018 DLP lecturer is Jim McQuaid (University of Leeds, UK), who is on tour right now in Hungary and Poland, presenting highlights from his work in the atmospheric sciences and on aerosols. Visit www.eag.eu.com/outreach/dlp/ for the latest news and to read the abstracts of his lectures.

Eagerly awaiting Lenny Winkel's EAG Distinguished Lecture at Eötvös University (Hungary) in October 2017.

The EAG Distinguished Lecture tours don't stop when the lecturer returns home. Videos of the lectures are made available to viewers worldwide on the EAG YouTube channel (www.youtube.com/user/EAGOffice).

Outreach activities have also been developed through the **EAG–GS Outreach Program**, a joint initiative of the EAG and Geochemical Society (GS). This program currently focuses on Africa, a continent where opportunities for education, research and training for young scientists remain limited compared to those available elsewhere in the world. Four leading geochemists—**Bernhard Wehrli, Pierre Deschamps, François Chabaux** and **Axel Hofmann**—have participated in the program so far, organising workshops, short courses, lectures and seminars across the continent.

Attentive audience at the University of Ghana, 2017 EAG–GS Outreach Program.

As part of the 2018 Outreach Program, the EAG and GS are co-sponsoring the **African Initiative for Planetary and Space Sciences**. Through financial support from the EAG and GS, two 4-day workshops for African researchers and international participants will be held aimed at strengthening the African vision for developing planetary and space sciences at the local, national, and regional scale.

For 2019, we are pleased to announce that Hasnaa Chennaoui Aoudjehane, a lecturer in meteoritics and planetary sciences at the University of Casablanca (Morocco), has been selected as the EAG–GS Outreach lecturer.

To find out more about previous, current and upcoming outreach activities at the EAG, visit www.eag.eu.com/outreach/.

EAG MEMBERSHIP: TIME TO JOIN OR RENEW!

As we near the end of the year, now is a good time to consider joining the European Association of Geochemistry or renewing your membership. New members joining after 15 October 2018 will receive a full year's membership for 2019. For more information on individual or institutional membership packages and the full range of benefits offered, visit www.eag.eu.com/membership/.

MEMBERSHIP BENEFITS

Conferences

- Member rates to attend the Goldschmidt conference
- Member rates to attend conferences and events organised by the Mineralogical Society of Great Britain and Ireland, the International Association of GeoChemistry, the International Society for Environmental Biogeochemistry, the Society for Geology Applied to Mineral Deposits, and the European Association of Geoscientists and Engineers.

Publications

- Print issues of *Geochemical Perspectives*
- Print and online issues of *Elements Magazine*
- Reduced subscription rates to *Chemical Geology* and *Geofluids*
- Member rates to purchase print publications by the Mineralogical Society of Great Britain and Ireland, the Italian Geological Society, the Italian Society of Mineralogy and Petrology and the French Quaternary Association
- Member rates to publish open access articles in *Mineralogical Magazine* and *Clay Minerals*

Early Career Scientist Support

- Sponsorship of students to attend workshops and conferences in Europe
- Ambassador Program, providing support for early career scientists based in Europe to attend conferences outside Europe
- Sponsorship of member-led workshops and conferences

Information and Networking

- Job postings and conference calendar
- Monthly newsletters
- EAG Blog, Twitter, Facebook and YouTube

Membership Rates

Student 1 year	€15
Student 3 years	€35

Professional 1 year	€30
Professional 5 years	€120

DID YOU KNOW?

If you are an EAG member and are organising a short course or small conference focused on a special topic or technique in geochemistry, you can apply for EAG sponsorship. The event, which should have at least 10 participants, should be based in Europe and may be organised in conjunction with a Goldschmidt conference held in Europe. EAG sponsorship supports students attending the event by up to €200 per student.

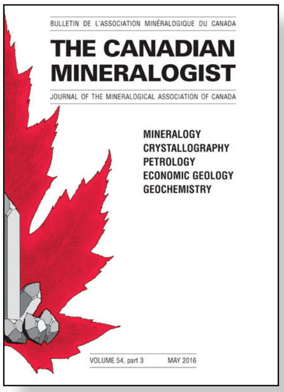
The next deadline for applications is 1 March 2019. Find out more at http://www.eag.eu.com/early-career/event-sponsorship/.

Mineralogical Association of Canada

www.mineralogicalassociation.ca

THE CANADIAN MINERALOGIST

Not Just Crystal Structures



BULLETIN DE L'ASSOCIATION MINÉRALOGIQUE DU CANADA

THE CANADIAN MINERALOGIST

JOURNAL OF THE MINERALOGICAL ASSOCIATION OF CANADA

MINERALOGY
CRYSTALLOGRAPHY
PETROLOGY
ECONOMIC GEOLOGY
GEOCHEMISTRY

VOLUME 54, part 3 MAY 2016

It's easy to assume that a journal with a name like *The Canadian Mineralogist* publishes a narrow range of topics. Indeed, there are even people who believe we only publish crystal structures! In reality, nothing could be further from the truth.

Mineralogy is significant to an incredible range of topics, and *The Canadian Mineralogist* publishes all of them. Two recent examples of mineralogy appearing in unexpected places include minerals found in food [Tansman et al. (2017) 55: 89-100] and in forensic igneous petrology [Clarke et al. (2017) 55: 145-177].

Of course, crystal structures do appear among our most cited papers [e.g. Burns (2005) 43: 1839-1894], but then so do pegmatites [Černý and Ercit (2005) 43: 2005-2026], platinum-group element fractionation in mafic magmas [Brenan and Andrews (2001) 39: 342-360], and the geochemistry of intermediate volcanic rocks [Gorton and Schandl (2000) 38: 1065-1073].

The most read papers show a similar range, beginning with scheelite as an indicator mineral [Poulin et al. (2018) 56: 265-302], followed by the mineralogy of a P–rare-earth element–Th deposit [Anenburg et al. (2018) 56: 331-354], the report of a new uranyl sulfate mineral [Kampf et al. (2018) 56: 235-245], the mineralogy of a vanadium–graphite deposit [Di Cecco et al. (2018) 56: 247-257], and pegmatites (Černý and Ercit 2005). The appearance of a pegmatite paper on both our most cited and most read lists is illustrative of the fact that *The Canadian Mineralogist* is well-known for pegmatite studies, and, at the time of writing, we are in the final stages of preparing a thematic issue that derives from the 2017 pegmatite conference in Norway; one of many interesting papers in this issue will be on the laser-induced breakdown spectroscopy of tourmaline (McMillan et al. 2018, in press).

Laser-induced breakdown spectroscopy is hardly the only developing analytical technique that we have published about: a recent thematic issue on gem deposits included a paper on hyperspectral imaging applied to gem exploration [Turner et al. (2017) 55: 787-797]. We have also published several papers in the environmental sphere: for example, recent articles on black rock coatings as records of emissions [Schindler et al. (2016) 54: 285-309; Caplette and Schindler (2018) 56: 113-127]).

So, I think you can see that *The Canadian Mineralogist* publishes papers over a wide range of topics (including crystal structures!) and we welcome manuscripts from all areas of the discipline.

Sincerely yours, **Lee A. Groat**
Editor, *The Canadian Mineralogist*

WELCOMING NEW MEMBERS OF COUNCIL

The MAC Executive approved the nomination of the following candidates for the vice president position for 2018–2020 and for the two positions of councillor for 2018–2021. As no additional nominations were received from the membership, the nominated candidates were declared elected by acclamation. The MAC Executive also appointed a new Finance Committee Chairman.

Vice President 2018–2020

Dr. Andrew Conly is an associate professor in the Department of Geology at Lakehead University (Ontario, Canada) where he has been a faculty member since 2003 and is now Director of the Lakehead University Mineralogy and Experimental Laboratory. He obtained his PhD from the University of Toronto (2003) and his MSc (1996) and HBSc (1993) degrees from Carleton University (Canada). Andrew is a mineral deposit specialist where his past studies focused primarily on the genesis of sediment-hosted base-metal deposits. However, at Lakehead University, Andrew has expanded his research into the fields of experimental petrology and environmental mineralogy, and, most recently, into the geology and mineralogy of graphite deposits. Andrew has an extensive history of professional service: twice served as Chair for the Mineral Deposits Division of the Geological Association of Canada, and is currently their Short Course Chair; Academia Representative on the Steering Committee on Chromite Research and Development for CANMET – Natural Resources Canada; Regional Vice-President (North America) for the Society for Geology Applied to Mineral Deposits; and Director for Canadian Institute of Mining, Metallurgy and Petroleum – Geological Society. Since 2010, Andrew has also been very much involved with the Mineralogical Association of Canada, where he has served as a councillor (2010–2013), Hawley Award Selection Committee Member, Selection Committee Member for student travel and research grants, and Selection Committee Member for awarding Mineralogical Association of Canada Foundation Scholarships to graduate students.

Finance Committee Chairman

Mr. Rémy Poulin is a research scientist in the Harquail School of Earth Sciences at Laurentian University in Sudbury (Canada). He obtained his BSc with Honours in geology from the University of Ottawa, followed by an MSc (2016) in Earth sciences from Laurentian University in the field of applied mineralogy. His MSc thesis, "A Study of the Crystal Chemistry, Cathodoluminescence, Geochemistry and Oxygen Isotopes in Scheelite: Application towards Discriminating among Differing Ore Deposit Systems", was supervised by Drs. Andrew M. McDonald and Daniel J. Kontak. Since 2017, he has been the electron microprobe technician and a sessional lecturer in the Harquail School of Earth Sciences. Mr. Poulin has been involved in numerous projects, focusing on the development of analytical methods (trace elements, cathodoluminescence) and mineral chemistry. Mr. Poulin is an applied mineralogist who uses his knowledge of mineralogy, mineralogical techniques and geochemistry to investigate complex geologic processes in a variety of earth systems. Mr. Poulin is also active in the geological community. He served on a number of university councils and was the secretary on the Modern Mining and Technology Sudbury executive committee from 2012 to 2014. Mr. Poulin has published articles in mineralogical journals (e.g. *The Canadian Mineralogist*) and has presented to the general public and at geological conferences such as GAC–MAC.

