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Uranium fixation with bacteria
G. Sulfurreducens from a biofilm incorporated C-labeled acetic acid and reduced U6+ to U4+, which was precipitated as uraninite on the surfaces of the bacteria. NanoSIMS can be used in combination with HR-TEM to track the uptake of radionuclides and identify the bioprecipitated mineral phases.

Study of Biogenic Nanoparticles
The composite C, N, and S mapping of a biofilm with NanoSIMS demonstrates that microbially derived extracellular proteins can limit the dispersal of nanoparticulate metal-bearing phases, such as the mineral products of bioremediation.
Red regions represent relatively pure Sulphur (as ZnS), Orange & Yellow: increased levels of Nitrogen in presence of ZnS. Light blue: presence of both C and N, with little to no S (no ZnS).
From: Extracellular proteins limit the dispersal of biogenic nanoparticles, John W. Moreau et al., SCIENCE, vol 316 (2007)

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Minerals, Microbes, and Remediation
Guest Editors: Anhuai Lu and Hailiang Dong

Mineral–Microbe Interactions and Implications for Remediation
Hailiang Dong and Anhuai Lu

Minerals as Substrates for Life: The Prokaryotic View
Gordon Southam

Remediation of Chromium and Uranium Contamination by Microbial Activity
Yangjian Cheng, Hoi-Ying Holman, and Zhang Lin

Clay–Microbe Interactions and Implications for Environmental Mitigation
Hailiang Dong

Microbial Oxidation of Sulfide Tailings and the Environmental Consequences
Xiancai Lu and Hongmei Wang

Interactions between Semiconducting Minerals and Bacteria under Light
Anhuai Lu, Yan Li, and Song Jin
In a previous editorial (Elements, December 2011), I discussed how difficult it is to predict with certainty the environmental impact of activities such as mining, energy production, and radioactive waste disposal. Here I shall continue on this theme with some musings on how regulatory decisions are made—particularly in the United States, the country with which I am most familiar. The first obvious point is that any activity such as mining or energy production will have an impact on the environment. Generally speaking the impact will be negative—loss of wildlife habitat, visual disturbance, air and water pollution. On the other hand there are benefits to society—we need energy and we need mineral resources. Ideally, conservation, substitution, and recycling will reduce these requirements, but they will not be eliminated, at least in the short term. We thus need to perform some sort of cost-benefit analysis. It is relatively easy to quantify the benefits but quite difficult to put an economic value on the costs. What is a scenic view worth? Wildlife habitat? Endangered species? These really come down to personal value judgments: regulations reflect some sort of consensus, although individuals often hold strongly differing opinions. And what about possible hazards that are not part of the normal operation of a project: how do we assign a probability (and hence a cost) that a pipeline will burst or that a major earthquake will occur? And who should bear this cost? The Fukushima Dai-ichi disaster made us all more sensitive to these questions.

There is also the question of how we make the decision, in particular, who are the “we”? Typically, the benefits of a major project such as the (now-canceled) Yucca Mountain radioactive waste repository and the (now-suspended) Keystone XL oil pipeline from Alberta to the US Gulf Coast are widely distributed across society, whereas the costs (or at least some of them, thinking of possible water pollution and disturbance of the landscape) are much more localized. Whose voice should be decisive in determining whether a project should be authorized? I have been reading editorials recently arguing that such decisions should be local—or at least each affected US state should have a veto. This seems reasonable at first sight, but is it realistic? Will any state ever volunteer to host a high-level radioactive waste repository? And if a state does volunteer, does a site in that state have the optimum geologic setting for a repository? In the case of the Keystone XL pipeline, is it appropriate that any one of the six US states and two Canadian provinces should be able to block a project whose impacts, for better or for worse, extend far beyond the boundaries of these jurisdictions? The Keystone XL project also raises the question of CO2 emissions and global warming. Should decisions on a global issue like this be in the hands of individual states, provinces, or even smaller political subdivisions? It seems to me that national governments must be able to make decisions on major projects. It is unfortunate, though, that these decisions tend to involve political considerations as much as the merits of the projects. Ultimately almost all decisions are challenged in courts of law. It seems reasonable to expect judges to decide whether proper procedures have been followed and regulations observed: it does not seem reasonable to expect them to evaluate scientific data or make what are essentially value judgments. Courts do, however, end up making such judgments: in our present political environment there seems no other way of reaching a resolution. In an ideal world we would have an agency that presented the scientific facts on a particular issue and was reasonably trusted by all parties involved. The ultimate decision, though, is a political as much as a scientific one. As scientists we need to present and disseminate the best information that we can. An informed public will reinforce the need for decisions to be made on a scientific basis. We hope that Elements can make a contribution to informing the scientific community and the public on some of these important issues.

We are making some progress in reducing the environmental impact of energy and mining projects. The planning process is including more sensitivity to environmental concerns, and our understanding of how to control the movement of contaminants and how to reclaim disturbed land is constantly improving. The public is also becoming more informed about the tradeoffs. Microbiological approaches, as discussed in this issue, are really in their infancy, but they are becoming increasingly important in reclamation and are contributing to an overall reduction in the impact of mining on the environment. We hope that the potential of these methods will be realized and that this will reduce some of the conflicts between economic and environmental priorities.

James I. Drever* (drever@uwyo.edu)
University of Wyoming

* Principal editor in charge of this issue
THIS ISSUE

Have you ever wondered why farmers plow their fields every spring? If you read Dong’s paper in this issue, you will learn that one of the purposes of tilling and plowing (and farmers no doubt do not know this!) is essentially to reoxidize structural Fe(II) in reduced smectite, thus counteracting the effects of microbes working hard to reduce the iron in clay minerals present in the soil. The more we learn about the interactions between microbes and minerals, the more complex the subject becomes. In his article, Southam reminds us that there are no bad or good microbes, only microbes exploiting favorable redox conditions to support their own lives. Located at the intersection of mineralogy and biology, this growing field of investigation requires multidisciplinary research teams: just glancing at the journals referenced in this issue is enlightening in this respect. Guest Editors Anhuai Lu and Hailiang Dong have chosen to highlight the applications of this research to remediation. This issue brings several contributions from Chinese colleagues; I hope you will enjoy the Chinese examples illustrating the articles.

MEMBERSHIP EVOLUTION

The first issue of *Elements*, in January 2005, was printed at 9000 copies; we now print 17,000 copies. There has also been a big shift in membership distribution: in 2005, US members accounted for 45.6% of the total readership, compared to 32% in the last mailing. Current member distribution is shown on this world map.

Geochemical Perspectives

You have either seen ads about *Geochemical Perspectives* or received the first two issues. Congratulations to the European Association of Geochemistry for launching this new publication, just as different from *Elements* in approach as could be: while *Elements* focuses on six short review papers on a topic, *Geochemical Perspectives* provides a lengthy overview of a theme written by one or two researchers and reflecting their personal experiences.

ABOUT DUPLICATE COPIES – PART 1

From time to time, we receive requests like the following: “I received two copies of the last issue; please eliminate this duplication of mailing.” *Elements* started up on a shoestring budget. Every decision was taken with a view to keeping the administrative overhead as low as possible. When faced with the issue of what to do about duplicate memberships, we studied the overlap in the memberships of the five founding societies and found it to be 20% (it has since stayed remarkably constant). We assume that most members do not want to receive multiple copies, so we do our utmost to eliminate duplicates. The savings are passed on to the member societies. If we were to ship all duplicate copies, the fee to societies, currently $15 per member, would need to be increased by about $3 per member.

For every mailing, the participating societies are asked to send their up-to-date member database in a standardized format. Alex Speer at MSA merges them. The software pairs potential duplicates, and each case has to be examined by a human who decides if it is indeed a duplicate. We estimate that we eliminate more than 99% of the duplicates: trying to eliminate all duplicates would be a very time-consuming task. You can help us eliminate duplicates by making sure you provide the same address for all your society memberships. But if you still receive a duplicate copy, put it to good use: use it as a promotional tool; give it to a colleague or student interested in the topic; or leave it in the students’ lounge.

On behalf of the editorial team,

Pierrette Tremblay (tremblpi@ete.inrs.ca), Managing Editor

ROBERT HOWIE • 1934–2012

*Elements* echoes Tomas Feininger’s words (from a posting on the MSA talk list). “Prof. Robert A. Howie died Saturday, 10 March. He was 88. Truly a loss to the mineralogical community. In 1962 (fifty years ago!), with the publication of the first volumes of the five-volume set of ‘Deer, Howie and Zussman’, Bob and his two tireless horsemen did remarkable service to the mineralogical-petrological community. Phenomenally productive through his long life, Bob was not only a brilliant mineralogist, but a fine person. He leaves a void to all readers of this post and will be missed. In 2005 Bob sent me what he thought was the only photo of the threesome together taken in 1976. The three are, of course, in the correct order (from left to right: Deer, Howie, and Zussman). Prof. Deer (on the left, pipe in hand) was a life-long pipe smoker and lived to 93. Prof. Howie relied on a cane, the result of a wound received in combat in Europe.”

Tomas Feininger
Université Laval, Québec, Canada
I have heard the analogy of a leaky pipeline being used to describe the process of developing from a student to an academic. I have seen the analogy in action throughout my career path, with many friends leaving along the way. It is true that academia is not right for everyone, and I suppose the process, however bruising it may be, helps individuals figure that out. There are many situations, however, when the cause of the leak is external—a sharp object puncturing the pipe, if you will. For those situations I would like to offer another analogy: the set of tools or patches that we as individuals, departments, and universities can offer to prevent or mitigate leaks from the pipeline. I cannot claim to have made it all the way through the pipeline; as I write this I am in the year leading to my thesis defense. I have had a lot of punctures, but the support of individuals and good departmental and university policies have prevented me from leaking out along the way so far. I want to share some of my experiences with you to provide food for thought for colleagues, departments, and universities wanting to help young colleagues make their way through the academic pipeline.

I was incredibly fortunate in having very patient, understanding advisors. My daughter was born when I was a master’s student at the University of Texas at Austin. It was a competition between finishing my thesis and her birth, and she won. During that time my advisor, Mark Cloos, was very understanding of my situation. He supported me throughout, both financially and personally, even lending a baby swing, which I kept in my office. Some days, I brought my daughter in her baby seat into the microprobe lab with me. She attended lectures in the graduate metamorphic petrology class I was taking, in which Bill Carlson graciously agreed to host an extra “student.” Although my daughter seems to have no interest in science, I often wonder how much metamorphic petrology sank into her subconscious that semester.

Later, during my PhD at Johns Hopkins University, John Ferry was extremely welcoming of my daughter. He also put up with the interruptions that life sometimes brings. My husband had an offer of a tenure-track faculty position in England while I was still working on my PhD. We felt it was an opportunity we couldn’t pass up, so we moved to London for a year to try it out. John was very supportive of me during this time even though I made very little progress on my PhD. Then, later on, health issues for both my husband and myself nearly derailed me again. It was quite a ride for several years, but my advisor, John, was a steadying influence throughout.

On-campus daycare, especially for babies, was something that made life as a graduate-student mother much easier. At the University of Texas there were several choices of on-campus daycare, and we chose a co-op daycare. It was the best daycare experience we had—I could listen to my daughter at lunchtime with just a short walk across campus. This was not the case at Johns Hopkins, and I spent a lot of time driving to and from daycare centers during the early years of my PhD.

Having a supportive spouse made a world of difference. As geologists, many of us spend time in the field. As a graduate student I had the opportunity to assist in several field excursions. My husband and daughter came along. They would go off and do something different during the day while I participated in the field work, and we would all meet up for dinner in the evening.

A proactive department chair, Mike Brown, and a forward-thinking spousal-hire policy at the University of Maryland helped me to land my current job. The department took a risk on an untested, freshly minted PhD by hiring me right out of my degree, but they offered me a two-year postdoctoral fellowship linked to a tenure-track faculty position to help get me started. For spousal hire to work, the fit has to be right for the departments of both spouses. When it works it can potentially benefit both the individuals hired and the departments.

Active mentoring for new faculty and general support from senior faculty, both within my department and in the wider community, have been critical to my career. My senior colleagues have exercised “tough love” in making sure that I know what is expected of me and encouraging me to do things that help me meet those expectations. They have pushed me to become involved in the greater geologic community in ways that I would not otherwise have considered, and, even though this has taken me outside my comfort zone at times, I have learned much in the process. They have pushed me to continually submit grant proposals, despite my early failures, offering advice on all aspects of the grant-proposal process. They continue to push me to produce high-quality work and write thoughtful papers about my results.

A number of professional development resources have helped me launch my career. The Early Career Geoscience Faculty workshop run by the On the Cutting Edge program was invaluable in giving me a clearer understanding of the tenure-track process in the United States and helped me develop my research and teaching. The workshop leaders continue to act as unofficial mentors as I move forward, plus the program introduced me to a peer group of tenure-track geoscience faculty at other universities.

Now for some ideas: If you are an advisor or mentor, remember that there is no single path through the pipeline for students, postdocs, and junior colleagues. Life’s “punctures” will ensure that their experiences will not parallel yours. Provide support in whatever way you can. Remember that we all have lives outside of our jobs, and sometimes, especially during adversity, we need help organizing and prioritizing. Make the expectations of academia as clear as possible so that those you mentor and advise have every chance of succeeding. While we may agree with Peter Doherty (Nobel Laureate in Medicine) that “You have to be willing to get up when you’re knocked down… We scientists are rather accustomed to falling flat on our faces!”, it sure helps to have someone give you a hand up the first few times.

Departments can be proactive when recruiting early-career faculty and think outside the box in their hiring policies. Mentoring programs for early-career faculty are crucial. Departments should offer a supportive environment in which junior faculty have the opportunity to succeed. Universities that provide faculty and students, as well as their partners and families, with affordable on-campus daycare and quality healthcare options create an atmosphere in which individuals can work more productively.

It is up to all of us to contribute to keeping the pipeline in good shape. Act in any way you can to promote policies that make life easier for those dealing with health issues, parenting, two-body problems, or any other issue that contributes to the leaky pipeline. Collectively, we can stem the leaks, so that there is always a supply of diverse, vibrant faculty.

Sarah Penniston-Dorland
Department of Geology, University of Maryland
College Park, MD 20742, USA

In her research, Assistant Professor Sarah Penniston-Dorland uses geochemical tracers and petrologic tools to investigate high-temperature processes in rocks as diverse as blueschists and amphibolites of the Catalina Schist and mafic and ultramafic igneous rocks of the Bushveld Complex.
Harry Y. (Hap) McSween Jr., Chancellor’s Professor and Distinguished Professor of Science at the University of Tennessee, has been awarded the J. Lawrence Smith Medal of the National Academy of Sciences (www.nasonline.org/programs/awards/j-lawrence-smith-medal.html). Hap is being honored for his pioneering studies of the igneous and metamorphic histories of the parent planets of the chondritic and achnondritic meteorites, with particular emphasis on his work on the geological history of Mars based on studies of Martian meteorites and spacecraft missions to the planet. The medal and prize of $25,000 are awarded for recent original and meritorious investigations of meteoritic bodies. The award, which is given every three years, was established after a gift from Sarah Julia Smith in memory of her husband and has been presented since 1888.

Hap, along with 16 others who have made major contributions to science, will be recognized at a ceremony on April 30, 2012, during the National Academy of Sciences’ 149th annual meeting.

Many congratulations, Hap!

IMA MEDAL TO DAVID GREEN

David Green from Tasmania has been selected as the winner of the third IMA Medal for excellence in mineralogical research. He follows Frank Hawthorne and Charles Prewitt in receiving this honor, which recognizes outstanding original research in mineralogy during the recipient’s career.

David Green was born and educated in Tasmania and had his first acquaintance with ultramafic and related rocks in 1956 when mapping an ultramafic complex in northern Tasmania. This interest in ultramafic rocks continued with his PhD research on the Lizard Peridotite, under C. E. Tilley at Cambridge. Following his PhD he was recruited by the Australian National University to work with A. E. Ringwood. Their first collaboration led to the creation of the “pyrolite” model, a prediction of the petrological character of the upper mantle. These two eminent scientists brought research in geoscience a major step forward by combining high-pressure and high-temperature equipment with the electron microprobe. The “new experimental petrology” led to three classic papers on the application of petrological studies to global tectonics, the gabbro to eclogite reactions and the genesis of basaltic magmas.