UPCOMING GAC–MAC–IAH JOINT MEETING

Québec, QC, Canada • 12–15 May 2019 • gacmac-quebec2019.ca

GAC-MAC-IAH
QUÉBEC 2019
Where geosciences converge

Councillors 2018–2021

Prof. Siobhan ('Sasha') Wilson is, as of 2018, an associate professor in the Department of Earth and Atmospheric Sciences at the University of Alberta (Canada). She obtained her BSc (Hons) in physics from McMaster University (Canada) and her MSc and PhD degrees in geological sciences from the University of British Columbia (Canada). Sasha held a NASA Postdoctoral Fellowship at the Indiana University node of the Astrobiology Institute (USA). She was a faculty member at Monash University in Melbourne (Australia) from 2011 through 2017, and she is currently at the University of Alberta. She received the 2016 E.S. Hills Medal from the Geological Society of Australia and the 2017 MAC Young Scientist Award for her contributions to geochemistry. She is a biogeochemist whose work focuses on environmental aspects of economic geology. Her team is working to understand and tailor carbon, sulfur, silica, metal and metalloid mobility within minerals in geoengineered landscapes, mining environments and mineral processing circuits, with a focus on developing solutions for metal sequestration/recovery and carbon sequestration. On the fundamental side, her group is working on understanding gas–mineral reactions and organomineralization in sedimentary systems**.**

Dr. Emmanuelle Cecchi is a research associate at the Institut national de la recherche scientifique (INRS-ETE) in Québec City (Canada). She was born in France but grew up in Gabon, where her passion for the Earth sciences was initiated and blossomed. She initially obtained her Diplôme d'études universitaires générales, Licence et Maîtrise (equivalent to a BSc) in Earth sciences at the University of Nice Sophia Antipolis (France), followed by a Diplôme d'Études Approfondies de 3$^{\text{ième}}$ Cycle (equivalent to an MSc), on the structure and evolution of the lithosphere, at Montpellier II University (France). She then journeyed across the pond to Canada, to the INRS-ETE in order to conduct her PhD ("Revalorisation of White Asbestos Tailings by Producing $MgCl_2$ using Carbochlorination") under the supervision of Drs. Guy Mercier and Mario Bergeron, completed in 2008. Dr. Cecchi accepted a post-doctoral fellowship at Laval University (Canada), where she worked on the project "Study of the Spontaneous Carbonation of Serpentine in Milling and Mining Waste, Southern Quebec". Since 2010, Dr. Cecchi has been a research associate at the INRS-ETE where she has been involved in numerous projects focussed on the environment and engineering, including the Canadian Rare Earth Element RandD Initiative (CREEN), contaminant-leaching prediction and mine-tailings valorization, the latter with a strong emphasis in the area of CO_2 sequestration. Dr. Cecchi can easily be classed as an applied mineralogist who uses her knowledge of mineralogy, mineralogical techniques and geochemistry to tackle real-world problems and issues. She also contributes to the promotion of the mineral sciences in Canada by volunteering her time; by mentoring and helping in the organization of a number of past and present meetings, including serving as a member of the Environmental Technical committee of CREER; by being a reviewer of submissions to various journals (e.g. *International Journal of Mineral Processing*, *Minerals*); and by being a member of the organizing committee for the Québec 2019 Geological Association of Canada–Mineralogical Association of Canada–International Association of Hydrogeologists (GAC–MAC–IAH) meeting.

THANKS TO OUTGOING MEMBERS OF COUNCIL

We extend our thanks to outgoing Past President, **Ron C. Peterson**, for his long-time commitment. Ron served first as Finance Chair for five years, then spent six years on the MAC Executive. We also thank **Michelle A.E. Huminicki** who served as Finance Chair, and to our outgoing Councillors **Anežka Borčinová Radková**, and **Ekaterina Reguir** for their years of service.

MAC AWARDS – CALL FOR NOMINATIONS

Peacock Medal

The Peacock Medal is awarded to a scientist who has made outstanding contributions to the mineralogical sciences in Canada. There are no restrictions regarding nationality or residency. The medal recognizes the breadth and universality of the awardee's contributions to mineralogy, applied mineralogy, petrology, crystallography, geochemistry, or the study of mineral deposits

Young Scientist Award

This award is given to a young scientist who has made a significant international research contribution during the early part of their career. The scientist will have received his/her PhD not more than 15 years before the award. He or she must be a Canadian working anywhere in the world or a scientist of any nationality working in Canada. The research areas include mineralogy, crystallography, petrology, geochemistry, mineral deposits, or related fields of study.

Leonard G. Berry Medal

The Leonard G. Berry Medal is awarded annually for distinguished service to the association. The award recognizes significant service in one or more areas, including leadership and long-term service in an elected or an appointed office. The medal is named after Leonard G. Berry (1914–1982), a founding member of MAC, editor for 25 years of *The Canadian Mineralogist* and its predecessor, and the first winner of MAC's Past-Presidents' (now Peacock) Medal.

Pinch Medal

The Pinch Medal is awarded every other year since 2001 to recognize major and sustained contributions to the advancement of mineralogy by members of the collector and dealer community. This medal is named for William Wallace Pinch (1940–2017) of Rochester (New York, USA) in recognition of his enormous and selfless contributions to mineralogy through the identification of ideal specimens for study and through his generosity in making them available to the academic community.

Nominations for the 2019 award and medals are to be submitted to **Andrew M. McDonald** (Department of Earth Sciences, Laurentian University, Sudbury, ON P3E 2C6, Canada); E-mail: mcdonald@laurentian.ca.

Please submit your nominations by **30 November 2018** for the Pinch Medal and by **31 December 2018** for the others. Check our website, **www.mineralogicalassociation.ca**, for additional details.

STUDENT TRAVEL/RESEARCH GRANTS

The MAC awards travel and research grants to assist honors undergraduate and graduate students in the mineral sciences. For more information, see www.mineralogicalassociation.ca/. **DEADLINE TO APPLY: 15 JANUARY 2019**

Association of Applied Geochemists

www.appliedgeochemists.org

28th INTERNATIONAL APPLIED GEOCHEMISTRY SYMPOSIUM (IAGS)

The 28th International Applied Geochemistry Symposium was held 16–21 June 2018 at the Convention Centre in Vancouver (Canada) in conjunction with the Resources for Future Generations (RFG2018) conference. The Association of Applied Geochemists (AAG) was well represented at the RFG2018: we had numerous technical sessions, three short courses and a field excursion. A highlight of the week was the AAG gala dinner, which was held at the Vancouver Aquarium where the AAG's gold and silver medals were awarded for 2016 and 2017.

CITATION FOR 2016–2017 AAG MEDALLISTS

Reijo Salminen, AAG 2016 Gold Medal

The 2016 Gold Medal for outstanding contributions to exploration geochemistry went to Professor Reijo Salminen (Geological Survey of Finland, retired). Professor Salminen has had a long and successful career in geochemical research in Finland and Europe, beginning in the late 1960s and culminating in becoming a research professor in geochemistry in the Geological Survey of Finland (GTK) from 1997 to 2010. During this time, he led numerous national and international geochemical mapping projects in Finland, the Barents Sea region and elsewhere in Europe, and managed large collaborative projects. He participated in the GTK's international geochemical mapping projects, including fact-finding, project planning and implementation missions in Tanzania, Uganda, Nigeria, Russia and Norway. He ran undergraduate and post-graduate courses in the universities of Helsinki and Turku (both Finland) and supervised graduate theses.

From left to right: 2016 winner of the Silver Medal, David Cohen; 2017 winner of the Gold Medal, Stu Averill; Pertti Sarala accepting the 2016 Gold Medal on behalf of winner Reijo Salminen.

Professor Salminen was a pioneer in developing geochemical mapping at different scales, particularly in the use of glacial till, and a leader of national and international geochemical mapping projects. His work has been widely acclaimed by the international geological community. His impressive publication record includes some 36 refereed scientific papers, and he was the lead author and/or editor of 15 geochemical atlases and books. He is, or has been, a member of the editorial boards of scientific journals, including *Geochemistry: Exploration, Environment, Analysis*. His leadership roles on international collaborative projects have included Chair of the European subcommittee of the International Union of Geological Sciences/International Association of GeoChemistry Working Group on Global Geochemical Baselines, and the Forum of Geological Surveys of Europe/EuroGeoSurveys Geochemistry Working Group (FOREGS) 1996–2006. Professor Salminen has remained active in international geochemistry projects since his retirement in 2010. He is a worthy recipient of the AAG 2016 Gold Medal.

Stu Averill, AAG 2017 Gold Medal

The 2017 Gold Medal for outstanding contributions to exploration geochemistry went to Stuart (Stu) Averill, founder of Overburden Drilling Management Ltd (ODM) and an innovator in applied geochemical methods. Stu has had a several-decades-long career of achievement in applied research, particularly in the development and application of innovative indicator mineral and gold grain methods for mineral exploration.

The Convention Centre in Vancouver (Canada).

Over the past 45 years, he has made important contributions to mineral exploration methods in the glaciated terrain of Canada and globally through his research and development at ODM in Ottawa (Canada). His extensive achievements include the initiation and improvement of rudimentary heavy mineral laboratory separation procedures to concentrate indicator minerals from surficial sediments, making such minerals more effective and practical for exploration. He also expanded the range of indicator mineral methods and suites to span a wide variety of deposit styles, from kimberlite-hosted diamonds to magmatic massive sulfide deposits. In addition, Stu developed a gold grain shape and surface texture classification that is now used worldwide, and he has discovered or delineated indicator mineral dispersal trains for more than 20 mineral deposits in North America and Chile.

During his long and successful career, Stu has been a generous collaborator with other scientists in government, industry and academia, and a willing mentor to students and junior geoscientists. He has contributed numerous presentations to past International Applied Geochemistry symposia and published many technical articles in *EXPLORE*. He is internationally acclaimed for his body of work and is a most deserving recipient of the 2017 Gold Medal.

David Cohen, AAG 2016 Silver Medal

The Association of Applied Geochemists' Silver Medal is given to those who have voluntarily devoted extraordinary time and energy to the affairs of the AAG. The 2016 Silver Medal is awarded to Dr. David Cohen of the University of New South Wales (Australia) for his dedicated service to the AAG. This reward is a reflection of his long-standing and continued service, particularly related to symposia coordination, student awards, council and presidential duties, and his ongoing drive to provide education and training to younger geoscientists.

David has served as a councillor or council member almost continually from 2000 to the present, including the Executive Council during his four years as AAG Vice-President (2006–2007) and President (2008–2009). He has held the position of Symposia Coordinator for more than 9 years and has been a prolific educator and geochemical short-course organizer at innumerable International Applied Geochemistry symposia (IAGS) and other geological conferences. He has also been a driving force behind the AAG student awards, which are often organized in parallel with an IAGS. David has consistently been a strong advocate for student awards as a means of fostering young scientists and retaining them as members of the AAG. He is also the AAG's representative on the Australian Geoscience Council, a position he has held since 2008. More recently, David has served on AAG's Strategy Committee, which is tasked with understanding where the AAG is with respect to its members and in developing a future strategy to ensure the longevity of the association over the coming decades. He is a worthy recipient of the 2016 Silver Medal.

The Clay Minerals Society

www.clays.org

THE PRESIDENT'S CORNER


Lynda B. Williams

Poet and Pulitzer Prize–winner Rita Dove spoke at the 2018 graduation ceremony at my Alma Mater, Smith College (Northampton, Massachusetts, USA). Her closing comments to the Class of 2018 caught my attention. She spoke of a simple path to wisdom: "Start with what you know; then, as you venture into the world … apply what you've learned along the way, never forgetting that the key to the kingdom of knowledge is linked to curiosity and appreciation."

Such a path was exemplified by the life and achievements of Robert (Bob) C. Reynolds (Dartmouth College, New Hampshire, USA), my first mentor in clay science and one of clay science's pioneers. At Bob's memorial service (2004) it was said that if Bob wanted to know what time it was, he would build a clock. Bob always approached science from the most fundamental of perspectives. On his office desk was one lone pad of yellow lined paper and a pencil. He used the basic principles of physics, combined with observation, to derive and predict X-ray diffraction patterns of oriented preparations of clay minerals. For one of his hobbies, he built his own shotgun and made his own bullets in order to kill a varmint that had been destroying his garden.


Sampling dike—Pierre Shale contacts near Walsenburg, Colorado
Drawing by Marti Nash

The sketch of Bob, featured above, was from his work with PhD student Paul Nadeau on the Pierre Shale near Walsenburg (Colorado, USA). When Bob bought his first Kawasaki 1200cc he took his class out to do experiments and to make acceleration curves for his new motorcycle. Later that week he broke a rib when the motorcycle fell on him in his driveway. Bob was fascinated by the science of life and never missed an opportunity to derive knowledge from his curiosity. For example, he is perhaps best known for his probability theory for interpreting the ordering of mixed-layered illite–smectite. He told me that he started to derive this physical relationship when his wife, RoseAnn, made him go with her to the opera. Sitting in the balcony, he noticed patterns in how people seated themselves, male/female/male/male, just like many patterns in clays he had seen; illite/smectite/illite/illite. And, thus, he began looking into the theory of 'nearest neighbor' ordering.

It was many years later that Bob met Victor Drits (Moscow, USSR). Drits had made many of the same discoveries that Bob had, but across the world and during the cold war. Their mutual appreciation for clay science led to years of collaboration with each other's students, the fruits of which are now some of the world's premier clay scientists working today.

The Clay Minerals Society is an international community of people with knowledge, curiosity and appreciation of worldwide contributions to science. We all seek a path to wisdom. Join us and meet the many other fascinating personalities that have shaped, and continue to shape, our organization.

Student membership is only US$35 per year and qualifies you for travel and research grants up to US$3,000, including a subscription to *Elements* magazine and on-line access to ***Clays and Clay Minerals***
Visit www.clays.org

Lynda B. Williams, Arizona State University
(Lynda.Williams@asu.edu)
President, The Clay Minerals Society

2018 CMS PROFESSIONAL AWARD RECIPIENT SPOTLIGHT


Dr. G. Jock Churchman

The 2018 Marilyn and Sturges W. Bailey Distinguished Member Award was presented to **Dr. G. Jock Churchman** at the 55th Clay Minerals Society Annual Meeting at University of Illinois at Urbana-Champaign (USA) in June. Jock Churchman is Adjunct Senior Lecturer at the University of Adelaide (Australia) and Adjunct Associate Professor at the University of South Australia. He obtained degrees in chemistry from Otago University in his native New Zealand. He studied the physical chemistry of halloysite for his PhD, under a fellowship from the New Zealand pottery and ceramics industry, and carried out research for this industry for a short time before beginning a two-year post-doctoral fellowship in soil science at the University of Wisconsin (USA). He has continued working on halloysite all of his career, while pursuing many other research topics on clays. These topics include the following: the surface chemistry of clays; the effect of clays on the physical properties of soils; clay–organic complexes in soils; environmental uses of clays, especially bentonites; weathering and soil formation. He has published nearly 150 papers and coedited four books, most recently *The Soil Underfoot: Infinite Possibilities for a Finite Resource* (CRC Press, 2014) and *Natural Mineral Nanotubes: Properties and Applications* (CRC Press, 2015). He has received awards from the New Zealand Society of Soil Science, Soil Science Australia, the Association Internationale pour l'Étude des Argiles (AIPEA). He was employed in the New Zealand Soil Bureau, Department of Scientific and Industrial Research, for 16 years and in the Commonwealth Scientific and Industrial Research Organisation's Division of Soils (later Land and Water) for 14 years. He has also held visiting fellowships for one year at Reading University (UK) and for six months at the University of Western Australia. He is a former Editor (now Emeritus) of *Applied Clay Science*. In 2005, he completed a BA (Hons) in philosophy with a thesis on the philosophical status of soil science and has published papers on this topic.

INDUSTRY RECOGNITION FOR DR. PRAKASH MALLA


Dr. Prakash Malla

Dr. Prakash Malla, Director of the Research & Development at Thiele Kaolin Company (based in Sandersville, Georgia, USA) and 2015–2016 CMS President, was recently named the Technical Association of the Pulp and Paper Industry (TAPPI) Fellow. Fellow is an honorary title bestowed upon a small percentage of TAPPI's membership and given to individuals who have made outstanding technical or service contributions to the industry and/or the association. During his 25 years at the Thiele Kaolin Company, Dr. Prakash Malla and his team have been involved in improving and developing kaolin products and in developing processes for improved paper coating and filling, as well as other industrial applications. He has served TAPPI in a variety of leadership roles, including Chairman of the Coating Division. Dr. Malla is a prolific author and the holder or co-holder of 15 US patents. The award was conferred during the annual PaperCon conference in Charlotte (North Carolina, USA). More information on the TAPPI Fellows program can be found at https://www.tappi.org/fellows/. Congratulations, Dr. Prakash Malla!

Japan Association of Mineralogical Sciences

http://jams.la.coocan.jp

JAPAN ASSOCIATION OF MINERALOGICAL SCIENCES AWARDEES

The Japan Association of Mineralogical Sciences (JAMS) is proud to announce the recipients of its 2018 society awards. The **Japan Association of Mineralogical Sciences Award** is presented to a maximum of two scientists in any one year and is awarded for exceptional contributions to mineralogical and related sciences. The **Manjiro Watanabe Award—**named in honor of Professor Manjiro Watanabe, a famous Japanese mineralogist, and founded at his bequest—is awarded every year to one scientist who has significantly contributed to mineralogical and related sciences over his or her long career. The **Sakurai Medal**—named in honor of Dr. Kin-ichi Sakurai, the discoverer of many new minerals—is awarded to a scientist who has made a lasting contribution to the study of new minerals.

Japan Association of Mineralogical Sciences Award to Susumu Umino

Susumu Umino

Susumu Umino is a professor at the Institute of Science and Engineering, Kanazawa University (Japan). He specializes in igneous petrology and physical volcanology, especially magma genesis and mantle evolution through subduction initiation. Professor Umino began his geological career by studying and experimenting on boninite from the type locality of the Bonin Islands (central Pacific Ocean, south of Tokyo). Based on the primitive melt inclusions in chromites derived from boninite, Umino found the coexistence of high-silica and low-silica boninite magmas, thereby providing constraints on the development of the mantle wedge during subduction initiation. Using these results, combined with Nd–Hf–Os isotopic analyses, he articulated the different origins of the boninite sources.

Professor Umino has also been engaged in a geological mapping project organized by the Oman government. He has been working on the Oman ophiolite and studying evidence for the different types of volcanic processes exhibited by the paleo-ridge system and how that ridge transformed into an ephemeral arc. Umino showed how the Oman protoarc magmas, including the boninites first reported by Tsuyoshi Ishikawa (in collaboration with Umino), both resembled and differed from the *T*–*P*–*X* evolution shown by the Izu–Bonin–Mariana protoarc magmas. In addition to submersible dives to seamounts off Hawaii (USA) and the East Pacific Rise, he joined Ocean Drilling Program (later becoming the Integrated Ocean Drilling Program) expeditions to Hole 504B (200 km south of the Costa Rica Rift) and Hole 1256D (equatorial East Pacific Rise), both of which drilled into intact oceanic crust.

Prof. Umino has been promoting a project MoHole, a plan to drill through the entire oceanic crust to the Mohorovičić Discontinuity and into the mantle to recover pristine, in-situ, mantle materials for the first time in human history.