David Green has been adept at selecting significant petrological observations or hypotheses and devising experimental strategies to investigate them. He has studied a wide range of topics, including mineral assemblages of peridotites and basalts at high pressures, the experimental calibration of mineral geothermometers and geobarometers, the reasons for compositional variability of basaltic magmas including the roles of carbon and hydrogen, the genesis of carbonatite magmas, the identification of carbonatite metasomatism in the Earth’s lithosphere, the origins of and relationships among lunar basalts, and the nature of the lunar interior.

Throughout his career, David Green has built research teams applying complementary approaches to diverse problems related to the petrology and geochemistry of natural rocks. He has remained active in science since retirement, recently making a significant contribution to discussion of the influence of H₂O in nominally anhydrous minerals on the melting of peridotite, which was published in Nature in 2010.

Eight Earth scientists were recently elected as members of the Academia Europaea (www.acadeuro.org), an international, non-governmental, not-for-profit association of individual scientists and scholars. Members are drawn from some 35 European countries and eight non-European countries. Membership is currently around 2300 and covers the natural sciences, humanities and letters. Founded in 1988, the Academia Europaea organizes workshops, conferences, and study groups; publishes the European Review and other academic materials; and provides expert advice on European science policy matters.

Olivier Appert (CEO of IFP Energies nouvelles) is an engineer with extensive experience in the energy sector in various French and international positions.

Jon Blundy is a petrologist interested in all things magmatic, from melting of the mantle to granite emplacement and the underground machinations of explosive volcanoes. He has made important contributions to understanding the partitioning of trace elements between crystals and melts. Jon is based at the University of Bristol (UK).

Georges Calas is a professor of mineralogy at Université Pierre et Marie Curie, Paris. He has published on structure/property relationships linked to transition elements and radiation defects in minerals and glasses, and he also has interests in environmental mineralogy, nuclear waste management, and materials science.

Herbert Huppert is an emeritus professor in theoretical geo-physics at Cambridge University. He has published widely on the principles of fluid mechanics as related to Earth sciences, meteorology, oceanography, and geology.

Paolo Papale is renowned for his research activities in the physics of volcanism. He is contributing to the establishment of a multidisciplinary, integrated approach to the study of volcano dynamics and to the forecasting of volcanic hazards.

Yanick Ricard’s research on the relations between the density variations in the mantle and the Earth’s gravity field linked the paleogeography of the Earth to present-day mantle anomalies as revealed by seismic tomography and satellite geodesy.

Tilman Spohn is the director of the Institute of Planetary Research of the German Aerospace Center and a professor of planetary physics at the Westfälische Wilhelms Universität Münster. He specializes in the thermodynamics of planetary interiors, the habitability of planets and the role of life in their geologic evolution.
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I confess that high-tech laboratory methods have long been a fascination of mine. I am always eager to see what the newest technology has to offer for recovering even more information out of one's samples; an obvious trend over recent decades has been the characterization of geomaterials at ever smaller scales. Selecting from the spectrum of available analytical tools, it is now possible to get detailed information about the physical and structural properties or the chemical and isotopic compositions of a sample at the submicron scale. Some methods are even able to provide detailed information down to the atomic scale, which is truly amazing.

Focused ion beam (FIB) technology has been available for investigating geomaterials for the better part of a decade. Most people familiar with this method know it as a means of milling precisely positioned sample foils; basically it is a very sharp knife used to prepare samples for the transmission electron microscope (TEM). After a location of interest on the surface of a polished sample has been selected—for example, a grain boundary that one wants to investigate—a FIB instrument can produce a thin foil penetrating down into the top tens of microns of the sample and with a positioning accuracy on the order of tens of nanometers. The sample foil, as little as 50 nm thick, is milled out of the sample using a very finely focused gallium ion beam (Fig. 1). FIB sample preparation has superseded older approaches relying on, for example, clouds of argon ions for eroding holes through a sample and thereby producing a bevelled edge at a random location.

A few weeks ago I took a walk across the hallway here in Potsdam to visit the dual-beam FIB laboratory, which features a FEI Quanta tool (Fig. 2). I had a very interesting chat with my colleague Luiz Morales, who runs the facility, and I learned much about recent advances in FIB technology. In contrast to previous-generation FIB instruments, “dual-beam technology” combines a finely focused ion beam (primarily used for eroding material from the sample surface) and an electron beam (used for extremely fine-scale imaging of the sample). Simply said, this configuration represents nothing less than the integration of FIB technology with a high-resolution scanning electron microscope (SEM). This tool offers not only the capability of sample milling at the nanometer scale but also the ability to characterize major element chemistry, crystal orientation, and the texture of a material as the foil is being prepared.

Here I would like to highlight two projects that particularly impressed me about this technology. The first was a study of the 3-D structure of a quartz–quartz grain boundary from Kruhl et al. (submitted paper). After initially milling a 10 µm wide, cube-like structure into the sample surface (Fig. 3a), an image of the 3-D geometry of the grain boundary it contained was built up by alternating between sample imaging using secondary electrons (SEM mode) and eroding back the surface of the cube in 100 nm steps (FIB mode). By repeating this cycle many times, it was possible to build up a very detailed map of the grain boundary over the entire 10 × 10 × 10 µm volume. The entire procedure took 10 hours, after which the exact structure of the grain boundary between the two quartz crystals could be visualized at ≤100 nm resolution in all directions. Using appropriate software, a detailed model of the grain boundary was generated, which can be visualized in a 3-D virtual space. The most obvious conclusion from this study is that this particular grain boundary was most certainly not a flat plane at the nanometer spatial scale (Fig. 3b).

The Elements

FOCUSED ION BEAM TECHNOLOGY: MORE THAN A SHARP KNIFE

Here I would like to highlight two projects that particularly impressed me about this technology. The first was a study of the 3-D structure of a quartz–quartz grain boundary from Kruhl et al. (submitted paper). After initially milling a 10 µm wide, cube-like structure into the sample surface (Fig. 3a), an image of the 3-D geometry of the grain boundary it contained was built up by alternating between sample imaging using secondary electrons (SEM mode) and eroding back the surface of the cube in 100 nm steps (FIB mode). By repeating this cycle many times, it was possible to build up a very detailed map of the grain boundary over the entire 10 × 10 × 10 µm volume. The entire procedure took 10 hours, after which the exact structure of the grain boundary between the two quartz crystals could be visualized at ≤100 nm resolution in all directions. Using appropriate software, a detailed model of the grain boundary was generated, which can be visualized in a 3-D virtual space. The most obvious conclusion from this study is that this particular grain boundary was most certainly not a flat plane at the nanometer spatial scale (Fig. 3b).
The second investigation involved the 3-D imaging of microstructures within a sample from the Lower Jurassic Posidonia Shale. Two parallel trenches were milled into the sample surface, followed by the milling of a third, broader trench connecting the two (Fig. 4a).

By alternating between milling (FIB) mode and imaging (SEM) mode, both the structure and the mineralogy of this complex material could be described at an impressive spatial resolution. Again using software for manipulating the data set within a 3-D virtual space, one can visualize the complex network of voids and secondary mineralization present within the highly heterogeneous, fine-grained matrix (Fig. 4a). Dual-beam FIB is obviously a very useful tool for a broad range of research themes: rheology, diagenesis, low-temperature mineralization, hydrology, and others.

Anyone interested in this technology is encouraged to have a look at some of the films resulting from these studies—I think you will be impressed. Visit Youtube.com and then search for “FIB + Potsdam + Quanta.” Focused ion beam technology has clearly moved from being a high-tech knife for cutting thin foils; it has become a powerful research tool in its own right.

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Potsdam, Germany

REFERENCE
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QEMSCAN® image of typical bauxite ore from Asia. Bauxite is the principle commercial source of aluminium. The distinctive sub-rounded particles in the image are known as pisoliths, which form at the Earth’s surface as a result of breakdown of a previous rock, typically basalt. No two pisoliths are the same – although they generally have a nucleus and core, which is then surrounded by several concentric layers.

Extraction of the aluminium from the ore involves complex chemical digestion techniques, and the efficiency of this process is significantly reduced if impurities other than aluminium hydroxide (green) are present in the ore, such as quartz (pink), clays (brown) and iron oxides (orange).
Yangjian Cheng is an assistant professor of biochemistry and microbial geochemistry in the State Key Laboratory of Structural Chemistry, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences. His current research involves the transformation and immobilization of Cr(VI) and U(VI) via microbes in the environment and microbial diversity at sites polluted with heavy metals. He is also interested in field bioremediation technologies in soil, sediments, and wastes.

Hailiang Dong is a professor of geomicrobiology, mineralogy, and geochemistry in the Department of Geology and Environmental Earth Science at Miami University, Ohio, USA. His research is on mineral–microbe interactions; microbial life in extreme environments, including the deep subsurface, saline lakes on the Tibetan plateau, and hot springs; and the bioremediation of heavy metals such as Tc and Cr. He applies high-resolution imaging techniques, spectroscopy, and molecular and cultivation methods to answer the question of “who is doing what.”

Hoi-Ying Holman is the director of the Berkeley Synchrotron Infrared Structural Biology Program at the Lawrence Berkeley National Laboratory, the head of chemical ecology in the Earth Sciences Division, and a principal investigator at the Virtual Institute for Microbial Stress and Survival. She is currently developing multimodal chemical imaging and perturbation approaches to investigate metabolic and structural/functional changes in living cells during stress-adaptive responses, and applies these approaches to bioenergy, radiation biology, and bioremediation. She received her PhD in environmental chemistry and chemical engineering from the University of California at Berkeley.

Song Jin is the chief technology officer of Next Fuel Inc. and an adjunct professor in the Department of Civil and Architectural Engineering at the University of Wyoming. His research work includes bioelectrochemical systems in the enhanced biodegradation of contaminants in groundwater and sediments, microbial interactions with minerals and contaminants in subsurface environments, and in situ microbial conversion and transformation of carbonaceous compounds. Song Jin received his PhD in zoology and environmental chemistry from the University of Wyoming.

Zhang Lin has been a professor of environmental science and physical chemistry at the Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences (CAS) since 2004. She received her PhD in physical chemistry from the Institute of Chemistry (CAS) in 1999 and occupied postdoctoral positions at the University of Wisconsin–Madison and the Lawrence Berkeley National Laboratory from 1999 to 2004. She investigates the microbial precipitation of minerals and the structure, properties, and transformation of biogenic nanoparticles. She also studies the growth kinetics of nanoparticles and the relevant environmental applications.

Anhuai Lu is a professor in the School of Earth and Space Sciences at Peking University and serves as director of the Research Center for Geomaterials and Environment. He is the chairman of the Commission on Environmental Mineralogy, and vice chairman of the Commission on Mineralogy in China. He is a member of the IMA Council. His research is on environmental mineralogy, the interactions between minerals and microbes, and the in situ remediation of wastewater and mine tailings. He has been a chief scientist for a multidisciplinary research group in China investigating the theme “Mechanisms of Environmental Response to Biominaleralization” (973 program), funded by the Chinese government.

Xiancai Lu is a professor of mineralogy and computational geochemistry at Nanjing University (Nanjing, China), where he received his BSc (1993) and PhD in geology (1999). His research interests include the surface chemistry of minerals, adsorption processes on mineral surfaces and in micropores in geological materials, microbe-mineral interactions under redox-dynamic conditions, and geoscience education. His group has used computational chemistry to develop an atomic-level knowledge of the surface chemistry and interface structure of clay minerals. More recently, he has focused his research on the microbial oxidation/reduction of various minerals in mine waste and its environmental consequences.

Gordon Southam is a professor in the Department of Earth Sciences and Biology and director of the Centre for Environment & Sustainability at the University of Western Ontario in London, Ontario, Canada. His research on bacteria–mineral interactions encompasses microbiology, geochemistry, and mineralogy, and includes the examination of life in extreme environments, the control of greenhouse gas emissions via bacterial carbonation reactions, the bioremediation of inorganic and organic pollutants, and the role of bacteria in the formation of ore deposits, in particular, the biogeochemistry of gold.

Hongmei Wang is a professor of geomicrobiology and vice dean of the School of Environmental Studies in the China University of Geosciences (Wuhan), where she received her PhD in 2001. She studies primarily the interaction between minerals and a variety of microbes from extreme environments, including acid mine drainage (AMD), peatlands, and subsurface caves. Her recent work on the reduction of crystalline iron in clay minerals by dissimilatory iron-reducing bacteria, sulfate-reducing bacteria, and methanogens enhances the understanding of iron cycling and has implications for bioremediation in AMD-impacted areas.
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The shown results are courtesy of Dr. Angela Halfpenny and Dr. Michael Verrall from CSIRO in Perth, Australia.

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Innovation with Integrity
Mineral–Microbe Interactions and Implications for Remediation

Hailiang Dong1,2 and Anhuai Lu3

INTRODUCTION

Minerals and microbes have coevolved throughout much of Earth history. They interact at the microscopic scale, but their effects are manifested macroscopically. Minerals support microbial growth by providing essential nutrients, and microbial activity alters mineral solubility and the oxidation state of certain constituent elements. Microbially mediated dissolution, precipitation, and transformation of minerals are either directly controlled by microorganisms or induced by biochemical reactions that usually take place outside the cell. All these reactions alter metal mobility, leading to the release or sequestration of heavy metals and radionuclides. These processes therefore have implications for ore formation and the bioremediation of contaminated sites.

Keywords: biosignature, coevolution, heavy metal, mineral–microbe interactions, remediation

COEVOLUTION OF MINERALS AND MICROBES

Minerals and microbes have coevolved over much of Earth’s history. The origin and evolution of life is thought to have been catalyzed by minerals. The prebiotic synthesis of primordial life-forms on early Earth was catalyzed by minerals such as pyrite (Wächtershäuser 1988) and clays. Self-replicating building blocks of organic molecules have been synthesized autocatalytically on pyrite surfaces, forming surface metabolists, a primitive, two-dimensional life-form. Polymerization of RNA monomers to oligomers can be catalyzed by the clay mineral montmorillonite (Ferris 2005).

Once life emerged on Earth, it began to interact with minerals in a variety of ways and has continuously and often irreversibly transformed Earth’s surface mineralogy. Sulfur-metabolizing bacteria may have existed around 3.5 billion years ago (Ga) and were responsible for pyrite precipitation and sulfur isotope fractionation (Wacey et al. 2011). Cyanobacterial communities formed patchy carbonate buildups in shallow seas as early as the Paleoproterozoic (3.5 Ga), and by the Neoarchean, they had become the principal builders of carbonate platforms (Altermann et al. 2006).

The “Great Oxidation Event” (GOE), a consequence of oxygenic photosynthesis by cyanobacteria starting at 2.45 Ga (Konhauser et al. 2011), raised the atmospheric oxygen level to >1% of the modern value and greatly diversified the species of minerals, from about 1500 to more than 4000 (Hazen and Ferry 2010). Many of these minerals, such as sulfates, oxyhydroxides, and nitrates, would not have developed in abundance in the anoxic environment prior to the GOE. Carbonate deposits formed between 2.25 and 2.06 Ga, which contain the greatest diversity in stromatolite types in Earth’s history, indicate robust microbial carbonate and phosphate biominaleralization (Hazen et al. 2008). Likewise, the deposition of abundant banded iron formations around this time (mostly 2.4–1.8 Ga) has been ascribed in part to Fe(II)-oxidizing bacterial activity (Konhauser et al. 2011).

The Neoproterozoic Era saw dramatic fluctuations of climate and atmospheric composition. Despite severe environmental variability, microbes persisted and continued to interact with minerals. Increasing deposition of clay minerals during the Neoproterozoic might have been caused by microbial activity in soil (Kennedy et al. 2006).
Meanwhile, microbes in the marine environment, including phototrophic bacteria, could have biomineralized phosphorous when rivers began to carry large quantities of phosphorus to the oceans (Hazen et al. 2008).

The dominant role of biology in the mineralogical diversity of the Earth’s surface is further illustrated by the multiplications of biological forms in the Phanerozoic, when microbes, as well as plants, invertebrates, and vertebrates, mediated the formation of numerous minerals (Hazen et al. 2008). Skeletal minerals, dominantly carbonates and phosphates, appeared in the early Cambrian. Some examples of minerals biologically generated during the Phanerozoic are jarosite, goethite, hazenite, γ-sulfur, and intracellular magnetic grains of greigite (Fe₃S₄) (Hazen et al. 2008).

The diversification of mineral landscapes on Earth’s surface, in turn, exerted a profound influence on the evolution of life. Because of the abundance of oxidized minerals after the GOE, those microbes that could respire on oxidants such as sulfate, ferric iron, and other oxidized metals, that is, microbes such as sulfate-reducing bacteria and iron-reducing bacteria, may have taken advantage of vast reserves of energy stored in chemical disequilibria between oxidants and organic/inorganic carbon. The activity of these organisms would have altered the global biogeochemical cycles of carbon, sulfur, nitrogen, and iron.