Japan Association of Mineralogical Sciences Award to Hiroshi Kojitani

Hiroshi Kojitani

Hiroshi Kojitani is a research associate in the Department of Chemistry at Gakushuin University (Japan). He has studied mantle minerals and their analog materials using the techniques of calorimetry, spectroscopy, X-ray diffraction and high-pressure–high-temperature experiments. He learned thermodynamic investigation methods of mantle minerals under the supervision of Prof. Masaki Akaogi at Kanazawa University and Gakushuin University. Kojitani's PhD thesis, focused on the melting enthalpies of mantle rocks and basalts, has subsequently been widely used in mantle dynamics simulations and for constraining potential mantle temperatures. After a postdoc at Prof. Alexandra Navrotsky's laboratory (University of California at Davis, USA), he started a crystal structure refinement study using powder X-ray diffraction to reveal the aluminum substitution mechanism with oxygen vacancies in $MgSiO_3$ bridgmanite. Similarly, he refined the crystal structures of calcium ferrite–type $MgAl_2O_4$, $NaMg_2Al_5SiO_{12}$ and $KMg_2Al_5SiO_{12}$ hexagonal aluminous phases, and postperovskite-type $CaRuO_3$, which is a quenchable analog of postperovskite-type $MgSiO_3$ that was first synthesized at high pressure and high temperature by Kojitani and his group. He has also refined the enthalpy and heat capacity data of $MgSiO_3$ bridgmanite, $MgSiO_3$ akimotoite, and Mg_2SiO_4 ringwoodite. Over the last decade, he had added the techniques of high-pressure Raman spectroscopy and lattice vibrational model calculations to his array of research methods for estimating the thermodynamic parameters of high-pressure minerals (based on lattice vibrational data). Using newly assessed thermodynamic datasets, he recently succeeded in the thermodynamic calculation of the post-spinel phase boundary in Mg_2SiO_4.

Manjiro Watanabe Award to Yuzo Kato

Yuzo Kato

Yuzo Kato, currently professor emeritus at the University of Ryukyus (Japan), received his PhD in 1968 from Tohoku University (Japan). His doctoral thesis, "Petrology of the Tertiary Granitic Rocks around the Kofu Basin, Central Japan", was supervised by Prof. Y. Ueda. After earning his PhD, he stayed at Tohoku University and continued working on the granitic rocks in the Kitakami mountains of northeast Japan while also helping to characterize the chemical compositions of reference rock standards that were being distributed by the Geological Survey of Japan. From 1979 to 2004, he worked at the University of the Ryukyus (Japan). There, both he and his students started a major geological, petrological, and geochronological investigation into the igneous rocks of the Ryukyu islands. In addition to land-based sampling, Professor Kato also surveyed the submarine volcanic activity around the Ryukyu arc: in the young back-arc basin of the Okinawa Trough he discovered a new type of pumice, which he termed "woody pumice". This type of pumice results from super-rapid cooling under high-pressure deep-sea conditions.

Professor Kato also performed a mineralogical study on the "tsunami boulders" of the Ryukyu Islands and revealed reliable past inundation heights and flow paths of paleo-tsunamis, which has helped in tsunami hazard assessments. He also performed a pioneering work on accretionary lapilli. By a detailed study of the morphological and internal structure of accretionary lapilli from diverse occurrence, he succeeded categorizing several types of accretionary lapilli based on their conditions of formation. And he has devoted much effort to spreading geological and mineralogical knowledge to the general public. Books by Prof. Kato include the *Atlas of Rocks and Minerals of the Amami and Okinawa Islands* (1985, in Japanese), which attracted public attention by providing a unique display from outcrop through hand specimen to photomicrograph for many typical rocks of the islands.

Professor Kato has greatly contributed petrological, mineralogical, volcanological, and mitigation studies of the Ryukyu island arc. He has also enthusiastically educated the public and popularized the geology of these fields. Since 2004, he has been an emeritus professor at the University of Ryukyus.

Sakurai Medal to Yasuhiro Takai

Yasuhiro Takai

Yasuhiro Takai, while working at the Department of Earth and Planetary Sciences in Kyushu University (present affiliation; Enecom Co. Ltd), discovered the new mineral hizenite-(Y) (International Mineralogical Association number IMA2011-30). Hizenite-(Y) was discovered in a druse in an alkali olivine basalt (the Higashimatsuura basalt) that occurs throughout the Higashimatsuura Peninsula (Japan). The Higashimatsuura basalt has yielded rare-earth minerals and three new minerals: kimuraite-(Y), kozoite-(Nd) and kozoite-(La). The type locality of hizenite-(Y) is the same as that of kozoite-(La). Rhabdophane-(Y) (IMA2011-31) which is rare-earth phosphate, was also discovered from the Higashimatsuura basalt by Dr. Takai. Hizenite-(Y) occurs as platy crystals and forms radial aggregates in very close association with tengerite-(Y) and lokkaite-(Y). Hizenite-(Y) is white in color and translucent to transparent. It has a vitreous to silky luster on cleavage planes, which are perfect on {001}. The ideal formula is $Ca_2Y_6(CO_3)_{11}\cdot 14H_2O$. Hizenite-(Y) is a member of tengerite family, which includes the mineral species tengerite-(Y), kimuraite-(Y), and lokkaite-(Y). The dimensions of the *a* and *b* axes of hizenite-(Y) are similar to those of the other tengerite-family minerals. Hizenite-(Y) has an alternating structure of kimuraite-(Y) and lokkaite-(Y) in a one-to-one relation along *c* axis. The name 'Hizen' is for the classic name of the locality of the mineral, and now, it remains as the name of town in Karatsu City, Saga prefecture.

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Original Articles

Laser step-heating $^{40}Ar/^{39}Ar$ analyses of biotites from meta-granites in the UHP Brossasco-Isasca Unit of Dora-Maira Massif, Italy – Tetsumaru ITAYA, Hironobu HYODO, Takeshi IMAYAMA and Chiara GROPPO

Spatial distribution of garnet indicating control of bulk rock chemistry in the Sanbagawa metamorphic rocks, Kanto Mountains, Japan – Mutsuko INUI and Ayato TANIFUJI

Early Miocene island arc tholeiite in the Mineoka Belt: Implications for genetic relationship with the Izu–Bonin–Mariana (IBM) arc – Hatsuki ENOMOTO, Yuji ICHIYAMA and Hisatoshi ITO

Mullite in a buchite from Asama volcano and its sub-micrometric core–rim texture with sillimanite – Yohei IGAMI, Akira MIYAKE and Norimasa SHIMOBAYASHI

Influence of low-molecular-weight dicarboxylic acids on the formation of calcium carbonate minerals in solutions with Mg^{2+} ions – Mako MIYASHITA, Eri YAMADA and Motoharu KAWANO

DMG SECTIONS: GEOCHEMISTRY AND PETROLOGY/ PETROPHYSICS

Participants at the DMG's 2018 Petrology/Geochemistry meeting in Göttingen (Germany).

The annual joint meeting of the Geochemistry and Petrology/ Petrophysics sections of the German Mineralogical Society (DMG) took place 9–10 July at the Geosciences Centre of the University of Göttingen (Germany). Approximately 40 geoscientists from 11 research institutes across Germany and Austria attended the meeting. Many of the participants were PhD students and postdocs. The oral and poster presentations spanned an enjoyably diverse range of topics, from cosmochemistry, experimental petrology and volcanology, to low-temperature isotope geology and methodological developments in mass spectrometry and radiometric dating methods. After an inspiring oral program (13 talks) and an equally inspiring poster session (12 presentations), the canonical barbecue of the meeting took place on the north campus of the university. This excellent barbecue was organized by the geosciences study association of the University of Göttingen, who made provision for both the carnivorous and the vegetarian/vegan options. The poster session and barbecue alternated with several possible tours for the participants. The first was a visit to two new exhibitions at the university's Mineralogical Museum: one on minerals, and one specifically on amber. The second was to various demonstrations at the laboratories of the mineralogy and isotope geology departments. We are greatly looking forward to an equally exciting meeting in Heidelberg in 2019!

Stefan Peters, **Sara Fanara** (Göttingen), **Ronny Schönberg** (Tübingen), **Timm John** (Berlin)

International Association of GeoChemistry

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WRI–16 AND AIG–13: THE 1st IAGC INTERNATIONAL CONFERENCE

Next year, like every three years, the Water–Rock Interaction (WRI) Working Group of the International Association of GeoChemistry (IAGC) will meet for a week of science and collegiality in a unique region of the world. For the first time, the Water–Rock Interaction and the Applied Isotope Geochemistry (AIG) Working Groups will organize a joint symposium, which has been consolidated as the **1st IAGC International Conference**. We hope to attract researchers and scholars from the fields of geochemistry, hydrology, geology, and environmental sciences, as well as colleagues from applied isotope geochemistry, to share their scientific findings and exchange ideas at the 1st IAGC International Conference, which will be held **21–26 July 2019 in Tomsk (Russia)**. The consolidated conference is planned to be a week-long meeting, with the technical program operating at two levels – first, as sets of technical sessions organized by both working groups around themes of their choice; second, as multiple inter-disciplinary symposia developed by the conference organizers. The local committee, led by Secretary General Natalia Guseva of the Tomsk Polytechnic University, is developing an interesting scientific program that will include pre- and post-conference excursions and opportunities to experience the culture of Siberia and Russia.

Participants interested in both the WRI and the AIG are asked to sign up on the WRI-16 website (http://wri16.com/). Manuscript submission is now open and instructions regarding format and content can be found under http://wri16.com/submission/paper-instruction. Authors are invited to submit no more than two manuscripts written in English **by 15 October 2018.** The early registration deadline for the conference is **15 February 2019**, followed by a late registration deadline of **30 March 2019**.

IAGC AWARD NOMINATIONS

The International Association of GeoChemistry is a private, not-for-profit international organization committed to excellence in the geochemical sciences. The association promotes the application of chemistry across the entire spectrum of the earth and environmental sciences. This is accomplished through sponsoring scientific conferences and educational activities, establishing internal specialist working groups, and disseminating new geochemical knowledge through scientific publishing, such as the IAGC's journal, *Applied Geochemistry*, and, of course, through *Elements*.

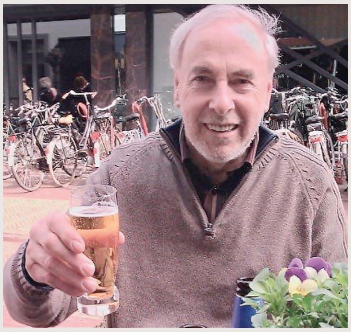
The IAGC encourages contributions to the field of geochemistry by recognizing individuals for outstanding scientific accomplishments, in the form of grants, certificates, awards, and medals.