Although the interactions occurred largely on the microscopic scale, the results were often macroscopic, with consequences both adverse and beneficial. Many of these consequences are recorded in sedimentary rocks, to serve as reminders of the powerful interactions that once occurred, and as biosignatures that reveal the mineral–microbe interaction history. It is to our advantage to learn from the rock record and to make use of the positive side effects of mineral–microbe interactions to remove heavy metals and radionuclides from contaminated environments, degrade organic contaminants, sequester CO₂, and generate energy.

**MAJOR MODES OF MINERAL–MICROBE INTERACTION**

Modes of mineral–microbe interaction can be classified from the perspective of either microbes or minerals. From the microbial perspective, the interaction can result in either biologically controlled mineralization (BCM) or biologically induced mineralization (BIM) (Frankel and Bazylinski 2003). In BCM, the nucleation and growth of crystals are genetically controlled by microbes; a typical example is magnetite in magnetosomes produced by magnetotactic bacteria. Carbonates, phosphates, and silica in marine animals are other examples (Dove 2010). Broadly speaking, mineralization controlled by protein templates belongs to BCM as well. BCM minerals have specific functions, such as for navigation (magnetite) or for providing a skeleton (carbonates, phosphate, and silica). In BIM, however, mineralization is not genetically controlled and occurs as a result of changes in microenvironments through microbial metabolism. Many examples of the products of BIM exist, such as clay minerals, (hydr)oxides, sulfides, carbonates, and phosphates (Frankel and Bazylinski 2003; Konhauser 2007; Dong 2012 this issue).

From the mineralogical perspective, mineral–microbe interactions can be classified into microbially mediated mineral dissolution, precipitation, or both (i.e. transformation and change in redox state). Minerals contain nutrients and energy that microbes need to sustain their metabolism and growth. Microbes break down minerals and release nutrients to support their growth (Fig. 1a). A good example is the microbial dissolution of basalt and volcanic glass to release phosphorus and other nutrients essential for growth (Fig. 1b) (Rogers and Bennett 2004). Under favorable conditions, microbes will also precipitate a number of biogenic minerals, such as carbonates, silicates, phosphates, sulfides, oxides, and even native elements (Konhauser 2007; Dong et al. 2009; Lu and Wang 2012 this issue). Many studies have focused on minerals with redox-sensitive elements, such as iron (Lovley 2000; Konhauser et al. 2011) and sulfur (Dahl and Friedrich 2008). Transformation of these elements from one valence state to another provides energy for driving the metabolic system of many microorganisms. In these redox reactions, varying amounts of energy are released, depending on the nature of the reactants and products and on the metabolic pathways employed by the microorganisms (Chapelle 2000).

The electrons transferred during redox processes can also be harnessed to produce energy through bioelectrochemical systems, such as the “microbial fuel cell” (Logan 2008). It has been suggested that electrically conductive pill or pilus-like appendages (nanowires) establish electron transport not only between bacteria and minerals but also among different microorganisms in a community (Gorby

**Figure 1**

(A) Schematic diagram showing mineral–microbe interactions. Microbes dissolve minerals and release nutrients that become available for uptake. These nutrients are portrayed as delicious “chocolate, ice cream and beer” available to the microbes to stimulate their growth. DRAWING COURTESY OF P. A. BENNETT (B) Scanning electron microscope photomicrograph of rod-shaped cells on a basalt surface; dissolution pits are visible underneath the bodies of the microbes (Roberts et al. 2004). Scale bar is 0.5 μm. IMAGE COURTESY OF J. A. ROBERTS, WITH PERMISSION FROM THE GEOLOGICAL SOCIETY OF AMERICA.
On Earth, a predominant renewable energy source for powering natural bioactivity is solar light, and phototrophic microorganisms are adapted to capture this energy. Nonphototrophic microorganisms have been excluded from light-centered metabolism due to their lack of photosensitive cellular compounds. Nonetheless, this deficiency does not necessarily preclude an ability to derive energy indirectly from the Sun through semiconducting minerals. Upon solar irradiation, semiconducting minerals, such as rutile (TiO₂), sphalerite (ZnS), and goethite (FeOOH), can give off electrons, and these electrons can be transferred to nonphototrophic microbes to support their growth (Fig. 2a). Alternatively, microorganisms in the biochemical chamber of a fuel cell can catalyze the oxidation of organic carbon, and the electrons produced can be transferred to the photocatalytic chamber to reduce electron acceptors (such as heavy metals and radionuclides) (Fig. 2b). Since the net energy consumed in such an integrated electrochemical cell is light energy, it is referred to as a light fuel cell (LFC) (Fig. 2) to distinguish it from a bioelectrochemical cell (Lu et al. 2012). In essence, LFCs exhibit an alternative mineral–microbe interactive pathway, which is fundamentally a natural, solar-driven biogeochemical process.

**FIGURE 2** Schematic diagram of a light fuel cell. (A) Electrons generated from the photocatalysis of a semiconducting mineral are transferred via an external circuit (R) to the biochemical chamber, where they act as a source of energy to support the growth of microorganisms. (B) Microorganisms in the biochemical chamber catalyze the oxidation of organic carbon and promote the transfer of electrons to the photocatalytic chamber, where they reduce electron acceptors (such as heavy metals and radionuclides).

**FIGURE 3** A chromium slag dump and wastewater near Yuezhou Township, Qujing City, Yunnan Province, China. Approximately 5000 tons of chromium slag were illegally disposed of in the last 10 years, leaving the slag exposed to air and water. Wastewaters with high concentrations of Cr(VI) and other metals are potentially discharged into the underlying soil and the Nanpan River, an upstream tributary of the Pearl River. This incident was reported in June 2011, and it took nearly a week to remove all the accumulated chromium slag and contaminated soil (~9000 tons) to downstream water bodies have been either isolated from any contaminant source or cleaned up. PHOTO: http://NEWS.SINA.COM, AUGUST 14, 2011

**IMPLICATIONS OF MINERAL–MICROBE INTERACTIONS FOR REMEDIATION OF HEAVY METALS AND RADIONUCLIDES**

Mineral–microbe interactions indirectly affect the geochemical fluxes and biogeochemical cycling of a large number of elements. Among them are toxic heavy metals (e.g. chromium) and radionuclides (uranium and technetium). Some of the radioactive elements entered the environment from mining activity and from nuclear weapons testing in the 1950s and 1960s. Some metallurgical and chemical industries produce large amounts of chromium slag and contaminate local soil and groundwater (Fig. 3). Another important source of heavy metals and radionuclides is nuclear power plant operations that release contaminants either by accident (such as Chernobyl in 1986 and the Fukushima Daiichi nuclear disaster in Japan in 2011) or due to improper long-term storage of radioactive materials. Other metals, such as lead, arsenic, antimony, and cadmium, are enriched in certain environments by either natural or anthropogenic processes. Because many of these metals and radionuclides are carcinogenic, their release into the environment and their fate cause intense scientific and public concern and are the subject of substantial research. For example, an issue of *Geomicrobiology Journal* dedicated to the topic of the geomicrobiology of radionuclides was published in July 2011. Heavy metals/radionuclides and their environmental effects have been highlighted in past issues of *Elements*: “The Nuclear Fuel Cycle: Environmental Aspects,” published in December 2006, and “Mine Wastes,” published in December 2011.

The mobility of these metals and radionuclides in groundwater aquifers, soils, and sediments is largely controlled by their interactions with minerals and microbes (Lovley 2000; Dong et al. 2009; Cheng et al. 2012 this issue). Heavy metals and radionuclides can be removed from solution through adsorption, coprecipitation, and redox transformations. Both microbes and minerals have large surface areas, and a range of metals and radionuclides can sorb onto their surfaces via electrostatic attraction and surface complexation. A number of metals and radionuclides can also substitute for other elements in mineral structures or form their own minerals (Cheng et al. 2012; Lu and Wang 2012;
The articles in this issue represent a small subset of mineral–microbe studies, as they focus on modern environments. We have strived to achieve a balanced coverage between fundamental and applied science and in terms of microbial versus mineral perspectives. Southam takes on a prokaryotic perspective; he describes mineral substrates as a source of nutrients and energy and discusses the resulting secondary mineral transformations that have important implications for the bioremediation of metals. Cheng, Holman, and Lin focus on some practical aspects of mineral–microbe interactions—the potential and limitations of the bioremediation of chromium and uranium—and highlight the importance of biologically mediated transformations, immobilization, and mineralization of toxic metals in the context of remediation. In the paper on clay mineral–microbe interaction, Dong discusses the microbial dissolution, formation, and transformation of clay minerals, and the microbial oxidation and reduction of iron in clay minerals. Lu and Wang highlight the role of microorganisms in the oxidation of sulfides and heavy metal release/sequestration in mine tailings, and they describe some implications for the mobility of these metals.

Uranium, chromium, and technetium are three important heavy metals with different sources and pathways (Cheng et al. 2012). A common feature of these three elements is that they are highly soluble and mobile in natural environments when they occur in their oxidized states [i.e. U(VI), Cr(VI), and Tc(VII)], but once they are reduced to lower oxidation states [i.e. U(IV), Cr(III), and Tc(IV)], their mobilities are greatly decreased because they occur as solids such as uraninite (UO₂), Cr(OH)₃, and TcO₂. A common strategy for removing these metals is to manipulate redox conditions in order to reduce the metals either chemically or biologically (Cheng et al. 2012). Biological reduction can be promoted by adding nutrients to stimulate native microbial activity (called biostimulation) or by injecting certain bacteria (bioaugmentation) (Fig. 4). A number of metal-reducing and sulfate-reducing bacteria are capable of reducing these metals enzymatically. When locally enriched, these reduced metals can form economically valuable deposits.

**Figure 4** Schematic diagram showing the biostimulation strategy. A dilute acetate solution is injected into a uranium-contaminated site, and anoxic conditions are created following consumption of oxygen by heterotrophic microorganisms. Under these conditions, metal-reducing bacteria couple the oxidation of acetate to carbon dioxide with the reduction of U(VI) to U(IV) (see inset). Because U(IV) is insoluble in groundwater and precipitates as a solid, uranium is removed from the groundwater. The zone of U(VI) removal is shown in the down-gradient direction of groundwater flow for the purpose of clarity. In practice, U(IV) removal should take place at or close to the zone of acetate injection.

**GEOLOGICAL RECORD OF MINERAL–MICROBE INTERACTIONS: BIOSIGNATURES**

Much of our knowledge about mineral–microbe interactions is derived from laboratory experiments and observations in modern systems. However, since the emergence of life on Earth, minerals and microbes have coevolved through mutual interactions on Earth’s surface. To understand this coevolution and its effects on the biogeochemical cycles of elements essential to life, such as C, N, S, Fe, and P, it is important to deduce the modes of mineral–microbe interactions in the past, the types of microbes and minerals involved, and even the rates of their interactions.

This level of understanding of past microbial activities and their mineralogical consequences requires the search for biomarkers that have been preserved in the geological record. Most biological molecules cannot survive diagenesis and metamorphism, but lipid biomarkers are an exception: they can be preserved in sedimentary rocks and used to infer past microbial communities (Olcott et al. 2005). Compound-specific stable isotope fractionation is a powerful tool for understanding the role of microbial metabolisms in the formation of minerals that have been preserved in the rock record. For ancient and highly altered rocks, however, geochemical biomarkers may be more robust.

Among geochemical biomarkers, morphological evidence is direct and often intuitive. Good examples include stalks produced by Fe(II)-oxidizing bacteria (Chan et al. 2010) and tubular textures in basaltic glass (Staudigel et al. 2006). The extracellular, twisted, ribbon-like stalks produced by Fe(II)-oxidizing bacteria have a physiological role in preventing the encrustation of cells by iron hydroxides. Likewise, the tubular textures in basaltic glass are produced by microbes that colonize nutrient-containing glass and grow perpendicular to previously existing fractures (Staudigel et al. 2006).

Biogenic minerals are robust biomarkers, but only a few minerals are known to be exclusively biogenic, including rosickyite (γ-sulfur) and hazenite [KNaMg₃(PO₄)₂·14H₂O] (Hazen et al. 2008). A potentially promising method for revealing the biogenicity of some minerals is thermal treatment followed by spectroscopic characterization. Untreated biogenic carbonates (aragonite and calcite) show the same characteristics as abiotic carbonates in infrared spectra, but after heating, the biogenic spectra are different (Orofino et al. 2010). A third line of geochemical evidence is the elemental composition and isotopic fractionation that are often characteristic of biotic processes. Enzymatic and biochemical activities prefer one element or isotope over another, resulting in measurable element or isotope fractionation. In addition to the research on conventional isotopes, such as C, N, and S, recent studies have focused on nontraditional isotopes, such as Mg, Ca, Cr, Mo, Fe, Cu, Zn, Cd, and Hg (Bullen and Eisenhauer 2009).

**IN THIS ISSUE**

Because of the broad nature of mineral–microbe interactions, it is impossible to provide a comprehensive coverage of the topic in a single issue of *Elements*. The articles in this issue focus on some practical aspects of mineral–microbe interactions—the potential and limitations of the bioremediation of chromium and uranium—and highlight the importance of biologically mediated transformations, immobilization, and mineralization of toxic metals in the context of remediation. In the paper on clay mineral–microbe interaction, Dong discusses the microbial dissolution, formation, and transformation of clay minerals, and the microbial oxidation and reduction of iron in clay minerals. Lu and Wang highlight the role of microorganisms in the oxidation of sulfides and heavy metal release/sequestration in mine tailings, and they describe some
engineered treatment technologies. Last, Lu, Li, and Jin report a pathway in which nonphototrophic organisms are able to harness solar energy via photocatalysis of semiconducting minerals.

CONCLUSIONS

The interactions of minerals and microbes are complex, and studying such a broad topic requires expertise in mineralogy, geochemistry, microbiology, and environmental engineering. Despite the fact that many observations and experimental studies have focused on modern interactions, ancient processes are equally exciting, as minerals and microbes have coevolved throughout much of Earth’s history. Studies of ancient mineral-microbe interaction processes are often much more challenging because of the lack of easily discernible biomarkers.

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A combined approach using lipid, morphological, mineralogical, elemental, and isotopic biomarkers is promising for identifying the footprints of ancient microbes in the geological record. Regardless of whether the processes are ancient or modern, microbial activity can cause significant changes in the mobility of heavy metals and radionuclides, which can result in the formation of metal deposits over geologic time or the immobilization of metals in modern contaminated sites.

ACKNOWLEDGMENTS

This work was supported by grants from the U.S. Department of Energy (DOE FG02-07ER64369 and DOE-SC0005333) to HD and by the National Basic Research Program of China (973 Program) (2007CB815602) to AL. 


GLOSSARY

Bioelectrochemical system (BES) – a system that contains an anode, a cathode, a conductive circuit (e.g. water, minerals, wires), and at least one bacterial species

Biomineralization – the process by which organisms produce minerals, often resulting in fossilization of cellular structure

Bioremediation – the use of biological agents, such as bacteria or plants, to remove or immobilize contaminants in polluted soil or water

Biologically induced mineralization (BIM) – mineral formation outside or on the cell as a result of the indirect effect of the microorganism’s metabolism

Biologically controlled mineralization (BCM) – nucleation and growth of mineral particles where an organism exerts a high degree of crystallochemical control

Diagenesis – any chemical, physical, or biological change undergone by sediment after its initial deposition and during and after its lithification. These changes happen at relatively low temperatures and pressures and result in changes to the rock’s original mineralogy and chemistry

Dissimilatory iron reduction (DIR) – the process by which bacteria respire on Fe(III), resulting in the production of Fe(II). This process is linked to the oxidation of either organic or inorganic compounds

Extracellular polymeric substances – polysaccharides, proteins, and nucleic acids secreted by microorganisms. These substances form extracellular matrix and promote cell agglomeration and biofilm formation

Great Oxidation Event – the biologically induced appearance of free oxygen in Earth’s atmosphere around 2.4 billion years ago due to photosynthesis

Heavy metal – a member of a loosely defined subset of elements that includes transition metals, some metalloids, lanthanides, and actinides; these normally have a high atomic weight and a specific gravity greater than 5.0. They can be toxic or poisonous to life often at very low concentrations

Illite – a clay mineral with a similar structure to muscovite and smectite (2:1 structure). Its composition lies between that of muscovite and smectite (2:1 structure). Its weight and a specific gravity greater than 5.0. They can be toxic or poisonous to life often at very low concentrations

Microbes or microorganisms – microscopic organisms that are comprised of either a single cell (unicellular) or a group of cells (multicellular). Microbes include bacteria, fungi, archaea, protists, some plants (such as green algae), and some animals (such as plankton). They are usually invisible to the naked eye.

Natural attenuation – a naturally occurring process, without any human intervention, that can reduce the toxicity, mobility, mass, or concentration of contaminants in water or soils. These processes include a variety of physical, chemical, and biological processes

Photocatalysis – acceleration of a photo reaction in the presence of a catalyst

Phototrophic microorganisms – microorganisms that use light as an energy source in the process of photosynthesis. Nonphototrophic microorganisms use either inorganic or organic substrates as a source of energy

Proton motive force – an energized state of a membrane produced by the expulsion of protons from the inner to the outer membrane surface through the action of an electron-transport chain

Radionuclide – an atom with an unstable nucleus that undergoes decay and emits gamma rays and/or subatomic particles

Secondary mineral – a mineral formed by the alteration of preexisting primary minerals through weathering, metamorphic activity, fluid–rock interaction, or biological activity

Semiconducting mineral – a mineral of intermediate electrical conductivity, between that of a metal and that of an insulator. Such minerals are characterized by a distinctive electronic structure with a filled valence band and an empty conduction band. Some semiconducting minerals are light sensitive and can carry out photocatalysis

Semiconductor photocatalysis – light-induced reactions on the surface of a semiconductor. When light with energy higher than the band gap of a semiconductor is absorbed, it generates a pair of electrons and positively charged holes that participate in redox reactions

Siderophore – a compound that forms strong complexes with Fe(III) and may contribute to the weathering of Fe oxides and silicate minerals

Smetite – a group of clay minerals with a 2:1 structure (i.e. one octahedral layer sandwiched between two tetrahedral layers) and that display the property of expansion and contraction during the wetting and drying cycle

Smetite-to-illite reaction – smectite is stable at low temperature and pressure and is a major constituent of surface soils and sediments. As these materials are buried, temperature and pressure increase, and smectite becomes unstable and transforms to illite

Sulfate-reducing bacteria (SRB) – bacteria that obtain energy from the transfer of electrons from hydrogen or organic compounds to sulfate

Superoxide dismutases (SODs) – a class of enzymes that catalyze the dismutation of superoxide into oxygen and hydrogen peroxide. As such, they are an important antioxidant defence in nearly all cells exposed to oxygen

Thermophile – an organism that prefers temperatures between 45 and 122°C for growth

Microbial fuel cell (MFC) – a type of bioelectrochemical system that consists of anodic and cathodic chambers, usually separated by a proton-exchange membrane that divides the two electrodes. The two electrodes are connected to a conductive wire. Microbes biodegrade (oxidize) substrates in the anodic chamber and transfer electrons through a circuit to a terminal electron acceptor at the cathode. This process can generate electricity.
Minerals as Substrates for Life: The Prokaryotic View

Gordon Southam*

INTRODUCTION

Prokaryotes (Bacteria and Archaea) are ubiquitous single-celled organisms that exhibit remarkable molecular and metabolic diversity. Under low-temperature aqueous conditions, nominally less than 100 °C, the biogeochemical cycling of iron and sulfur by prokaryotes causes the dissolution and precipitation of various minerals and affects the bioavailability of toxic heavy metals. Prokaryotes can also directly oxidize or reduce compounds of elements such as As, Cu, Cr, Fe, Hg, Mn, Mo, and U, affecting metal bioavailability and hence the design of bioremediation processes (Hugenholtz et al. 1998; Ehrlich and Newman 2008). In the present-day world, the growth of iron- and sulfur-cycling microorganisms is most active in marine sediments, in natural acid rock drainage sites, and in acid mine drainage environments (Nordstrom and Southam 1997; Toner et al. 2009). This may cause the release of toxic metals and also, in some cases, the immobilization of toxic metal “pollutants.” In geologic materials, microorganisms grow as complex associations of cells on mineral substrates and within sediments. In these systems, bacteria can catalyze mineral- (and metal-)transforming redox reactions on the scale of millimeters, far greater than the typical micrometer-scale of individual cells, through “extracellular” electron-transfer processes (Marshall et al. 2006; Nealson 2010).

Microorganisms usually require trace amounts of some metals (e.g. Cu, Ni, Zn, and Co) for vital biochemical reactions and as cofactors that assist in the functioning of certain enzymes. However, micromolar to millimolar concentrations of heavy metals can be toxic to microorganisms, blocking functional groups of enzymes and transport systems for essential nutrients. Genetically based resistance mechanisms are dominated by efflux systems, which “pump out” toxic ions that enter cells; these systems require energy in order to function (Silver and Phung 2005). Intuitively, metal resistance is essential for bioremediation processes because the organisms must be able to tolerate elevated concentrations of potentially toxic metals.

With the exception of hydrothermal systems such as deep-ocean black smokers, the biogeochemical dissolution of minerals by prokaryotes generally begins with crystalline materials much larger than the microbes degrading them. Subsequent secondary mineral precipitation of the metals released by dissolution of primary minerals results in phases with increased surface area and higher hydration states relative to the original minerals. Because biogenic minerals are very fine grained and typically amorphous, they are more susceptible to biogeochemical cycling, that is, they are easier to dissolve (Lovley and Philips 1987). With increased industrialization, the overall amount of metals cycling within the biosphere has increased, particularly in terrestrial ecosystems, which do not possess a means of removal of metals comparable in scale to ocean sedimentation. Prokaryotes, in some cases a single species, can contribute both to an environmental problem (the release of toxic metals) and to remediation (the precipitation of another metal under identical redox conditions). The remainder of this article examines mineral substrates and secondary mineral products (primarily) from a prokaryotic perspective. For bioremediation to work, we need to take a microbial perspective to understand how metal transformations occur and why prokaryotes would want to do the things we are asking of them.

METAL SULFIDES

In aerobic environments, the colonization of metal sulfides, such as pyrite, by acidophilic iron- and sulfur-oxidizing bacteria (Fig. 1A) demonstrates the ability of these bacteria to use solid substrates as electron donors through the biooxidation of iron at the microbe–mineral interface (reaction 1; see Mielke et al. 2003), and to transfer these electrons to molecular oxygen (reaction 2):

\[
\text{Fe}^{2+} \rightarrow \text{Fe}^{3+} + e^- ;
\]  

(1)

\[
\text{O}_2 + 4 \text{ H}^+ + 4 e^- \rightarrow 2 \text{ H}_2\text{O} .
\]  

(2)
The overall biooxidation of iron by acidophilic iron-oxidizing bacteria can be written as:

\[ 4 \text{Fe}^{2+} + \text{O}_2 + 4 \text{H}^+ \rightarrow 4 \text{Fe}^{3+} + 2 \text{H}_2\text{O} \ . \]  
(3)

The biooxidation of iron can catalyze the abiotic oxidation of other metal sulfides (e.g. millerite; reaction 4), releasing heavy metals into solution through the chemical reduction of ferric iron and at the same time “regenerating” ferrous iron, the source of energy for the microbes:

\[ 8 \text{Fe}^{3+} + \text{NiS}_2 + 4 \text{H}_2\text{O} \rightarrow 8 \text{Fe}^{2+} + \text{Ni}^{2+} + 2\text{SO}_4^{2-} + 8 \text{H}^+ \ . \]  
(4)

These linked bio(geo)chemical reactions are the basis for the biohydrometallurgical processing of ore (Rawlings et al. 1999) and for the supergene weathering of metal sulfides. In supergene weathering (supergene enrichment), metals are released in the oxidizing, near-surface environment and then reprecipitated near the groundwater table where conditions become reducing. The metals can accumulate as economic deposits at the redox boundary (Enders et al. 2006). The biooxidation of metal sulfides exposes viable, acidophilic iron- and sulfur-oxidizing microbes to very high (micromolal to millimolal) concentrations of metals. To survive in these metal-rich environments, iron- and sulfur-oxidizing bacteria expend energy to pump these metals out of their cells (Dopson et al. 2003). The biooxidation of metal sulfides that are naturally exposed, or exposed to active weathering by the disposal of sulfidic mine wastes at the Earth’s surface, can lead to the formation of acid (mine) drainage (AMD; see Lu and Wang 2012 this issue), which precipitates characteristic iron oxide minerals (see Metal Oxides section, below). However, viable Acidithiobacillus spp. (common sulfide-oxidizing bacteria) do not readily immobilize these precipitated metals on their cell surface (Fig. 1a). Acidithiobacillus spp. have been anthropomorphically characterized as good bacteria when they are used in industrial bioleaching operations, or bad bacteria when they cause AMD. They are neither good nor bad; they are simply exploiting favorable redox conditions to support life.

Dissimilatory sulfate-reducing bacteria (SRB) oxidize low-molecular-weight organic compounds by using oxidized sulfur compounds as their terminal electron acceptor. This releases hydrogen sulfide and bicarbonate as by-products of metabolism. Ferrous iron in solution (see reaction 4) can then react with the H$_2$S to produce sulfide as a precipitate. The basic biochemical (reaction 5) and geochemical (reaction 6) reactions mediated by SRB (see Fig. 2) reverse the overall biooxidation process discussed above:

\[ 2 \text{CH}_2\text{O} + \text{SO}_4^{2-} \rightarrow \text{H}_2\text{S} + 2 \text{HCO}_3^- ; \]  
(5)

\[ \text{Fe}^{2+} + \text{H}_2\text{S} \rightarrow \text{FeS}_\text{(s)} + 2 \text{H}^+ . \]  
(6)

Other metals, such as Ni$^{2+}$ and Cu$^{2+}$, can be substituted for Fe$^{2+}$ in reaction (6), precipitating these metals from solution as NiS$\text{(s)}$ and CuS$\text{(s)}$ and decreasing their bioavailability. The sulfides produced by SRB can chemically reduce...
iron and manganese oxides, increasing the complexity of the metal and sulfur chemistry. Dissimilatory SRB are being exploited as biocatalysts for the removal of metals from AMD by promoting reactions 3 and 4 (Doerr et al. 2005). Whether naturally occurring or produced in the laboratory, biogenic metal sulfides are submicrometer-scale (Fig. 2), three to four orders of magnitude smaller than typical metal sulfides found in rocks and mine tailings. These fine-grained minerals are more susceptible than the original sulfides to chemical or biological oxidation and, therefore, represent a potential environmental liability if exposed to oxidizing conditions.

**METAL OXIDES**

The biooxidation of iron and manganese occurs under circumneutral conditions (reactions 7 and 8) or under extremely high concentrations of iron (and/or manganese) in acidic systems:

\[
4 \text{Fe}^{2+} + \text{O}_2 + 10 \text{H}_2\text{O} \rightarrow 4 \text{Fe(OH)}_3 + 8 \text{H}^+ ; \quad (7)
\]

\[
2 \text{Mn}^{2+} + \text{O}_2 + 2 \text{H}_2\text{O} \rightarrow 2 \text{MnO}_2 + 4 \text{H}^+ . \quad (8)
\]

As an example, the Rio Tinto, Spain (Fig. 3a), precipitates highly hydrated, amorphous metal oxides (Figs. 3b, 4). The formation of metal oxide can occur through abiotic or biological (enzymatic) oxidation of iron and manganese (Tebo et al. 2004; Kappler and Straub 2005). These metal oxides can also precipitate from solution prior to adsorption to cells. The oxidation of iron under anaerobic conditions produces iron oxides with comparable toxic metal adsorption properties (Hohmann et al. 2010; McAllister et al. 2011). Metal precipitation can occur directly on individual cells or around the periphery of microcolonies encased within capsules or exopolymeric substances (Chan et al. 2009) and on the surfaces of inorganic materials, such as clays (Dong 2012 this issue). These oxide precipitates possess anionic and cationic charged groups, allowing for extensive interaction with soluble metal cations and...
metaloids. The precipitation of metal oxides on, or within, highly charged biogenic polymers, i.e. capsule, can protect the internal microcolony from the deleterious effects of mineralization (Fig. 4), allowing for continued microbial growth and mineral precipitation.

Soluble heavy metals and metalloids (e.g. Ni, Cu, AsO$_3^{3-}$) can substitute within the mineral structure of iron and manganese oxides, enriching these precipitates with toxic metal ions wherever these oxides occur, typically at aerobic/anaerobic interfaces where the reduced metals encounter an oxidizing environment. In these systems, the oxides can function as an ion exchange “resin,” reducing the direct bioavailability of the metals. From an applied perspective, heavy metal adsorption by biogenic iron and manganese oxides can be used in bioremediation; it also explains the success of geochemical exploration programs that target metal anomalies in soils and sediments (Mann 2010).

Anaerobic, heterotrophic, metal-respiring prokaryotes, which require organic carbon for their metabolism, catalyze a number of thermodynamically favorable reactions, including the reductive dissolution of Fe–Mn oxyhydroxides (reaction 9), which releases Fe$^{2+}$, Mn$^{2+}$, and any sorbed trace metals into solution (Fig. 5) (Kieft et al. 1999; Dixit and Herling 2003):

$$\text{CH}_2\text{O} + 4 \text{Fe(OH)}_3 + 8 \text{H}^+ \rightarrow \text{CO}_2 + 4 \text{Fe}^{2+} + 11 \text{H}_2\text{O} . \quad (9)$$

Similarly, microbial degradation of complex organic compounds, such as cellulose and lignin from plants, to simpler molecules, such as acetate, citrate, and oxalate, can enhance metal solubility by forming soluble, metal–organic complexes. Under conditions where the availability of an electron acceptor is limiting, prokaryotes are able to produce organic “nanowires”—fibers capable of transferring electrons from the inside to the outside of a cell—facilitating growth using solid substrates such as iron oxides (Kieft et al. 1999; Nealson 2010). Some of the metals that are released under anaerobic conditions can become precipitated as metal sulfides through bacterial sulfate reduction.

Dissimilatory metal reduction does not always solublize metals. Some of the metals reduced by prokaryotes can also form hydroxides and oxides—for example, the reduction of uranium in solution (Marshall et al. 2006; reaction 10)—thus immobilizing these metals under anaerobic conditions (see Cheng et al. 2012 this issue):

$$\text{CH}_3\text{O} + 2 \text{UO}_2^{2+} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + 2 \text{UO}_2\text{(OH)}_2 + 4 \text{H}^+ . \quad (10)$$

Metal-reducing prokaryotes could conceivably catalyze the release of some metals and metalloids into solution (e.g. Ni, Cu, AsO$_3^{3-}$), causing toxic levels of these metals at the same time as uranium is remediated.

One of the most unusual iron oxides (and an unusual iron sulfide) is formed by magnetotactic bacteria, which synthesize magnetosomes—biogenic chains of nanophase magnetite ($\text{Fe}_3\text{O}_4$) or greigite ($\text{Fe}_3\text{S}_4$) (Bazyllinski and Frankel 2004; Pósfai and Dunin-Borkowski 2009). Using these biogenic chains, magnetotactic bacteria are able to orient themselves in the Earth’s magnetic field, enabling more efficient, directed motility so that they can maintain their position within zones possessing optimum, low-oxygen growth conditions. While fundamentally fascinating, due to their ability to control mineralization, magnetotactic bacteria do not produce minerals on a scale that could be utilized for bioremediation or, more importantly, for removal of toxic metals through magnetosome synthesis.

SILICATES

While the preservation of microbial remains is most likely to occur within silicate minerals (Konhauser 1998), bacteria and fungi can be active agents of chemical weathering of silicates such as feldspars (Gadd 2007; Uroz et al. 2009). Silicate rocks represent a source of apatite, providing phosphorus, an essential, and often limiting, nutrient for the increase of biomass and for microbial metabolism (Rogers and Bennett 2004). Silicate rocks also contain a wide range of heavy metals, such as Cu, Ni, Zn, and Cd (Ehrlich and Newman 2008); however, these metals are generally released only at trace metal/nutrient levels through microbial weathering. Organic acids produced by the death and decay of microorganisms can also aid in silicate dissolution by forming aqueous silicate–organic complexes (Rogers and Bennett 2004), which will also cause the release of trace metals into solution. With the exception of ultramafic rocks, which can possess significant (percent) quantities of nickel as sulfides, the trace metals in silicate rocks primarily represent nutrients for microorganisms rather than a source of toxic metals requiring remediation.