A notable example is the Ingerson International Lecturer Award, based on a bequest by the first President of the IAGC, Dr. Earl Ingerson. An IAGC Ingerson International Lecturer is selected every two years; the award consists of a certificate and a complementary one-year membership to the IAGC. The lecture is scheduled either at an International Geological Congress, at a suitable scientific meeting organized by an IAGC Working Group, or at some other prestigious international/national meeting of another scientific society during the second year after an International Geological Congress. The lecturer is expected to be available for seminars at academic and research institutions during the following two years and to publish an article in the IAGC's journal *Applied Geochemistry* during their term.

Another example is the Faure Award, which given to the best student research presentation at each IAGC-sponsored conference or IAGC-organized technical session at a major conference. A student research presentation is defined as one with a student as senior author that is presented at the meeting by the student. This award consists of a certificate and a complementary one-year membership to IAGC. In addition, there will be a profile of the award recipient in the *IAGC Newsletter* and on the IAGC's website.

We strongly encourage members to nominate those peers and colleagues who have made significant contributions to the advancement of geochemistry for one or more of the numerous IAGC awards. A complete list of IAGC awards, plus the nomination instructions, can be found at the IAGC website: http://www.iagc-society.org/awards.html.

REMEMBRANCE – MELVYN (MEL) GASCOYNE (1948–2018)



Mel Gascoyne passed away 14 July 2018 after a career of scientific contributions to geochemistry and a record of distinguished service to the geochemical community. Mel served as an associate editor for *Applied Geochemistry* for 23 years, from 1988 to 2011, handling manuscripts on nuclear waste disposal, radioactivity in the environment, formation waters, and U-series geochronology. During this time, Mel also served as IAGC Secretary from 1992 to 2002 and then as Business Office Manager from 2003 to 2010. To many in the geochemical community, Mel is best known for the generous time commitments and his ability to promote science. He served the science he loved through lengthy years of dedicated service, particularly to the IAGC and its journal, *Applied Geochemistry*. Appropriately, Mel received the IAGC Distinguished Service Award in 2011. The geochemistry community mourns his passing.

European Mineralogical Union

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XIII INTERNATIONAL GEORAMAN CONFERENCE

The XIII International GeoRaman Conference was held 10–14 June 2018 in the wonderful city of Catania (Italy). The conference was organised by the University of Catania (Dipartimento di Scienze Biologiche Geologiche e Ambientali) and the University of Parma (Dipartimento di Scienze Matematiche, Fisiche e Informatiche). The aim of this GeoRaman conference was to provide a scientific forum to present and promote research on the application of Raman spectroscopy to the study of geological materials and processes.

The conference topic was interpreted in a broad sense, including mineralogy, petrology, archaeometry, exobiology, gemmology, forensics and the analysis of biological molecules. The following topics were covered: provenance studies, mineralogy and gemmology, petrology, field and experimental volcanology, geothermobarometry and fluid geochemistry, cultural heritage and archaeology, planetary analysis and space exploration, astrobiology, paleobiology, carbonaceous materials, biomineralisation and the environmental sciences, and forensic applications.

The first GeoRaman conference was held in 1986 in France. Since then, many beautiful cities have played host to this conference: Valladolid (Spain) in 1999; Prague (Czech Republic) in 2002; Hawaii (USA) in 2004; Almunecar (Spain) in 2006; Gent (Belgium) in 2008; Sydney (Australia) in 2010; Nancy (France) in 2012; St. Louis (Missouri, USA) in 2014; and Novosibirsk (Russia) in 2016.

A total of 133 participants attended the XIII GeoRaman Conference, and they came from a large number of countries: Australia, Belgium, China, Czech Republic, Finland, France, Germany, Greece, Hungary, Italy, Nederland, Norway, Poland, Russia, Spain, UK, USA. The attendees, who had the pleasure of listening to some 70 presentations, were from universities and from public and private organisations. There were three plenary lectures. The first was given by Howell Edwards (Faculty of Life Sciences, University of Bradford, UK), who talked on the applications of Raman spectroscopy in archaeology. The second was given by Rafaella Georgiou (Synchrotron SOLEIL, Université Paris, France), who talked about the problems associated with characterising and identifying the organic carbon compounds used in carbon-based artists' pigments and in paleontological specimens. The third lecture was given by Claudia Conti (Institute for the Conservation and Valorisation of Cultural Heritage, National Research Council of Italy), who discussed how to analyse subsurface molecular components at micrometre scales and how this can be applied to the conservation and materials sciences.

The conference was sponsored by the Societa Italiana di Mineralogia e Petrologia (SIMP), the European Mineralogical Union (EMU), TimeGate, Bruker, Renishaw, WITec, Cavallotto and Jasco. Four grants for young researchers were sponsored by SIMP, two such grants were sponsored by the EMU.

Some of the presentations will be published in a special issue of the *Journal of Raman Spectroscopy* (which has an impact factor of 2.969).

The XIII GeoRaman Conference received very positive feedback from the attendees. For more information on the XIII International GeoRaman Conference, please visit the web site https://sites.google.com/view/georaman2018/home

THE 28th V.M. GOLDSCHMIDT CONFERENCE®

The 28th V.M. Goldschmidt Conference, organized by the Geochemical Society (GS) and the European Association of Geochemistry (EAG), was held 12–17 August 2018 in Boston (Massachusetts, USA). Nearly 3,100 delegates participated in the six-day meeting (Sunday through Friday), making it the largest North American Goldschmidt Conference to date.

As always, the meeting reflected the cooperation of the entire geochemical community. Hundreds of scientists contributed to the success of the conference by volunteering as theme and session chairs, grant application reviewers, mentors, and student helpers.

The Local Organizing Committee was chaired by Shuhei Ono (Massachusetts Institute of Technology, USA) and Steve Parman (Brown University, USA) and ensured that attendees had the opportunity to experience the beautiful city of Boston during the week. The Local Organizing Committee also coordinated field trips, workshops, and a new program for local kindergarten-through-12th-grade educators. Other members of the committee included Ethan Baxter (Boston College, USA), Dawn Cardace (University of Rhode Island, USA), Meredith Hastings (Brown University, USA), Katherine Kelley (University of Rhode Island, USA), and Andrew Kurtz (Boston University, USA).

The Science Committee was chaired by Tim Lyons (University of California, Riverside, USA) and Daniela Rubatto (University of Bern, Switzerland) and also included Hagit Affek (Hebrew University of Jerusalem, Israel), Fang Huang (University of Science and Technology of China), Ann Pearson (Harvard University, USA), Graham Pearson (University of Alberta, Canada), Roberta Rudnick (University of California, Santa Barbara, USA), Cara Santelli (University of Minnesota, USA), and Maria Schönbächler (ETH Zürich, Switzerland).

The meeting was organized into 14 themes for which 3,076 abstracts were received. The Science Committee, theme chairs, and session leads did an outstanding job reviewing and organizing the abstracts into a coherent and well-organized program, with 1,761 oral presentations and 1,315 posters. Delegates came from all over the world: the 20 countries with the largest number of participants were: the United States, China, Germany, the United Kingdom, Canada, Japan, France, Australia, Switzerland, Korea, India, the Netherlands, Israel, Brazil, Belgium, Denmark, Poland, Spain, Italy, and Chile.

FIGURE 1 Prof. Adina Paytan (University of California, Santa Cruz) received the 2018 Endowed Biogeochemistry Lecture certificate before presenting her talk, "Isotopes, Genes and Technology the Past, Present and Future of Corals."

The daily plenary talks featured fascinating topics that ranged from the deep ocean to the distant stars. Prof. Sara Seager (Massachusetts Institute of Technology, USA) presented, "Mapping the Nearest Stars for Habitable Worlds" on Monday. The 2018 Paul Gast Lecture, "Oxygen Loss in Coastal Waters: Impact on Geochemical Cycles," was delivered on Tuesday by Prof. Dr. Caroline Slomp (Utrecht University, Netherlands). On Wednesday, Prof. Tuba Özkan-Haller (Oregon State University, USA) gave her talk, "Transforming Academia: Advancing Diversity, Inclusion, and Social Justice in the Geosciences." On Thursday, Prof. Fumio Inagaki (Japan Agency for Marine–Earth Science and Technology, Japan) presented "Exploring Deep Microbial Life in the Planetary Interior: What Are the Limits of Habitability?" Then on Friday, EAG President Bernard Marty (Centre de Recherches Pétrographiques et Géochimiques in Nancy, Centre nationale de la recherche scientifique and Université de Lorraine, France) delivered "Origin and Early Evolution of Terrestrial Volatiles." All five plenary lectures can be viewed online at www.youtube.com/user/goldschmidtconf.

FIGURE 2 Pu Yue (Northeastern University, USA) discussed his poster on Monday.

Those who attended the Wednesday morning sessions got an unexpected break when the convention center's fire alarm sent everyone outside. Fortunately, there was no fire and the conference resumed quickly. One good thing came of the alarm: the convention center gave the GS a discount on Wednesday morning's coffee break to apologize for the disruption. The GS has decided to use the savings to fund 15 student grants at a future Goldschmidt Conference.

FIGURE 3 The student helper team is integral to making the conference run smoothly: they assist delegates with registration, uploading their talks, and so much more.

A MORE INCLUSIVE GOLDSCHMIDT

About a year ago, the GS and EAG began discussions on how to make the Goldschmidt Conference a more inclusive conference for everyone who attends. The GS Ethics Committee led the effort to write a code of conduct, which was put into place at this year's meeting. To support implementation of this code, the societies trained a group of volunteers to serve as points of contact for any delegate who had questions or experienced harassment during the conference. This initiative was named AMIGo, short for A More Inclusive Goldschmidt. The Local Organizing Committee also made diversity and inclusion a focus of the conference. Wednesday's plenary was devoted to this topic, and a workshop addressed the issue of sexual harassment in the workplace.

FIGURE 4 On Tuesday evening, attendees enjoyed the collection on display at the Harvard Mineralogical and Geological Museum. The museum hosted a mixer for Goldschmidt participants.