THE PROKARYOTIC PERSPECTIVE

Interaction among toxic metals, minerals, and prokaryotes can occur through several mechanisms. Prokaryotes possess a wide range of structural cell-envelope polymers, possessing carboxyl, phosphoryl, and hydroxyl groups that can bind heavy metals and remove them from solution (Ginn and Fein 2008). Intuitively, the adsorption of metals within cell envelopes should not produce significant negative effects on the cells. For example, the replacement of divalent cations, such as Ca$^{2+}$ and Mg$^{2+}$, by divalent toxic metals will not affect the stability of the cell envelope. Therefore, as long as the cell envelope is functioning as an ion-exchange resin (similar to the iron oxides, above), then the biochemistry within the cell will not be influenced by the toxic effect of the metals. However, once the ion-exchange capacity of the cell envelope has been saturated, metals will enter the cell.
Prokaryotes may respond to the presence of intracellular toxic metals by pumping them out of the cells (Silver and Phung 2005). The metabolic cost of this strategy, assuming the cell possesses the appropriate genetic capacity/metallorresistance mechanism, is an expenditure of energy, which will continue for as long as the cell is exposed to the metals. If the cell does not possess the capacity to cope with a particular metal or the ability to withstand a particular concentration of metal, then damage to biochemical processes will ensue, which can lead to cell death, thus harming any bioremediation process. The challenge for bioremediation is designing a system that is able to withstand natural variability, for example, storm events that can increase flow rates (overall metal loading) and potentially increase metal concentrations.

As single, typically micrometer-scale, cells, prokaryotes possess a higher surface area to volume ratio than all other life forms, which helps facilitate nutrient acquisition for growth and provides a tremendous surficial biominalization potential (Beveridge 1981). The mineral adsorption reactions described above are also thought to serve as nucleation sites for the precipitation of metals from solution or the adsorption of minerals already formed within the aqueous phase. As a result of the formation and/or binding of minerals, the amount of metal precipitated typically exceeds what would be expected on the basis of the number of reaction sites within the cell envelope. This mineral growth is most active at the outer surface of the bacterium, where the minerals nucleate and where space constraints by the envelope polymers do not inhibit metal precipitation. Mineral growth outward from these nucleation sites also (initially) prevents a bacterium from being completely encrusted in mineral. This is clearly important to an organism that obtains its nutrients by diffusion, and it allows cells to persist in metal-stressed environments.

For active, mineral-forming prokaryotes, the benefit from precipitation of iron, manganese, and uranium (hydr) oxides via physiologically driven redox processes or through the formation of by-products that react with metals (i.e. sulfide produced by dissimilatory SRB) must be worth the inherent liability of forming minerals that can enclose these organisms within a mineral “tomb.” For these prokaryotes, the risk associated with mineral formation, potentially blocking the interface used for nutrient acquisition and waste-product disposal, must be worth the metabolic cost.

Although the armoring of cell surfaces is presumably deleterious to individual cells, it may not matter to populations of microbes. In mineral-forming environments, some cells are more extensively mineralized than other adjacent cells (Figs. 2, 3, 4). This mineralogical heterogeneity demonstrates that nonmineralized cells can persist in metal-stressed systems and, presumably, that chemical gradients exist on the scale of individual microbes. The nucleation of fine-grained minerals on prokaryotic cells can be easily observed in ultrathin sections (ca 70 nm thick) using transmission electron microscopy (TEM) because the minerals are more electron dense (darker) than cells (Fig. 4). Selective armoring of individual cells during mineralization will reduce the cell surface area available for nutrient uptake. Consequently, such mineralized microbes starve and die, and the production of protons by the cell’s energy-generating electron-transport chain dissipates (Urrutia Mera et al. 1992). Without the competition from hydronium ions within the cell envelope, mineralization continues, reducing the concentration of soluble, toxic heavy metals in the surrounding microenvironment, thereby promoting the survival of the remaining nonmineralized microbes. The bioremediation of toxic metals will inherently cause the complete mineralization of some cells (Fig. 4; Konhauser 1998); for bioremediation to work, new biomass must be produced to replace the cells that are lost.

**OUTLOOK**

The bioremediation of toxic metals can be promoted through a range of processes, some of which are highlighted in this issue of *Elements*. However, these fine-grained minerals are easily redissolved if redox conditions change, and they become thermodynamically unstable (Fig. 5). The active cycling of minerals and metals at or near the Earth’s surface presents a challenge to bioremediation efforts because the fine-grained, hydrated, nanophase materials that form can be easily oxidized or reduced by other prokaryotes, producing soluble metal (metalloid) by-products. Based on lessons from the limited preservation of microfossils in the geologic record, biogenic minerals can only be found in chemically and biogeochemically stable environments. Therefore, the design of bioremediation strategies must be site-specific, targeting specific metal/mineral products. Also, conditions must be maintained at the site such that the biogenic minerals produced during bioremediation remain stable and are not exposed to conditions that result in redissolution.

**ACKNOWLEDGMENTS**

Support for the work presented in this article was provided by Westminer Canada Ltd. and Natural Sciences and Engineering Research Council of Canada Discovery Grants to T. J. Beveridge and to G. Southam. The *Thermus* sample examined using transmission electron microscopy was provided by Jim Frederickson, Pacific Northwest National Laboratory, Richland, WA, USA. I thank two anonymous reviewers, as well as H. Dong, J. Drever, and P. Tremblay, for their editorial contributions.

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Remediation of Chromium and Uranium Contamination by Microbial Activity

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Abstract: Anthropogenic sources of the toxic metals chromium and uranium have contaminated the ecosystem and become major public and political concerns. Biomineralization, a process by which microorganisms transform aqueous metal ions into amorphous or crystalline precipitates, is regarded as a promising and cost-effective strategy for remediating chromium and uranium contamination. This review describes the potential and limitations of bioremediation for these two toxic metals and highlights the importance of biologically mediated transformation, immobilization, and mineralization of toxic metals during the course of remediation. It also provides nonspecialists with an introduction to several of the main approaches to remediation and acknowledges some questions about this technology that remain to be answered.

Keywords: toxic metal contaminants, chromium, uranium, biomineralization, bioremediation

INTRODUCTION

Bioremediation refers to the use of organisms, particularly microorganisms, to transform or degrade a contaminant to make it harmless (Antizar-Ladislao 2010). One well-characterized example is the bioremediation of the Exxon Valdez oil spill off the Alaska coast; the treatment has largely eliminated pollutants and wastes along hundreds of miles of coastline (Atlas and Hazen 2011). Currently, bioremediation is regarded as a cost-effective remediation technology potentially appropriate for large polluted areas, such as contaminated water and soil. Its potential safety and efficiency will certainly accelerate further development of the technology.

Biomineralization is the process by which living organisms influence the precipitation of metal elements and produce inorganic minerals (Benzerara et al. 2011). It is a critical connection between the biosphere and the lithosphere. The process can occur through either biologically controlled mineralization (BCM) or biologically induced mineralization (BIM). BCM has also been referred to as boundary-organized biomineralization and organic matrix-mediated mineralization. There are several important differences between BCM and BIM. In BCM, the microbe “intentionally” synthesizes minerals that meet specialized functions. In BIM, the microbe “unintentionally” precipitates metal ions as a result of its metabolism or as a form of protection against certain environmental conditions. Normally, the mineral produced via BIM is an inorganic precipitate and hexavalent uranium [U(VI)], the toxic and highly soluble forms of these elements, are of great concern as environmental pollutants. When reduced to Cr(III) or U(IV), these species are generally much less soluble, less bioavailable, and hence less toxic. Thus, by adding appropriate nutrients at contaminated sites to stimulate microbial activity, many indigenous microorganisms can minimize the mobility of contaminants by transferring them to stable, nonmobile phases, such as mineral precipitates or crystals. This technology is regarded as a promising, environmentally friendly, and cost-effective way to remediate chromium and uranium contaminants.

ENVIRONMENTAL POLLUTION OF CHROMIUM AND URANIUM

Chromium ranks as the 21st most abundant element in the Earth’s crust. The world production of Cr is approximately 107 metric tons (tonnes) per year: 60–70% is used in alloys, including stainless steel, and 15% is used in chemical industrial processes such as leather tanning, pigments, and electroplating. Industrial activities have resulted in widespread Cr(VI) contamination in soil and natural waters. The production of one tonne of chromium products can generate about 2.5 tonnes of chromium residues containing 1% Cr(VI). In China alone, the metallurgical and chemical industries discharge up to 600,000 tonnes of chromium slag annually, and traditional chromate plants have already generated over 2.5 million tonnes of Cr(VI)-containing wastes. In many areas, rain and runoff have leached the soluble Cr(VI) from the slag and polluted large areas of soil and water supplies (Fig. 1). This can lead to severe environmental consequences. For example, in Liaoning Province, China, the Cr(VI) concentrations in drinking water wells near a ferrochromium-production factory reached 20 mg/L. Between 1970 and 1978, stomach and...
chromate-due to contamination of mine tailings, in addition to large areas of evaporation ponds. In China, it is estimated that the 442 operating nuclear power plants with a total net installed capacity of approximately 370 GW were in operation in 30 countries; an additional 65 nuclear power plants are under construction in 16 countries (International Atomic Energy Agency data, 2011). It is estimated that the 442 operating nuclear power plants consume 66,000–69,000 tonnes of uranium fuel annually. Production of one tonne of UO$_2$ fuel requires mining ~750 tonnes of uranium ore (Abdelouas 2006). The processing of uranium ore yields large amounts of uranium-containing waste and wastewater. In the United States alone, radionuclide contamination, including uranium, at 120 sites totals more than 3 million cubic meters of buried waste, 1.8 billion cubic meters of affected groundwater, and 75 million cubic meters of contaminated sediments (Hu et al. 2010). Globally, there are over 4000 uranium mines and more than two-thirds of uranium-contaminated mine tailings, in addition to large areas of evaporation ponds (Fig. 2). Such contamination constitutes a serious, long-term environmental problem, and a knowledge of uranium’s chemical and transport behavior is needed to guide potential remedial actions.

**BIOREMEDIATION OF CR(VI) CONTAMINATION**

**Mechanisms of Bacterial Resistance to Chromium**

No microbe can treat chromium pollution unless it can survive in that contaminated environment. In order to survive in such an environment, various chromium-tolerance mechanisms have been developed during microbial evolution by natural selection (Fig. 3). (1) A plasmid-encoded transporter ChrA (a protein-like pump embedded in the cell membrane) allows the efflux from the cytoplasm of any chromate that enters the cell through sulfate transporters. (2) Extracellular reduction of Cr(VI) is dominant among bacteria because reduced Cr(III) cannot be transported across the cell membrane. (3) Intracellular reduction of Cr(VI) to Cr(III) may generate oxidative stress, as well as cause damage to the protein or DNA. Detoxifying enzymes protect the cell against oxidative stress and reduce the toxic effects of chromate (Ramirez-Diaz et al. 2008). (4) Bacteria can form extracellular capsules to obstruct the passage of Cr(VI) into the cell. As an example, we have observed capsule formation in *Enterobacter cloacae* due to interaction with Cr(VI) over time (Fig. 4, **top panel**). Considering that the *E. cloacae* strain is able to reproduce in a nutritionally rich medium amended with a high concentration (800 mg/L) of Cr(VI) as chromate CrO$_2^{2-}$, we propose that capsule formation outside the cell may serve to prevent Cr(VI) penetration into the cell interior (Yang et al. 2007). A similar phenomenon was also observed in the bacterium *Arthrobacter* sp. k-4 (Fig. 4, **bottom panel**).

**Chromate-Reducing Mechanisms of Bacteria**

Since the discovery of the chromate-reduction capability of *Pseudomonas* in 1977, a large number of chromate-reducing microbes have been isolated. These microbes can reduce Cr(VI) either through an enzymatic reduction pathway (sometimes also referred to as direct reduction) or through a nonenzymatic reduction pathway (sometimes also referred to as indirect reduction) (Kamaludeen et al. 2003).

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**Figure 1** Schematic diagram of soil and water polluted by chromium slag heaps. The photo on the left shows chromium-polluted water in Shenyang, northeastern China. The chromium slag heap, visible on the left, is located near a stream. Water as far as 8 km downstream from here exceeds the recommended maximum levels for chromium. The right-hand photo shows a chromium slag heap in Changsha, Hunan Province, China. It is only about 20 m from an urban neighborhood and 100 m from the Xiangjiang River.

**Figure 2** An evaporation pond at a uranium-processing plant in the southwestern part of the Turpan-Hami Basin, Xinjiang, China. The plant treats ore from a sandstone-type uranium deposit using in situ leaching technology.
In enzymatic reduction, chromate is taken up by microbes and then enzymatically reduced. The Cr(VI) reductase enzyme may be present in the membrane, cytoplasm, or periplasm (the periplasm is the space between the inner and outer membrane in Gram-negative bacteria). For instance, the YieF dimer, a soluble protein found in the cytoplasm, may be an obligatory four-electron chromate reducer (Ackerley et al. 2004). The dimer is thought to transfer three electrons to chromate and one to molecular oxygen, thus reducing Cr(VI) directly to Cr(III) in one step. ChrR, another soluble enzyme with chromate reductase activity, generates a Cr(V) intermediate when chromate is reduced. As Cr(V) is a very toxic intermediate product, organisms using YieF may be more suitable candidates for chromate bioremediation than those using ChrR (Ackerley et al. 2004). Cr(V) occurs as an intermediate in Shewanella oneidensis MR-1 during the reduction of Cr(VI), suggesting that a one-electron transfer is the first step under anaerobic conditions. A Cr(V) intermediate has also been observed during the reduction of Cr(VI) to Cr(III) by other organisms (Suzuki et al. 1992). Holman and colleagues used electron spin resonance (ESR) to study the formation and decomposition of Cr(V) by basalt-inhabiting bacteria (Kalabegishvili et al. 2003). Cr(V) also occurred during the reduction of Cr(VI) to Cr(III) by Ochrobactrum anthropi (Fig. 5a). However, the occurrence of Cr(V) was transient and it was eventually converted into stable Cr(III) (Fig. 5b) (Li et al. 2008).

In nonenzymatic reduction, the products of microbial metabolism and/or decomposition, such as Fe^{2+} or H_{2}S, can mediate the reduction of Cr(VI) to Cr(III) (Kamaludeen et al. 2003). For example, sulfate-reducing bacteria oxidize...
organic sources to reduce sulfate to sulfide. Dissimilatory iron-reducing bacteria reduce Fe$^{3+}$ to Fe$^{2+}$. Both sulfide and Fe$^{2+}$ are effective reductants of Cr(VI) under certain conditions. Some organic molecules that may differ from those in microbial metabolic processes, such as intracellular thiol compounds or extracellular polymeric substances, can also reduce Cr(VI).

**Organic-Cr(III) and the Chromium Biogeochemical Cycle**

Microbial reduction of Cr(VI) to Cr(III) has been extensively investigated for bioremediation purposes. Most early reports emphasized the reduction of Cr(VI) and often did not specify the forms of Cr(III) end products. The reduced chromium was thought to be trivalent chromium hydroxide or an oxide precipitate, based on the behavior of Cr(III) in inorganic environments, which may differ from that in organic-rich environments, such as culture media or within the intracellular environment of microbes (Puzon et al. 2005). Recent studies have shown that the reduced Cr(III) end products are complex, particularly in organic-rich environments (Cheng et al. 2010).

Because the formation of soluble Cr(III) species complicates remediation strategies for Cr(VI), understanding the factors that affect the immobilization of Cr(III) is important. In the *O. anthropi* system, some important functional groups determine the destiny of the reduced Cr(III) (Cheng et al. 2010). X-ray absorption fine structure (XAFS) analysis of the cell debris of *O. anthropi* clearly showed that the coordination of Cr(III) occurs on the cell surfaces via a chelating coordination with carboxyl and amino functional groups similar to the structure of glycine-Cr(III) (Fig. 6, left panel). However, competitive coordination experiments of reduced Cr(III) revealed that small and soluble molecules, such as amino acids and their derivatives, or multicarboxyl compounds, have stronger coordination ability with Cr(III) than cell debris (Fig. 6, right panel). Therefore, to ensure effective immobilization of Cr(III) by cells, the small molecules mentioned above should be avoided as much as possible during the remediation process. Moreover, our preliminary experiments showed that the organo-Cr(III) species could convert into Cr(OH)$_3$ nanoparticles over time.

However, the transformation is very slow, taking nearly two years to occur under experimental conditions. The Cr(OH)$_3$ nanoparticles may transform over time by dehydration to yield a more stable form, such as Cr$_2$O$_3$, making the approach conducive to the long-term immobilization and mineralization of chromium. Though the detailed phase-transformation mechanism from organo-Cr(III) to inorganic-Cr(III) needs further study, we propose that organo-Cr(III) complexes might be intermediates in the chromium biogeochemical cycle. They can be produced during chromate reduction in organic-rich environments and then further mineralized over time.

**BIOREMEDICATION OF U(VI) CONTAMINATION**

**U(VI)-Reducing Mechanisms in the Environment**

Similarly to Cr(VI), U(VI) anions are soluble, mobile, and toxic. Reduction of the soluble, oxidized form of uranium to insoluble U(IV) is an important mechanism for the immobilization of uranium in groundwater and for the formation of some uranium ores. Previously, U(VI) reduction in the environment was thought to be predominantly an abiological reaction in which naturally occurring sulfide, molecular hydrogen (released by microorganisms), or organic compounds could directly serve as the reductant (Lovley et al. 1991). The function of microbes was thought to be restricted to nonenzymatic reduction. However, Lovley and Phillips (1992) found that the reduction of U(VI) can also be the direct result of enzymatic reduction by bacteria in natural environments. Enzymatic reduction of U(VI) by *Desulfovibrio desulfuricans* is much faster than nonenzymatic reduction of U(VI) by sulfide, even when cells of *D. desulfuricans* are added to provide a potential catalytic surface for the nonenzymatic reaction.

It is currently unclear whether the direct or indirect mechanism dominates the microbial reduction of U(VI), especially in heterogeneous natural environments. In heterogeneous porous media, the indirect mechanism—for example, electron shuttling through low-molecular-weight organic or inorganic compounds—may be more important than direct enzymatic reduction due to pore space limitation of the direct microbial surface contact.
The formation of organo-Cr(III) species during the reduction of Cr(VI) by *O. anthropi* in an organic-rich environment. (Left) XAFS spectra showing that the reduced Cr(III) can bind to the cell surface via chelating coordination with carboxyl and amino functional groups, which is similar to the coordination situation of Cr(III)-glycine. This conclusion is derived by comparing the coordination shell (O and N atoms) of the chromium. For details see Cheng et al. 2010. (Right) Reduced Cr(III) competitively coordinates to organic molecules, such as amino acids, EDTA, and Tris [tris(hydroxymethyl)aminomethane], which exhibit various colors. Thr, Ser, Cys, Met, and Gly are the abbreviations for threonine, serine, cysteine, methionine, and glycine, respectively.

**The Diversity of the Bioremediation Products of U(VI)**

Similarly to the bioremediation strategy for Cr(VI), after enzymatic reduction by microbes, the highly mobile uranyl anions are converted to insoluble and low-valence uranium phases, such as uraninite, so as to decrease their mobility and hence minimize their environmental effects. The product of microbial reduction of U(VI) to U(IV) has often been reported to be the mineral uraninite. However, Bernier-Latmani et al. (2010) found that the reduction products include a variety of U(IV) species other than uraninite. The reduction of U(VI)-phosphate and U(VI)-citrate complexes by the bacterium *Thermoterrabacterium ferrieducens* and *Clostridium* spp. leads to the formation of the U(IV) mineral ningyoite [CaU(PO₄)₂·H₂O] and soluble U(IV) complexes, respectively (Bernier-Latmani et al. 2010). Furthermore, U(VI) reduction by *Desulfobacterium* spp. could lead to the formation of a mononuclear U(IV) phase [a U(IV) atom surrounded by light-element shells] rather than uraninite (Fletcher et al. 2010). Field studies, including work on the product of biostimulated U(VI) reduction in Oak Ridge sediments and on sediment from a naturally reduced zone at the Rifle Integrated Field Research Center in the United States, have demonstrated that U(VI) can be reduced to U(IV), but the U(IV) species does not appear to be uraninite (Kelly et al. 2008).

**U(IV) Stability and Reoxidation**

The properties, and hence stability, of uraninite are also dependent on its crystallite size, structure, and composition (Schofield et al. 2008). Biogenic uraninite particles have diameters of 2–3 nm, and the lattice constants are consistent with UO₂₋₀ exhibiting a high degree of intermediate-range order (Sharp et al. 2009). Variations in the uraninite crystalline structure or surface area could impart different stabilities and resistance to oxidation (Sharp et al. 2009). Biogenic uraninite can be oxidized and remobilized by several common environmental constituents (Matthew et al. 2010). For example, ferrihydrite, molecular oxygen, and manganese oxides can oxidize biogenic uraninite rapidly and extensively (Ulrich et al. 2009; Matthew et al. 2010). Nitrate also induces U(IV) oxidation through the production of reactive intermediates (i.e. NO₂⁻, NO, and NO₂) and through direct respiration (Beller 2005).

Coarse-grained uraninite is generally regarded as the most desirable product of bioreduction due to its low solubility. Similarly to biogenic chromium precipitates, the long-term stability of biogenic uraninite with respect to oxidative dissolution is the key to the success of in situ bioreduction strategies for remediation of subsurface U(VI) contamination (Ulrich et al. 2009). The properties of biogenic uranium minerals can be highly variable. The main variables affecting the behavior of biogenic uranium minerals are the oxidation potential, pH, temperature, and chemical composition of the aqueous and solid matrix. These variables govern the thermodynamic and kinetic processes that affect the long-term stability, including aqueous complexation, sorption, precipitation, and dissolution (Liu et al. 2009).

**DISCUSSION AND FUTURE DIRECTIONS**

The eventual success of bioremediation of Cr and U will ultimately depend on the stability of the products. Microbially mediated mineralization occurs when a microorganism modifies its local microenvironment in a way that creates conditions for extracellular chemical precipitation of Cr and U mineral phases. Although the microorganisms considered here do not control the biominalization process, they facilitate it by means of plasmid-determined microbial efflux, microbial metal reduction, and metabolite excretion (e.g. sulfide, oxalate). They also furnish surfaces with chemically reactive sites for sorption, nucleation, and formation of Cr or U precipitate.

Cr–microbe and U–microbe interactions are a vital part of natural biosphere processes and can have beneficial consequences for bioremediation. However, the interactions in the environment are not easily predicted from observations of individual isolates or cellular components. New and complex approaches will need to include dynamic interfacial processes that involve a multitude of interacting microbial species and various bioorganic materials and the structures they create. We must gain an understanding of how microscale biological and chemical interactions control the formation of specific minerals.

Driven by the realization that large amounts of land contaminated with Cr and U cannot be economically remediated using conventional chemical or physical approaches, significant resources have become available for studying Cr and U biomineralization. Genomic-enabled interdisciplinary biogeochemical studies should facilitate the advancement of biominalization research and enable the use of microbes for recycling metal wastes and for in situ bioremediation.
Heavy metal mineralization as mediated by microbial activity is not restricted to Cr(VI) and U(VI). Magnetosomes in magnetotactic bacteria and manganese nodules on the seafloor may reflect biomineralization. Precious-metal ions, such as Au(III) and Ag(I), may be converted to metals through interaction with microorganisms. Soluble metals, such as Se(VI), Pb(II), Tc(VII), and Hg(II), may also be reduced to their insoluble forms [Se(0), Pb(0), and Tc(IV)] or volatile forms [Hg(0)]. The scope of work has been extended to the in situ remediation of acid mine drainage by stimulating the growth of bacteria. For example, injecting organic nutrients in situ will stimulate the growth of dissimilatory iron-reducing bacteria and sulfate-reducing bacteria, which will in turn increase the pH value, reduce sulfate, and immobilize copper, zinc, iron, nickel, and related toxic metals (see Lu and Wang 2012). Microbes play important roles in the environmental fate of toxic metals. Thus, the immobilization of soluble toxic metals via microbial activity, regarded as a promising, environmentally friendly, and cost-effective method, merits further study.

ACKNOWLEDGMENTS

We would like to thank Drs. Liyun Lin and Hailiang Dong for their careful revisions of this manuscript. Financial support for this study was provided by the National Basic Research Program of China (973 Program) (2007CB815601, 2010CB933501), the National Natural Science Foundation of China (NSFC) (40902097, 40772034), the Outstanding Youth Fund of the NSFC (21125730), the Chinese Academy of Science Foundation (KJCX2-YW-N50), and the Opening Project of the Key Laboratory of Solid Waste Treatment and Resource Recycle (09ZXGK05). Additional funding was provided by the U.S. Department of Energy through contracts DE590 AC02-05CH11231 and DE-AC02-05CH11231.

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Clay–Microbe Interactions and Implications for Environmental Mitigation

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INTRODUCTION

Clay minerals are ubiquitous in soils, sediments, and sedimentary rocks, and they play important roles in environmental processes. Microbes are also abundant in these geological media, and they interact with clays via a variety of mechanisms, such as reduction and oxidation of structural iron and mineral dissolution and precipitation through the production of siderophores and organic acids. These interactions greatly accelerate clay mineral reaction rates. While it is certain that microbes play important roles in clay mineral transformations, quantitative assessment of these roles is limited. This paper reviews some active areas of research on clay–microbe interactions and provides perspectives for future work.

KEYWORDS: clay minerals, microorganisms, oxidation, reduction, transformation

CLAY MINERALOGY

Clay minerals are likely the minerals that we encounter most commonly in our daily lives. They form the soils in which plants grow, and they are the primary materials in a range of products and applications, including cat litter, animal feed, pottery, china, oil absorbants, pharmaceuticals, cosmetics, wastewater treatment, and even antibacterial agents. Clay minerals such as kaolinite and smectite have long been used to treat ailments of the digestive tract in certain countries (Ferrell 2008).

The diversity of clay mineral applications can be attributed to the chemistry and structure of these minerals. Clay minerals are hydrous aluminum layer silicates with structures similar to those of micas. Unlike the micas, however, interlayers of clay minerals contain a low cationic charge to “glue” adjacent silicate sheets, and water molecules can enter or exit the interlayer regions easily. Thus, these materials swell or shrink under wet or dry conditions. Clays are common products of the weathering and hydrothermal alteration of various rocks, but they can also precipitate directly from aqueous fluids. Because of their low-temperature genesis, clay minerals are very common in soils, sediments, and sedimentary rocks. Depending on their specific mode of formation, clay minerals can form extensive deposits of economic value (Fig. 1).

Because clay minerals are common in low-temperature environments where microorganisms thrive, the interactions between clays and microbes are important to a number of surficial processes. Microorganisms can dissolve, precipitate, and transform clay minerals and thus change their physical and chemical properties. Some of these changes are beneficial, whereas others are not desirable.

Some of these interactions generate distinct mineral assemblages in the ancient rock record, producing biosignatures.

Although clay mineralogy has been studied for more than half a century and various applications have been developed, the important role of microbes in clay mineral transformations has been recognized for only about 20 years. In the last decade, interest in this field has risen dramatically, as it has become clear that reduced clays can sequester toxic metals and radionuclides and that clays can degrade organic compounds (Stucki and Kostka 2006; Dong et al. 2009). In this article, I will start with a short review of clay mineralogy and then follow with a comprehensive overview of clay mineral–microbe interactions. I will end with a consideration of the environmental implications of clay mineral–microbe interactions and the outlook for future developments.

CLAY MINERALOGY

Clays are built of tetrahedral and octahedral sheets, typically in a 1:1 or 2:1 ratio. A 1:1 clay structure consists of one tetrahedral sheet and one octahedral sheet, and

FIGURE 1 This vermiculite deposit in Weili, Xinjiang, China, was formed from the weathering of phlogopite by meteoric water. Photo courtesy of Tongjiang Peng, Southwest University of Science and Technology, China

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examples include kaolinite and serpentine. A 2:1 clay structure consists of an octahedral sheet sandwiched between two tetrahedral sheets (Fig. 2), and examples include smectite, illite, and vermiculite.

Of special importance are two 2:1 clay mineral families: smectite and illite (Fig. 3). Smectite minerals are 2:1 layer silicates with a total negative charge between 0.2 and 0.6 per half unit cell. The low charge accounts for the capacity of smectites to swell. A member of the smectite family called nontronite (iron-rich smectite) has the following ideal formula:

\[
(K_{0.01}Na_{0.30}Ca_{0.13})(AlO_2)_{3.45}Fe^{3+}_{1.27}Fe^{2+}_{0.06}Mg_{0.12}\]

\[
(Si_{5.75}Al_{0.15}Fe^{3+}_{0.26})O_2(OH)_4.\]

The large cations (Na\(^+\), Ca\(^2+\), and K\(^+\)) enter the interlayer space to balance the net negative charge created by the substitution of trivalent Al and Fe for tetravalent Si in the tetrahedral site and divalent Mg for trivalent Fe in the octahedral site.

Illite minerals have the same basic structure as smectite, but with a higher net negative layer charge of 0.6 to 0.9 per half unit cell, a result of the greater degree of tetrahedral and/or octahedral substitution. A typical illite from Silver Hill, Montana, USA, has the following formula:

\[
(Mg_{0.09}Ca_{0.06}Fe_{1.27})(Al_{2.52}Fe^{3+}_{0.77}Fe^{2+}_{0.06}Mg_{0.43}Ti_{0.06})
\]

\[
(Si_{6.73}Al_{2.23})O_2(OH)_4.\]

Because of the higher charge of the interlayer cations, the electrostatic attraction between the basal surface and the interlayer cations is stronger in illite than in smectite. Consequently, illite does not expand when hydrated.

Smectite is stable at low temperature and pressure, which are the typical conditions in soils and surficial sediments. As soils and sediments are buried, smectite becomes unstable and transforms into illite according to the following reaction:

smectite + Al\(^{3+}\) + K\(^+\) → illite + silica .

Three important variables drive the smectite-to-illite (S-I) reaction: time, temperature, and potassium concentration. The S-I reaction is of special significance because the extent of the reaction, termed “smectite illitization,” is associated with a specific combination of temperature and time. These same conditions can trigger maturation, migration, and trapping of hydrocarbons (Pevear 1999). Thus, the S-I reaction is often used as an index for the generation of petroleum and natural gas. In terrigenous sediments, the S-I reaction typically takes place over the temperature range of about 90–120°C (Moore and Reynolds 1997). To better understand the kinetics and the controlling conditions for this reaction, laboratory simulation experiments are typically performed (Huang et al. 1993). These efforts reveal that, in the absence of any microbial activity, conditions of 250–350°C and 50–100 MPa are often needed to achieve realistic reaction rates (a few months) (Huang et al. 1993; Kim et al. 2004). However, in the presence of microbial activity, this reaction occurs via various mechanisms, at much lower temperatures and pressures over shorter time durations.

### MICROBE–CLAY MINERAL INTERACTIONS

#### Microbial Dissolution of Clay Minerals

In soils and sediments, microorganisms play important roles in the dissolution of clay minerals, contributing to elemental cycling, soil fertility, and water quality. Microbes accelerate clay mineral dissolution either through redox reactions of structural iron (see below) or through the release of metabolic by-products. In contrast to abiotic dissolution where pH is a primary driving force, biotic dissolution requires many organic compounds to destabilize the mineral structure. These compounds include siderophores (a group of element-scavenging compounds that contribute to the weathering of Fe oxides and silicate minerals), organic acids, iron chelators (small organic molecules that bind to Fe and help its transport), and extracellular polymeric substances (high-molecular-weight compounds composed of polysaccharides that are secreted by microorganisms into the environment). In microbially mediated clay mineral dissolution, the mineral surface reactivity seems to play a secondary role (Grybos et al. 2011).

Microbially mediated mineral dissolution is usually incongruent, meaning that certain elements are removed preferentially relative to others, producing nonstoichiometric minerals. Silica is a common dissolution product and has been observed in both laboratory experiments and natural mineral assemblages. This material is largely amorphous, with particle sizes in the nanometer range. Other biogenic minerals include pyrite, siderite, and vivianite. A mineral assemblage of quartz, pyrite, and calcite has been used to recognize the role of microbes in mediating mineral reactions in ancient marine sediments and in regulating global Si and Fe fluxes (Vorhies and Gaines 2009).

#### Microbial Formation of Clay Minerals

Clay minerals are common weathering products at low temperatures and neutral to acidic pH. Therefore, it is common to find that microbes are involved in the process of rock weathering and clay formation. In fact, microbially catalyzed rock and mineral weathering rates can be orders of magnitude higher than the chemical equivalent, especially when rocks and minerals contain nutrients such as phosphorus, a limiting nutrient in microbial metabolism (Rogers and Bennett 2004). Fisk et al. (2006) showed that microbial weathering of mafic silicates, basalts, and glasses produces many varieties of clay minerals, such as smectite, zeolite, and serpentine. Typically, microbes do not precipitate clay minerals directly, but the products of their weathering reactions reprecipitate to form clay minerals when conditions become favorable. Reactive sites on bacterial surfaces can promote nucleation. Indeed, poorly crystalline clay minerals are commonly observed as surface coatings on microbial cells (Konhauser 2006). Upon aging, the primary precipitates on bacterial filaments and cell walls
are likely transformed into crystalline clay minerals. In this process, extracellular polymeric substances can serve as a template for clay mineral synthesis.