CONFERENCE GRANTS

The 2018 conference offered a significantly larger number of grants this year thanks to support from several sources. The U.S. National Science Foundation provided a grant that funded students who identify as members of underrepresented groups in science and engineering or who attend underrepresented institutions in the USA, such as small universities and colleges. The GS provided matching funds for this group. The National Aeronautics and Space Administration (NASA) provided grants for students and post-docs working in planetary geology, cosmochemistry, and astrobiology. The GS and Elsevier also provided grants for students and early career scientists from low-income or lower-to-middle-income economies, as defined by the World Bank. In total, 70 delegates received grants to help them attend the conference.

FIGURE 5 Delegates applaud Prof. Sara Seager's talk on the search for habitable worlds.

FIELD TRIPS AND WORKSHOPS

A number of workshops that were held before and during the conference offered in-depth looks at scientific and career strategy topics. Several were presented at Boston University, which also provided housing for more than 300 delegates during the week. The Local Organizing Committee planned three field trips, all of which sold out. Participants visited areas around the states of Massachusetts and New Hampshire to learn about New England's regional geologic history, and some took a whale-watching cruise off Cape Cod (Massachusetts).

MEDIA COVERAGE

The incredible science presented during the 28th V.M. Goldschmidt Conference has implications that stretch far beyond the meeting itself. Press officer Tom Parkhill and the media team distributed eight press releases throughout the week to promote both the conference and geochemistry to a wide audience. The releases generated significant media attention, with articles and interviews appearing in publications such as *Newsweek, The Independent, BBC Radio, Die Welt, Scientific American*, and many more. All of the press releases can be found at goldschmidt.info/2018/pressReleasesView.

COMMUNICATING SCIENCE

The Local Organizing Committee and the Science Committee organized a special thematic session, "Communicating Science: Outreach and Education," which examined challenges that scientists and educators face when trying to teach geochemistry topics to students and the general public. The session included traditional oral presentations and posters, as well as talks from invited experts in Earth-science education. Participants learned strategies for translating complicated topics into age- and expertise-appropriate content for audiences, including elementary schools, university students, policy makers, and the general public.

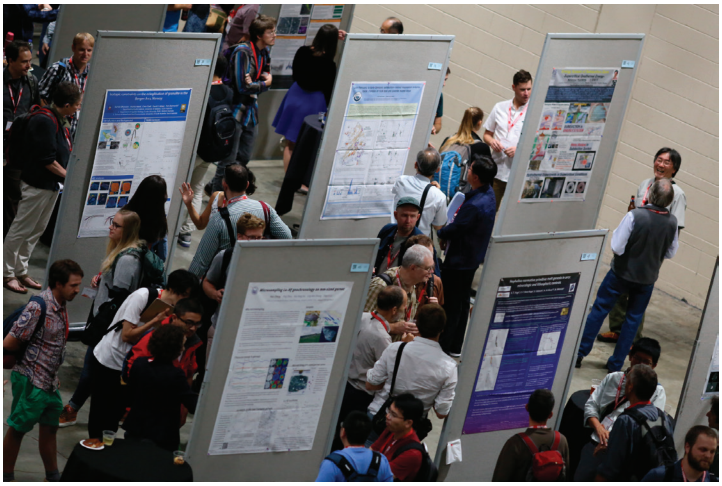

FIGURE 6 One of the conference's most popular components, the afternoon poster sessions provided dedicated time for delegates to discuss their science.

SPONSORS AND EXHIBITORS

A successful Goldschmidt would not be possible without the support of generous sponsors. The GS and the Local Organizing Committee wish to thank Thermo Fisher Scientific, Curtin University, and the Geochemist's Workbench for their support of the 2018 conference. The Gordon and Betty Moore Foundation, ACS [American Chemical Society] Earth and Space Chemistry, American Geophysical Union, *Elementa: Science of the Anthropocene*, and the Geological Society of America who supported the student program. Finally, our warmest thanks go to the many exhibitors who shared their expertise with delegates throughout the week.

HOPEWELL METEORITIC METAL BEADS: CLUES TO TRADE 2,000 YEARS AGO

Timothy J. McCoy[1]

DOI: 10.2113/gselements.14.5.360

Naturally occurring iron metal is exceedingly rare on the surface of the Earth. Thus, it is little wonder that civilizations dating back thousands of years used iron meteorites—naturally occurring alloys of Fe, Ni, Co and a variety of trace elements—to manufacture knives, fishhooks, adzes, and amulets, among other objects. Perhaps the best known of these is the meteoritic metal blade of a dagger found with the mummified body of King Tutankhamun (Egypt's 18th dynasty boy pharaoh who ruled ~1332–1323 BC). Unfortunately, the rarity of these materials typically makes it impossible to apply destructive techniques that might allow researchers to not only confirm a meteorite origin, but also identify the meteorite used during manufacturing. Fortunately, the inhabitants of what is today the central United States produced meteorite artifacts in abundance, allowing for the kind of analyses that provides clues to 2,000-year-old trade routes.

Exotic materials, including copper, silver, obsidian, mica, and shells, and the building of mounds, including earthworks and burial mounds, are a hallmark of the Native American Hopewell culture (~400 BCE to 400 CE) (Prufer 1961) within the Middle Woodland period in eastern North America. The sources of these materials span much of eastern North America: shells from the Gulf of Mexico, silver from Ontario (Canada), obsidian from modern-day Yellowstone National Park. Although a volumetrically miniscule proportion of the artifacts, meteoritic metal represents the most exotic and traceable of these materials. Artifacts of iron metal were first recognized from Hopewell sites in modern day Ohio (USA), including from mounds near Chillicothe (Ohio). The famous Tiffany and Company gemologist George F. Kunz (1856–1932) first suggested a connection between numerous Hopewell artifacts from Ohio, including beads and adze blades, and the Brenham (Kansas) pallasite meteorite. Kunz based his hypothesis on the shape of the included olivine crystals and the relative proportions of metal and olivine in this stony-iron meteorite. A definitive connection between Ohio Hopewell meteoritic iron and the Brenham pallasite finally came with the advent of instrumental neutron activation analyses of meteoritic irons. By determining the trace-element chemical composition of both the artifacts and the metal within the Brenham meteorite, Wasson and Sedwick (1969) convincingly demonstrated a match.

A significant impediment to a full understanding the importance of meteorites in Hopewell culture is the absence of a confirmed relationship between any other Hopewell meteoritic artifact and a known meteorite, other than the Ohio Hopewell–Brenham link. In the summer of 1945, the Illinois State Museum excavated a group of mounds in Mason County (Illinois) about 1.5 miles south of the town of Havana and identified a bead string that contained 22 meteoritic iron beads interspersed by shell beads (McGregor 1952). Wood from the same mound yielded an age of 2,336 ± 250 years BCE, which is consistent with ages for the Ohio Hopewell sites. In the meteoritic metal beads (Fig. 1), alternating bands of low-Ni kamacite and high-Ni taenite are heavily deformed and roughly concentric to the center of the bead. The outer surface and inner hole are filled with limonite.

The Havana beads are chemically grouped with three North American iron meteorites: Anoka (Minnesota); Edmonton (Kentucky); and Carlton (Texas). Among these, Anoka was found as multiple masses on opposite sides of the Mississippi River in Anoka and Champlin, Minnesota. Coupled with the fact that the Havana site occurs along the Illinois River, a tributary to the Mississippi, warranted further investigation of the similarity between Havana and Anoka. To this end, both materials were analyzed for major, minor, and trace elements by electron microprobe at the Smithsonian Institution (Washington DC), by laser ablation inductively coupled mass spectrometry at the University of Maryland, and by instrumental neutron activation analysis at the University of California at Los Angeles. The Havana beads and the Anoka iron were found to be remarkably similar in chemical composition, with most elements within 10% of each other. Exceptions were elements that were concentrated in the phosphate mineral schreibersite (P, Ag, and possibly W) and elements that may have been contaminated by other artifacts (e.g. Cu). This finding is also consistent with the idea that schreibersite—a mineral that cross cuts Anoka and is more brittle than the surrounding Fe–Ni metal—may have provided a mechanism for removing portions of the meteorite to shape the beads.

Figure 1 Two Havana (Mason County, Illinois) meteoritic metal beads with a 1 cm cube for scale. The bead on the left is cut perpendicular to the central hole, illustrating the extensive alteration of the bead and infilling of the central hole. The bead on the right is cut parallel to the central hole and exhibits a concentrically deformed structure. Photo: Smithsonian Institution.

The beads were made by cold-working the metal into strips and then joining the ends to form a hollow, tubular bead (Fig. 2). Staff at the Smithsonian Institution, including myself, also undertook a bead-making experiment using a wood-fueled fire for heating and using lithics (rocks) for deformation, simulating contemporary Hopewell technology. Thinning was achieved by three cycles of heating for ~15 minutes in a red-orange wood-fueled fire interspersed with periods of deformation by the lithics to produce a final sheet 2–3 mm thick. This sheet could easily be fashioned into a cylinder by hammering it around a twig. The cylindrical bead so-produced shares a number of similarities with the Havana bead, including the degree of curvature and deformation of the Widmanstätten pattern and the fragmentation of the schreibersite.

The movement from source to final location for these meteoritic beads provides an interesting test of the competing models of trade that was engaged in by the Hopewell peoples. The movement of material between Hopewell sites has been envisioned in one of two ways. The first is as a regularized exchange system by which material moved through

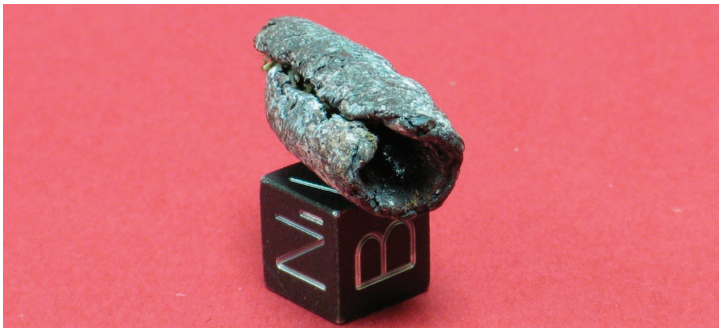

Figure 2 Meteoritic metal bead formed from the Anoka (Minnesota) iron using wood-fueled fire for heating and lithics for deformation (i.e. hammered using rocks). Photo: Smithsonian Institution

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multiple exchanges before reaching their destination: the so-called Hopewell Interaction Sphere described by Struever (1964). The second is as long-distance logistic trips to sites of known resources: the "one-shot" model of Griffin et al. (1969). While most of the exotic materials (e.g. obsidian, mica, copper) used by the Hopewell occurred in abundance at their sources, that is not universally true of meteorites. The Brenham meteorite, which is the source of the meteoritic metal beads identified at the Hopewell mounds in Ohio, has produced many tons of material up to the present. As such, the idea that an expedition might visit that site for the specific purpose of returning material to Ohio seems tenable.

In contrast, the beads identified from the Havana mound almost certainly originated from a single mass. The Havana mounds were located along the banks of the Illinois River, a tributary of the Mississippi River, and the Anoka meteorite fell near the Mississippi River (Fig. 3). In this case, the idea of exchange seems more likely. The Havana Hopewell center likely interacted with both the adjacent Trempeleau Hopewell, which extended from southwestern Wisconsin up the Mississippi River to the find site of the Anoka meteorite, as well as the more distant Ohio Hopewell, which centers on southern Ohio. The connection of the Trempeleau and Havana Hopewell via the Mississippi River further supports the hypothesis that the Anoka mass was recovered by the Trempeleau and, ultimately, traded to the Havana center.

Figure 3 Map of the central United States of America. Locations of Hopewell culture Native American archeaological sites are indicated by open circles. Image: Smithsonian Institution.

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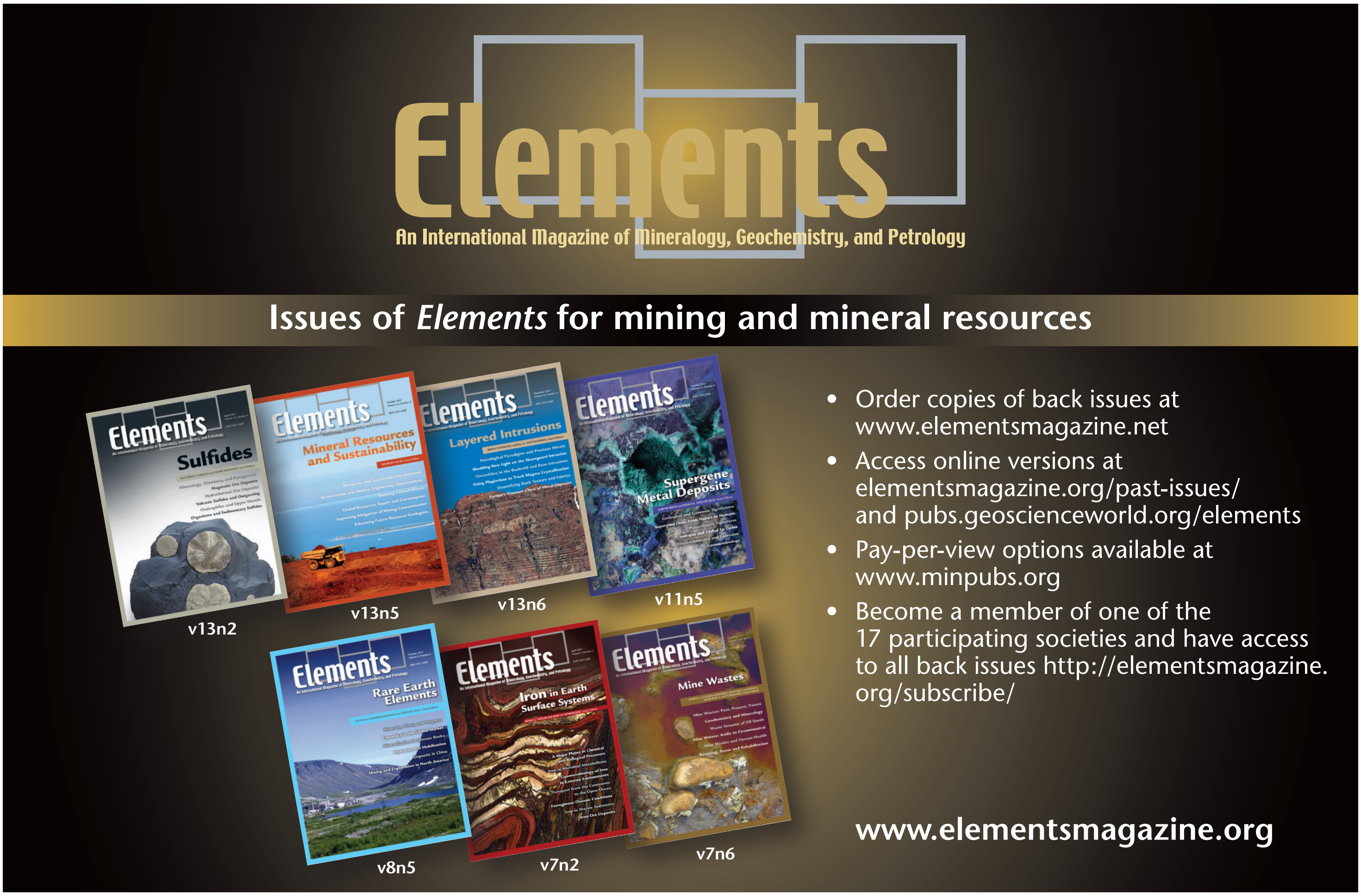

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October 7–9 GIA International Gemological Symposium, Carlsbad, CA, USA. Web page: gia.eventsair.com/QuickEventWebsitePortal/gia-symposium-2018/gia-symposium

October 14–18 Materials Science & Technology 2018, combined with ACerS 120th Annual Meeting (MS&T18), Columbus, OH, USA. Details forthcoming

October 25–28 25th Session of the Petrology Group of the Polish Mineralogical Society, Brunów, Sudetes, Poland. Web page: www.ptmin2018.uni.wroc.pl

November 4–7 Geological Society of America Annual Meeting, Indianapolis, IN, USA. E-mail: meetings@geosociety.org; Web page: www.geosociety.org/meetings

December 3–7 Short Course, Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences, Potsdam, Germany. Web page: sims.gfz-potsdam.de/short-course/

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2019

January 27–February 1 42nd International Conference and Expo on Advanced Ceramics and Composites (ICACC'19), Daytona Beach, FL, USA. Web page: ceramics.org/meetings/acers-meetings

February 18–22 DTTG workshop: Qualitative and Quantitative Analysis of Clays and Clay Minerals, University of Greifswald, Germany. Information: www.dttg.ethz.ch/workshop2019.html

February 24–27 Smart Mining: Resource for Connected World, Denver CO USA. Web page: www.smeannualconference.com/

March 10–14 TMS (Minerals, Metals & Materials Society) 2018 148th Annual Meeting & Exhibition, San Antonio, TX, USA. Web page: www.tms.org/tms2019

March 18–22 50th Lunar and Planetary Science Conference, Houston area, USA. Web page www.hou.usra.edu/meetings/lpsc2019/

March 31–April 4 257th ACS National Meeting & Exposition, Orlando, FL, USA. Web page: www.acs.org/

May 12–15 GAC–MAC 2019, Quebec City, QC, Canada. Webpage: gacmac-quebec2019.ca/

May 19–22 AAPG 2019 Annual Convention & Exhibition, San Antonio, TX, USA. Web page: www.aapg.org/events/conferences/ace

June 20–21 Mineralogical Society of America Centennial Symposium, Washington, DC, USA. Details forthcoming.

July 8–12 82nd Annual Meeting of the Meteoritical Society, Sapporo, Japan. Web page: meteoriticalsociety.org/?page_id=18

July 15–19 5th Earth Educators Rendezvous, Nashville, TN USA. Webpage: serc.carleton.edu/earth_rendezvous/2019/index.html

July 20–24 American Crystallographic Association Meeting, Covington, KY, USA. Web page: forthcoming

July 22–26 Ninth International Conference on Mars, Pasadena, CA, USA. Web page: www.hou.usra.edu/meetings/ninthmars2019/

August 4–8 Microscopy & Microanalysis 2019, Portland, OR, USA. Web page: www.microscopy.org/events/future.cfm

August 18–23 Goldschmidt 2019, Barcelona, Spain. Web page: Goldschmidt.info/2019

August 18–23 32nd European Crystallography Meeting (ECM-32), Vienna, Austria. Web page: ecm2019.org/home/

August 25–29 258th ACS National Meeting & Exposition, San Diego, CA, USA. Web page: www.acs.org/

September 11–14 European Conference on Mineralogy and Spectroscopy 2019, Prague, Czech Republic. Web page: ecms2019.eu/

September 22–25 Geological Society of America Annual Meeting, Phoenix, AZ, USA. Web page: www.geosociety.org/GSA/Events/Annual_Meeting/GSA/Events/gsa2019.aspx

September 29–October 3 Materials Science & Technology 2019 Technical Meeting and Exhibition (MS&T19), Portland, OR, USA. Webpage: www.matscitech.org/

September 30–October 3 Large Meteorite Impacts and Planetary Evolution VI Conference, Brasilia, Brazil. Information: wolf.uwer@gmail.com

December 9–13 AGU Fall Meeting, San Francisco, CA, USA. Details forthcoming

2020

January 26–31 43rd International Conference and Expo on Advanced Ceramics and Composites (ICACC'20), Daytona Beach, FL, USA. Web page forthcoming

February 23– 27 TMS 2020 149th Annual Meeting & Exhibition, San Diego, CA, USA. Webpage: www.tms.org/tms2020

March 22–26 259th ACS National Meeting & Exposition, Philadelphia, PA USA. Web page: www.acs.org/

June 21–26 2020 Goldschmidt Conference, Honolulu, HI, USA. Webpage forthcoming

August 2–6 Microscopy & Microanalysis 2020, Milwaukee, WI USA. Web page forthcoming