**Microbial Reduction of Fe(III) in Clay Minerals and Its Effects on Their Physical and Chemical Properties**

Iron is the fourth most abundant element in the Earth’s crust and occurs in all clay minerals (Moore and Reynolds 1997; Stucki 2006). Clay minerals often account for about half the iron in soils and sediments. Much of the structural iron in clay minerals is ferric iron, which can be reduced either chemically or biologically. In a typical bioreduction experiment, structural Fe(III) in clay minerals serves as an electron acceptor, and organic matter acts as an electron donor in either a nongrowth or growth medium (Fig. 2). After a few weeks, the color of the solution changes to deeper green in the experimental tubes (Fig. 4a) indicating reduction of Fe(III) to Fe(II). Iron-reducing bacteria typically attach themselves to clay mineral surfaces during bioreduction (Fig. 4b, c).

To date, a wide range of bacteria and archaea have been used to reduce structural Fe(III) in clays (Dong et al. 2009; Liu et al. 2011; Bishop et al. 2011). In general, methanogens are less efficient in reducing structural Fe(III) than iron-reducing and sulfate-reducing bacteria. Smectites have been shown to be more reducible than other clay minerals, likely due to their high layer expandability, low layer charge, and high surface area (Dong et al. 2009).

Multiple factors influence the rate and extent of Fe(III) bioreduction. The most important are the microbe/clay ratio, the clay mineral surface area, the chemistry of the aqueous medium, the presence or absence of electron-shuttling compounds, and temperature (Dong et al. 2009). Even under ideal conditions, not all structural Fe(III) in clay is biologically reducible, likely due to an inhibition effect of biogenic Fe(II) that may be released during reductive dissolution of clay and then sorbed onto clay and bacterial surfaces. The sorbed Fe(II) may block electron transfer and hinder further bioreduction. This inhibition effect may be alleviated by removing Fe(II) from clay and bacterial surfaces through dynamic flow of the aqueous solution. The incomplete reduction of structural Fe(III) by microorganisms may also be caused by inhibition due to the accumulation of solid products on reactive clay and cell surfaces or by change to the energetics of the system (Dong et al. 2009).

What happens to the clay mineral structure and chemistry during and after Fe(III) bioreduction is a matter of debate. Several studies have reported that bacterial reduction of structural Fe(III) causes small and fully reversible changes in the structure and chemistry of the clay mineral. Other studies have observed reductive dissolution (Dong et al. 2009; Stucki 2011). It is now clear that both mechanisms operate and that the relative importance of one versus the other depends on many factors, including the nature of the clay minerals (i.e. iron content, layer charge, and crystal chemistry), the extent of reduction, the chemistry of the aqueous medium, and the type and nature of the microorganisms. Among these, the extent of reduction appears to play an important role. When the extent of reduction is small (<30%), the smectite structure remains stable, but above this threshold, it becomes unstable and the clay mineral may dissolve, with the formation of secondary mineral phases such as amorphous silica, siderite, vivianite, and illite, depending on the specific experimental conditions (Dong et al. 2009 and references therein).

The reduction of structural Fe(III) to Fe(II) tends to decrease the surface area, interlayer spacing, water swellability, and hydraulic conductivity of clay minerals. In general, reduction increases the negative layer charge and cation exchange capacity (Stucki and Kostka 2006; Stucki 2011), while the interlayer cations become less exchangeable. These physical and chemical changes of clay minerals would have profound effects on soil fertility and contaminant mobility. For instance, a decrease in the reactive surface area and the associated collapse of smectite layers would decrease the adsorption capacity of nutrients and even trap some nutrients (such as K and ammonium) in the smectite interlayer that would otherwise be available to plants. To overcome this problem, farmers may need to apply fertilizer more frequently to maintain a constant crop yield. Similarly, reduced smectites can more efficiently degrade pesticides, thus making them less effective in killing pests (Stucki and Kostka 2006). An alternative approach that mitigates these adverse effects is for farmers to till their agricultural lands, thus reoxidizing the reduced soils. Tilling soils has probably been practiced for thousands of years, but farmers may not be fully aware of this redox effect! The purpose of tilling and plowing is essentially to reoxidize structural Fe(II) in reduced smectite. However, reoxidation does not restore all the physical and chemical properties, and some of the changes are permanent (Stucki and Kostka 2006). With multiple cycles of reduction and oxidation, soil properties may deteriorate to a point where soil fertilization is increasingly needed. Because of the predominance of clay minerals in soils and their recyclable nature, the deterioration of soil properties is primarily due to clay mineral redox cycling.

![Figure 3](https://www.minersoc.org/Pages/gallery/clayPix/index.html) (B) platy illite from the Rotliegend of northern Germany. Images courtesy of the images of Clay Archive of The Clay Minerals Society (www.minersoc.org/Pages/gallery/clayPix/index.html)
Iron reduction may also exert a beneficial effect. One example is decreased contaminant mobility if, after structural Fe(III) reduction, contaminants are trapped inside the interlayer and thus become less exchangeable. For the purpose of remediation, iron reduction can be accelerated by injecting certain microbes or nutrients into the soil to stimulate indigenous microbes (Stucki et al. 2007).

Microbial Oxidation of Fe(II) in Clay Minerals

Microorganisms can also oxidize structural Fe(II) in clay minerals, but the mechanisms and controlling factors are poorly understood. Shelobolina et al. (2003) have shown that the oxidation of structural Fe(II) in smectite by Desulfotobacterium frappieri is coupled with the reduction of nitrate, which has implications for removing nitrate contamination from the environment using reduced clay minerals. Limited data indicate that, compared with chemical oxidation of structural Fe(II) by nitrate alone or by air, the rate of microbially mediated, nitrate-dependent Fe(II) oxidation appears faster (Yang 2010).

The Microbially Mediated Smectite-to-Illite Reaction

Although the importance of the S-I reaction has long been recognized, the role of microbes in promoting this reaction was only recently demonstrated (Kim et al. 2004). Under favorable conditions, the iron-reducing bacterium Shewanella oneidensis MR-1 can reduce structural Fe(III) in nontronite to Fe(II) and partially dissolve the nontronite. Upon recombination of the dissolved constituents, illite precipitates from the aqueous solution (Fig. 5). Because of compositional differences between nontronite and illite, the dissolution of one unit of nontronite does not make one unit of illite. More likely, the dissolution of multiple units of nontronite precipitates one unit of illite, with excess Si and Fe precipitated as silica and siderite or vivianite, depending on the chemistry of the solution. This microbially catalyzed S-I reaction took place in the laboratory at room temperature and pressure in 2 weeks, in contrast to the slow abiotic reaction rates in either a laboratory simulation system (250–350 °C, 50–100 MPa, for 4–5 months) (Huang et al. 1993) or in the natural environment (Pevear 1999).

Subsequent experiments under geologically more realistic conditions have expanded these initial results. The presence of organic matter favors microbial mediation of the S-I reaction (Dong et al. 2009). Anaerobic, thermophilic (65–68 °C), metal-reducing bacteria isolated from the deep subsurface were found to have the same ability as mesophilic bacteria in promoting the reaction under favorable conditions (alkaline pH, external supplies of Al and K) (Dong et al. 2009). Even sulfate-reducing bacteria and methanogens are capable of promoting the reaction. These results show that several types of microbes are capable of promoting this important mineral reaction under diagenetic conditions.

All these previous experiments used nontronite to study the role of microbes in the S-I reaction. Nontronite, an iron-rich smectite, is not a typical clay mineral in soils or recent sediments; instead, beidellite and montmorillonite, both iron-poor smectites, are more typical. Nonetheless, these compositions all contain structural Fe, and structural Fe in smectites in general is assumed to behave like Fe in nontronite. Under this assumption, recognition of the microbial role in promoting the S-I reaction is important for multiple reasons. First, this microbially mediated S-I reaction provides an example of the catalytic effect of microbes in mediating certain geological processes; this recognition is in some sense comparable to the discovery of the microbial role in promoting dolomite precipitation (Vasconcelos et al. 1995). Second, the microbially catalyzed S-I reaction provides a physical basis and mechanism for refining the smectite illitization model, with possible implications for petroleum exploration (Huang et al. 1993). Third, when coupled with microbial measurements, this newly recognized model offers an explanation of why the S-I reaction occurs in certain modern sediments under low temperature and pressure (Kim et al. 2004). The microbially catalyzed S-I reaction has even been proposed to have occurred in ancient marine sediments, in which the reduction of structural Fe(III) dissolved smectite and formed biogenic minerals such as quartz, pyrite, and carbonates (Vorhies and Gaines 2009). Fourth, dramatic changes associated with the S-I reaction would significantly affect the physical and chemical properties of soils and sediments; thus, it is important to understand the rate and extent of this reaction when designing strategies for maximizing nutrient retention and minimizing contaminant mobility. Fifth, the illitization of smectite, a major component of bentonite used in radioactive waste disposal, releases water and leads to changes in hydraulic conductivity (Mulligan et al. 2009). This change would have a major effect on the stability of bentonites used for high-level radioactive waste disposal and could potentially result in the failure of waste canisters (Perdrial et al. 2009).

ENVIRONMENTAL APPLICATIONS

Redox-manipulated clay minerals have a wide range of applications. Below, I highlight a few examples for environmental remediation.

Heavy Metal Remediation Using Redox-Manipulated Clay Minerals

There are several mechanisms for the remediation of heavy metals by clay minerals. One classical strategy is adsorption and absorption, which take advantage of the high external
Transmission electron microscope image showing the microbially catalyzed smectite-to-illite reaction. A thick packet of illite layers (each 1.0 nm thick) formed in the matrix of smectite (1.3 nm thick layers). The selected area electron diffraction patterns show a diffuse ring pattern for smectite and discrete Bragg reflections for illite. From Kim et al. (2004), reproduced with permission from the American Association for the Advancement of Science.

and internal surface area of clay minerals. Although this strategy may be effective in the initial removal of heavy metals, it may not be permanent because these inorganic contaminants can be remobilized if the environmental conditions change. Other strategies involve the coprecipitation of metals and radionuclides into clay mineral structures (Brandt et al. 2007). This strategy may be more “permanent” as clay minerals are fairly stable under a wide range of conditions.

A more recent approach is redox manipulation facilitated by microbes. It is assumed that Fe(II) in smectite, possibly produced via the biological reduction of structural Fe(III), reduces oxidized forms of heavy metals, such as Tc(VII), according to the following general reaction (Jaisi et al. 2009):

\[ \text{structural Fe(II)} + \text{Tc(VII)} \rightarrow \text{structural Fe(III)} + \text{Tc(IV)} \, . \]

A number of studies have examined the interactions of clay-associated Fe(II) with heavy metals and radionuclides, including Tc (Jaisi et al. 2009; Bishop et al. 2011), U (Zhang et al. 2009, 2011), and Cr (Taylor et al. 2000). Even when excess Fe(II) is available in an experimental protocol, not all Fe(II) is reactive. Fe(II) reactivity depends on the chemical environment of Fe(II) in clay minerals. For Tc(VII) reduction, Fe(II) in smectite is the most reactive, and Fe(II) in illite the least (Bishop et al. 2011). Differences in surface area, surface charge, layer expandability, and layer charge between smectite and illite are important factors in accounting for this difference (Bishop et al. 2011). For this reason, any transformation of smectite to illite has an adverse effect on metal reduction and immobilization. Conversely, any method to reverse the S-I reaction would be of benefit. Not only does smectite reduce and immobilize Tc(VII), but the reduced Tc(IV) resides inside the mineral matrix, minimizing the potential for remobilization (Jaisi et al. 2009).

Reduced structural Fe(II) in smectite is an effective reductant for Cr(VI) as well. Sorption of Cr(VI) onto a clay mineral surface appears to be a prerequisite for subsequent reduction. Unlike Tc(VII) and Cr(VI), U(VI) reduction by clay-associated Fe(II) is kinetically slow. For some clay minerals, such as nontronite, redox chemistry may favor the oxidation of U(IV) by Fe(III), which is opposite to the direction of the Tc(VII) reduction reaction. Because of the rapid oxidation of U(IV) by structural Fe(III) in nontronite, uranium can serve as an electron shuttle for microbial reduction of structural Fe(III) in chlorite (Zhang et al. 2009), with the implication that Fe(II) in nontronite may not reduce and immobilize U(VI).

**Organic-Contaminant Degradation**

In addition to heavy metal remediation, reduced smectites have been found to be effective in degrading organic compounds, including pesticides, 2,4,6-trinitrotoluene, nitroaromatics, carbon tetrachloride, chlorinated and nitroaliphatic compounds (Stucki and Kostka 2006 and references therein; Fialips et al. 2010). Because reduced smectites remove these compounds from aqueous solution much faster and to a greater extent than their oxidized counterparts (supposed to have similar surface area and adsorption capacity), the removal mechanism appears to be by degradation. The detection of various degradation products further supports such a mechanism.

**Advantages of Microbially Mediated Clay Minerals in Remediating Inorganic and Organic Contaminants**

Coupled with microbial activity, clay minerals exhibit certain properties that can be explored for waste disposal. First, iron-bearing clay minerals help establish the physical/hydrogeological conditions of redox transition zones because of their small size and limited hydraulic conductivity. Because typical clay minerals in soils and sediments, such as smectite, provide a solid-phase reservoir of Fe(III) and Fe(II) (3–5% total iron, with the ferric/ferrous ratio depending on redox state; Stucki 2006), they can buffer the redox conditions through the transition zone and minimize any chance of reoxidizing reduced heavy metals and radionuclides.

Second, because iron redox cycling largely occurs in the solid state, especially when the extent of cycling is small, Fe(III) produced from the reduction of heavy metals or the degradation of organic compounds can be recycled back to Fe(II), generating a renewable source of electrons. Methods have been discovered for the in situ reduction of Fe(III) within soil or sediments by stimulating indigenous Fe-reducing bacteria through the addition of a carbon source and an electron donor, such as ethanol or glucose (Stucki et al. 2007).

Third, because of low permeability and rapid particle agglomeration, clay minerals are ideal matrices to immobilize metals and radionuclides for long-term disposal. Secondary contamination can be minimized because of low oxygen penetration (Jaisi et al. 2009).

**OUTLOOK**

Despite the past 20 years of research, challenges and many unanswered questions still remain. Much of our understanding of microbially mediated clay mineral transformation is qualitative. It is still poorly known to what extent these mineral reactions are mediated by microbial activity in nature. What is the relative importance of abiotic versus biotic effects in mineral evolution? How have clay–microbe interactions evolved through geological history? To what extent do such interactions contribute to ocean chemistry and atmospheric composition?

Our knowledge of microbe–clay interactions is largely derived from laboratory experiments that are greatly simplified relative to what happens in nature. For example, typical bioreduction experiments use pure microbial cultures and pure clay minerals in a defined buffer or medium, mostly at room temperature and pressure, in static batch reactors. However, in nature, microbes exist in communities, and they may cooperate or compete in their interaction with minerals. Furthermore, several clay
minerals may be present, often mixed with various Fe oxides and other silicates. Aqueous media such as groundwater aquifers are often complex, with various types of organic matter present. Natural systems are usually dynamic, with varying rates of flow. How can laboratory-based results be extrapolated to complex field applications? What possible issues are involved in spatial and temporal scaling? These questions are especially relevant to the microbially catalyzed S-I reaction model, as it is not yet clear how widely this model is applicable to the overall picture of clay diagenesis. The laboratory-optimized conditions may be satisfied only in certain geological environments. The lack of these conditions may be the reason why smectite in soils and sediments persists despite the presence of active microbial processes (mostly non-iron-reducing activity). Likewise, illite in modern sediments is mostly derived from the erosion of sedimentary rocks and is not necessarily biogenic in origin. Future studies should focus on the identification of these conditions in natural settings and quantitatively assess the relative importance of the biotic versus abiotic effects on the S-I reaction.

Reduced smectites have shown great promise in contaminant remediation. Although the degradation of organic compounds by reduced smectites has been well established, the application of reduced smectites to heavy metal and radionuclide remediation is at an early stage. How can such a strategy be implemented at the field scale? How do clay mineral redox manipulations impact aquifer porosity and permeability and, subsequently, metal transport behavior? Would clay minerals enhance, rather than retard, metal transport?