August 9–14 Meteoritical Society Annual Meeting, Glasgow, UK. Webpage: meteoriticalsociety.org/?page_id=18

August 16–20 260th ACS National Meeting & Exposition, San Francisco, CA USA. Web page: www.acs.org/

October 4–8 Materials Science & Technology 2020, combined with ACerS 122nd Annual Meeting (MS&T20), Pittsburgh, PA USA. Web page: forthcoming

October 25–28 Geological Society of America Annual Meeting, Montreal, Canada. Web page: forthcoming

The meetings convened by the societies participating in *Elements* are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol (more meetings are listed on the calendar she maintains at https://sites.google.com/a/udayton.edu/akoziol1/home/mineralogy-and-petrology-meetings). To get meeting information listed, please contact her at akoziol1@udayton.edu

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  By P. Valera, A. Sanna, A. Marcello and S. Pretti
  View online in the Lyell Collection: http://geea.lyellcollection.org/content/early/2018/06/12/geochem2017-066
- **The mafic alkaline volcanism of SW Madagascar (Ankililoaka, Tulear region): ^{40}Ar/^{39}Ar ages, geochemistry and tectonic setting**
  By C. Cucciniello, A. P. le Roex, F. Jourdan, V. Morra, C. Grifa, L. Franciosi, L. Melluso
  View online in the Lyell Collection: http://jgs.lyellcollection.org/content/175/4/627
- **Maximising the value of Portable XRF data in exploration: An example from Marirongoe, Mozambique**
  By René Sterk, Gazley, Matthew P. Wood, Katie S. Collins and Geoff Collis
  View online in the Lyell Collection: http://geea.lyellcollection.org/content/18/2/142
- **Mineralogy and Geochemistry of Peridotites and Chromitites in the Aladag Ophiolite (S. Turkey): Melt Evolution of the Cretaceous Neotethyan mantle**
  By Dongyang Lian, Ph.D., Jingsui Yang, Yildirim Dilek, Alexander Rocholl
  View online in the Lyell Collection: http://jgs.lyellcollection.org/content/early/2018/07/06/jgs2018-060

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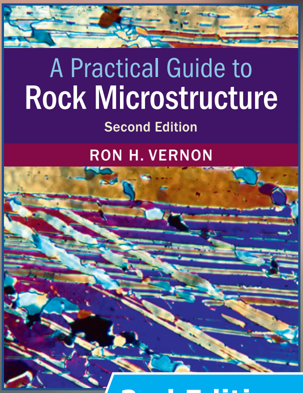
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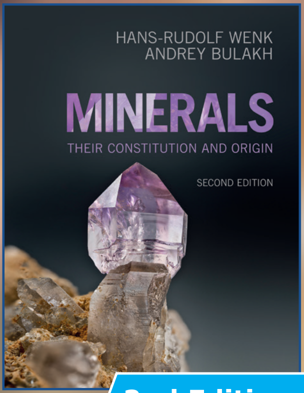
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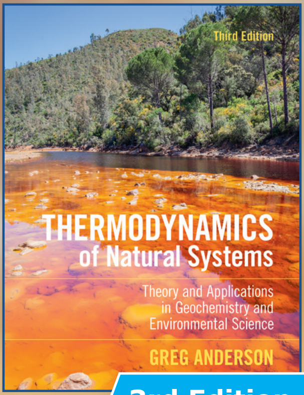
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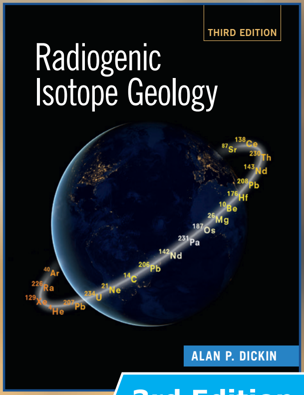
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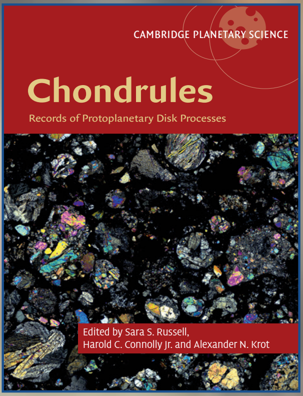
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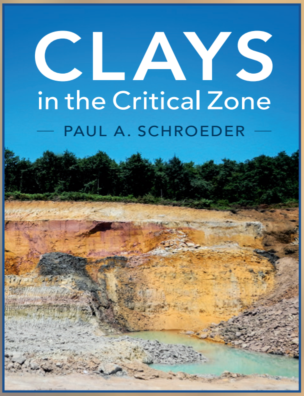
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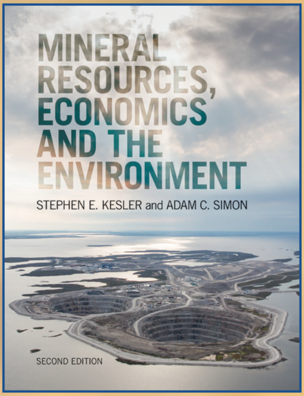
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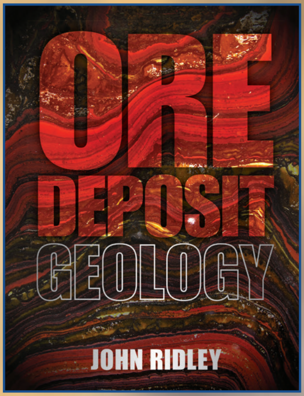
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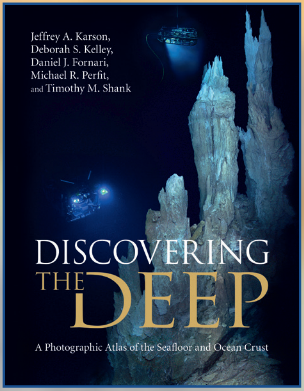
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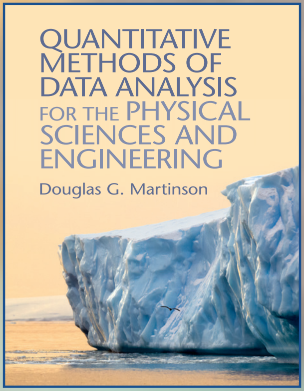
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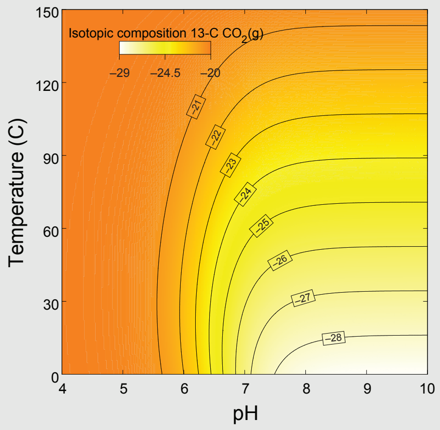

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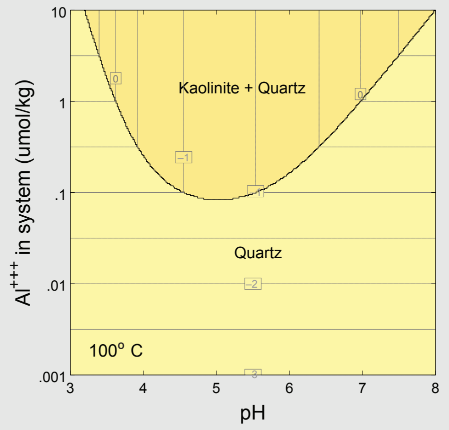

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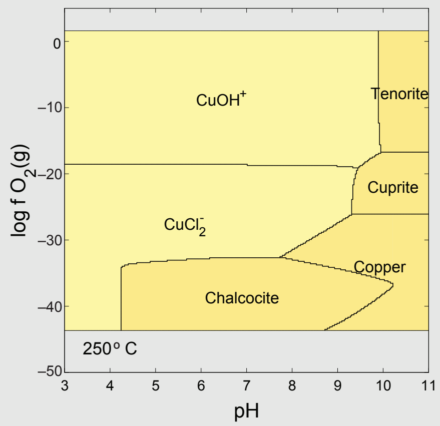

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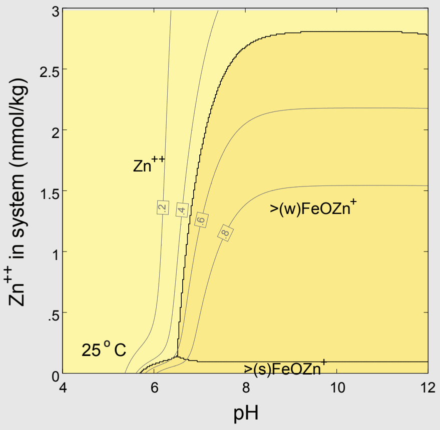

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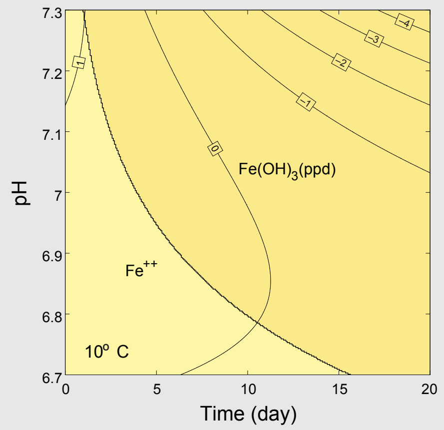
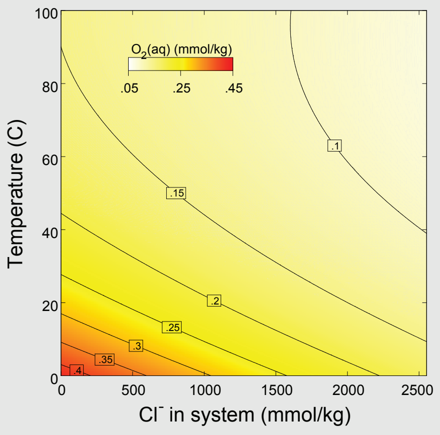


Kinetic reactions



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