As interest in this field is growing, we can anticipate that answers to these questions will be forthcoming. Certainly there are many opportunities and challenges facing researchers who are dedicated to studying clays and microbes. I hope that this review will encourage collaboration among clay mineralogists, soil scientists, microbiologists, and environmental engineers.

ACKNOWLEDGMENTS
I am grateful to the many students and colleagues who have allowed me to share the joy of their discoveries. To Jinwook Kim, Deb Jaisi, Dennis Eberl, Gengxin Zhang, Michael Bishop, Deng Liu, Jennifer Seabaugh, Junjie Yang, Jing Zhang, Timothy Fischer, Linduo Zhao, and others, I extend my thanks for their contributions to this effort. This work was supported by grants from the National Basic Research Program of China (973 Program) (2012CB215505), the National Science Foundation of China (41030211), and the U.S. Department of Energy (DE FG02-07ER64369 and DE-SC0005333). I am grateful to James Drever, Peter Heaney, and an anonymous reviewer, whose comments improved the quality of the manuscript.

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DE-SC0005333). I am grateful to James Drever, Peter Heaney, and an anonymous reviewer, whose comments improved the quality of the manuscript.
Microbial Oxidation of Sulfide Tailings and the Environmental Consequences

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INTRODUCTION

An estimated 1150 million tons of heavy metals (Cu, Pb, Co, Zn, Cd, and Cr) have been mined since the Stone Age (Sheoran and Sheoran 2006). Today, mining activities generate about 5 × 10⁹ tons of mill tailings per year worldwide. Sulfide tailings are the main source of heavy metal contamination in the areas around polymetallic mining sites, especially in rapidly developing countries where environmental remediation has not been thoroughly implemented. Tailings are the fine-grained waste produced from ore processing involving crushing, grinding, milling, and chemical flotation. They are generally disposed of in impoundments or ponds (Fig. 1). The mineralogy and chemistry of tailings depend on the ore type, the mineral-processing technology used, and weathering processes (Jamieson 2011). As the extracted metals make up only a small fraction of the whole ore, more than 90% of the ore eventually becomes tailings. Sulfide minerals are usually the main heavy metal-bearing components in tailings. Other unwanted minerals include silicates, oxides, hydroxides, and carbonates (Lottermoser 2007). The types of silicate minerals and metallic oxides vary among different ore types. Silicate minerals are generally stable during oxidation and can remain in tailings. When exposed to air, sulfides are oxidized chemically and microbially into sulfates (e.g. gypsum and jarosite), iron oxides, and iron hydroxides (e.g. goethite and ferrihydrite), while carbonates totally disappear. Sulfide oxidation can be described simply as an acid-producing process accompanied by precipitation of various hydrous ferric oxides and sulfates (Nordstrom 2011; Southam 2012 this issue).

The oxidation of sulfides in tailings results in environmentally detrimental acid mine drainage (AMD) and decreases the pH value of pore water to around 2.0. At Iron Mountain, California, the pH of AMD is even as low as ~3.5 (Nordstrom 2011). With the aid of bacteria, such acidic water can easily leach heavy metals from fresh tailings. The metals can then be transported into soils and streams or filtered down into groundwater, thus posing a threat to the environment.

Despite the low pH and high metal concentrations, AMD and the surface portion of tailings can harbor special microbial communities. Since the first isolation of a sulfur-oxidizing bacterium from ores in 1902 by Nathanson, numerous microorganisms have been isolated. These microorganisms have developed various tolerance mechanisms to survive in such harsh environments. Although their abundance is low, microbial communities can be diverse and include archaea, bacteria, yeasts, and fungi (Nordstrom 2011). Most of the archaea and bacteria are autotrophic as they can obtain their carbon needs from CO₂ in the environment and fulfill their energy needs by oxidizing sulfides in tailings. The largest concentration of bacteria (10⁹ cells g⁻¹ dry weight of tailings at the La Andina copper mine, Chile)

Keywords: tailings, heavy metals, sulfide, microbial oxidation, secondary mineral

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has been reported at the bottom of the surface oxidation zone of tailings, where iron- and sulfur-oxidizing microorganisms are dominant (Diaby et al. 2007).

Fe(III)− and sulfate-reducing bacteria have also been found in tailings under anoxic to suboxic and acidic conditions. In general, Desulfobulbus spp. and the combined group Desulfosarcina–Desulfococcus are the most important sulfate-reducing bacteria. They can reduce sulfate into reduced S (e.g. H₂S or elemental sulfur). Their abundance and activity vary greatly with the seasons as a result of fluctuating physicochemical conditions (temperature, pH, organic carbon availability, etc.). For example, below the oxic−anoxic interface in a Pb−Zn dammed tailings pond (15−20 cm below the surface), the absolute abundance of sulfate-reducing bacteria increases in summer, possibly due to high temperature and high labile carbon availability, but their reductive activity does not always follow the same trend (Praharaj and Fortin 2008). The mechanism of this phenomenon remains unclear. Dissimilatory iron-reducing bacteria are a group of reductive bacteria that can reduce Fe(III) to Fe(II) and concomitantly oxidize low-molecular-weight organic matter. To date, little is known about the activity of these bacteria in mine tailings, although geochemical evidence indicates that they may be active. The activity of iron-reducing bacteria exhibits an inverse relationship to the activity of sulfate-reducing bacteria due to their competition for common electron donors (Praharaj and Fortin 2008). At present, the spatial distribution and geochemical roles of iron-reducing bacteria are not fully understood and merit further study.

**ROLES OF MICROORGANISMS IN THE TRANSFORMATION OF HEAVY METALS**

**Physicochemical Conditions in Tailings Impoundments**

The physicochemical conditions within tailings may change remarkably over time. Generally, the shallow part (less than 15−20 cm below the surface) of the tailings is commonly the active oxidation zone, where secondary minerals (e.g. goethite, jarosite, and gypsum) form. The heavy metals bound in sulfides may be either released into pore water or sequestered by secondary minerals via adsorption or coprecipitation. In this zone, the pore water is often acidic (pH <4.0, generally), and autotrophic (i.e. capable of fixing inorganic carbon to organic carbon), oxidizing bacteria prevail in its microbial community. In contrast, in the reduction zone in the deep part (normally more than 5−6 m below the surface) of the tailings, where the pore water becomes slightly alkaline due to alkalinity-producing reduction reactions (Southam 2012), dissimilatory iron-reducing bacteria and sulfate-reducing bacteria become dominant. Microbial reduction of sulfate and Fe³⁺ is the main geochemical process, and thus sulfides [e.g. pyrite, mackinawite (Fe₇S₈)] and siderite are usually detected here. The transition zone, sandwiched between the oxidation and reduction zones, is the most active region and normally lies near the water table. The depth of the transition zone varies with the season, rainfall amount, and local climate. In arid regions, the transition zone is often deeper, whereas in humid regions it tends to be shallower. In addition, the content of organic matter in tailings may also affect the depth of the transition zone because the decomposition of organic matter generally consumes oxygen (Lottermoser 2007).

**Microbial Oxidation in the Top Portion of Sulfide Tailings**

The oxidation of metal-containing sulfides restricts the mobility of heavy metals in near-surface tailings. Microbes can accelerate the oxidation of sulfide by an average of 34 times relative to the abiotic rate ( Olson 1991). Although the total dissolution rates of sulfides vary considerably with oxygen content, pH, the available surface area, and the type of sulfide mineral, cell-normalized dissolution rates cluster more tightly, ranging from 2x10⁻⁴ to 6x10⁻² μM Fe cell⁻¹ day⁻¹ ( Edwards et al. 2000). Adhesion and biofilm formation are the key factors for microbial oxidation of sulfides. Bacteria preferentially attach to poorly crystallized minerals or minerals with defects or fractures. Such adhesion can form an interfacial microenvironment between the outer membrane of a bacterial cell and the surface of a sulfide mineral. Extracellular polymeric substances secreted by bacteria can enhance the surface corrosion of sulfides and heavy metal release by various metabolism-related reactions and chelation effects ( Röhrwerder et al. 2003).

Different shapes of etch pits can be observed on microbially oxidized surfaces of sulfides in laboratory experiments, including isolated, ditch-like, and branch-like pits. The sizes of the ditch-like and branch-like etch pits are normally larger than those of bacterial cells (Fig. 2). In contrast, no such etch pits were observed on the surfaces of sulfides exposed to H₂SO₄ solutions with pH ranging from 2.0 to 3.0 ( Lu et al. 2006). Thus, these irregular pits are interpreted as being the result of microbial oxidation of sulfides.

Three mechanisms for microbial oxidation of sulfides have been proposed: indirect leaching, contact leaching, and cooperative (symbiotic) leaching (Tributsch 2001) (Fig. 3a). In the indirect-leaching mechanism, bacteria only oxidize...
Fe²⁺ in solution to Fe³⁺, which can subsequently oxidize the sulfur in sulfides. Fe³⁺ can also oxidize disulfide and monosulfide to thiosulfate and polysulfide, respectively (Schippers and Sand 1999). In the contact mechanism, electrostatic force drives the attachment of bacterial cells to the sulfide surface (Rohwerder et al. 2003). After attachment, uronic acid residues containing Fe(III) on the attached cell surface facilitate the decomposition of sulfide, which results in the formation of etch pits. In cooperative (symbiotic) leaching, bacteria in the surrounding electrolytes may obtain nutrients from soluble and particulate sulfide produced by contact leaching and, in turn, assist the leaching process (Rohwerder et al. 2003). In a bioleaching experiment using Acidithiobacillus ferrooxidans, two types of corrosion pits were observed on the (100) surface of biooxidized pyrite: round or rhombic deep holes and rod-shaped shallow pits similar to the shape of bacterial cells (Fig. 3b). The rod-shaped pits are thought to be the result of pyrite oxidation by attached bacterial cells. The deep holes are similar to those observed on abiotically leached (100) and (110) surfaces by ferric ions (Ndlovu and Monhemius 2005). These isolated deep holes are believed to result from the oxidation of pyrite by ferric ions derived from microbial oxidation reactions.

**Microbial Reduction Reactions in Deep Zones**

Dissimilatory iron-reducing bacteria and sulfate-reducing bacteria are important members of microbial communities in deep zones of tailings impoundments. Sulfate-reducing bacteria can reduce dissolved or solid forms of sulfur (e.g. gypsum, jarosite, etc.) and produce H₂S, and thus subsequently precipitate dissolved metals (especially iron, copper, and zinc) as sulfides (Southam 2012). Dissimilatory iron-reducing bacteria can reduce ferric ions by coupling oxidation of organic compounds or hydrogen; this mechanism typically results in the formation of soluble Fe⁴⁺ complexes and various Fe³⁺-bearing phases, including magnetite (Fe₃O₄), siderite (FeCO₃), vivianite [Fe₃(PO₄)₂·6H₂O], and green rust ([Fe₂⁺Fe³⁺₂⁺(OH)₁₂](CO₃⁻[H₂O]₂·2H₂O)). Meanwhile, the adsorbed metalloid elements (e.g. arsenic) on iron (oxy)hydroxides are released. Iron-reducing bacteria transfer electrons to Fe(III) (oxy)hydroxides and oxides via Fe³⁺ reductases, conductive extracellular appendages, and dissolved humic substances serving as electron shuttles (Roden et al. 2010). Besides Fe(III), U(VI), Cr(VI), As(V), and other heavy metals may also be utilized by some species of dissimilatory iron-reducing bacteria as electron acceptors (Cheng et al. 2012 this issue).
[PbFe₆(SO₄)₄(OH)₁₂] due to the microbial oxidation of galena (Romero et al. 2010). In the acid discharge of the abandoned Monte Romero mine (Iberian Pyrite Belt, southwestern Spain), the precipitation of schwertmannite was responsible for the removal of more than half the arsenic load from solution within a few hours (Acero et al. 2006). When aged for 353 days with its coexisting acidic water in the lab, schwertmannite was transformed into goethite plus H₃O-jarosite during the first 164 days, and subsequently into pure goethite. Coincident with this mineral transformation was the depletion of Al, Cu, Pb, and As in the solution (Acero et al. 2006). Unfortunately, hardpan cannot stabilize heavy metals permanently, as adsorbed heavy metals can be leached out during natural flooding events.

Transformation of Secondary Minerals and the Fate of Heavy Metals

Biogenic ferric hydroxide, oxides, and hydroxysulfates in the top portion of the sulfide tailings will undergo further microbial reduction or dissolution under anaerobic conditions or other important environmental changes. Sulfate in schwertmannite can be reduced by sulfate-reducing bacteria under anaerobic conditions within two weeks, and at the same time greigite (Fe₃S₄) can be formed from the available Fe²⁺ (Gramp et al. 2009). Furthermore, chemical or microbial dissolution of secondary minerals can remobilize the heavy metals initially either adsorbed on or coprecipitated with them and result in the formation of new minerals. For example, during the dissolution of plumbojarosite under acidic and alkaline conditions, Pb can be remobilized, and the released Pb can be scavenged by the formation of PbSO₄. It has also been confirmed that the

Figure 4 Scanning electron micrographs of As-bearing minerals (indicated by arrows) in a hardpan at the Shizishan Cu–Au mine, Tongling, eastern China. (A) Scorodite (FeAsO₄·2H₂O), (B) cafarsite [Ca₉(Fe²⁺, Fe³⁺)₆-7(AsO₃)₁₂·2(H₂O)], (C) arsenolite (As₂O₃), and (D) As-adsorbed goethite, in which the content of As is as high as 2.59%, as indicated by energy dispersive X-ray spectrometer analysis.

Figure 5 (A) Iron hardpan-covered surface of a closed tailings impoundment in the Shizishan Cu–Au mine, Tongling, eastern China. (B, C, D) False-color micro-X-ray fluorescence maps showing the qualitative distribution of As(III), As(V), and Fe(III) in an Fe oxyhydroxide particle isolated from the hardpan shown in (A). The color change from blue, green, and yellow to red represents an increase in elemental concentration. This analysis was carried out at the Shanghai Synchrotron Radiation Facility.
Ag bioreduced from silver jarosite at neutral pH by *Shewanella putrefaciens* VN32 is precipitated as nanoparticles within the cell structures and on adjacent mineral grains (Weisener et al. 2008). These newly formed minerals, especially sulfides, will stabilize the heavy metals as long as oxygen is absent (Southam 2012). Desorption and transport of As(III) and As(V) adsorbed on iron hydroxides in tailings caused by microbial reduction also occurs. However, the released arsenic can be readsobered onto reduced Fe(II) phases (e.g. hydroxycarbonate green rust) (Herbel and Fendorf 2006).

It is notable that mineral transformation is closely related to environmental changes, such as temperature, pH, redox conditions, and the presence of microbes. Biogenic schwertmanite can be aerobically transformed to jarosite at elevated temperature and elevated monococation (NH$_4$)$_2$SO$_4$ concentration (Wang et al. 2006). The transformation of schwertmanite to goethite can be enhanced by increased pH, but inhibited by the presence of sulfate (20 mM) and dissolved organic matter (20 mg L$^{-1}$) (Knorr and Blodau 2007). Recently, an Fe(II)-catalyzed pathway for schwertmanite transformation under anaerobic conditions was reported in both the lab and the field (Burton et al. 2008). At pH >5, Fe(II) enhanced the rate of transformation of schwertmanite to goethite by several orders of magnitude. At pH >6, Fe(II)$_{aq}$ (≤5 mM) caused complete transformation of schwertmanite to goethite in only three to five hours (Burton et al. 2008).

**ENVIRONMENTAL TREATMENTS**

**On-Site Treatment with Inhibitors**

Since the release of heavy metals due to sulfide oxidation in tailings can cause serious environmental problems, decreasing the mobility (stabilization) of heavy metals is the main strategy for AMD treatment related to tailings disposal. Many studies have concluded the use of bactericides to prevent microbial oxidation of sulfides. For example, various anionic surfactants and food preservatives have been tested in the field to suppress the direct contact between microorganisms and minerals and thus inhibit the growth of Fe- or S-oxidizing bacteria (Kleinnmann 1999). Alkyl benzene sulfonates are considered the most cost-effective and reliable inhibitors. Bacteria living in extremely acidic environments generally possess a multi-layered cell wall, which allows them to maintain an approximately neutral internal pH. Anionic surfactants at low concentration can damage the cell wall, which allows hydrogen ions to enter the cell, slows down Fe(II) oxidation, and may even cause destruction of the bacterium (Kleinnmann 1999). However, the use of bactericides is only a short-term solution and might cause other unexpected environmental risks, such as the development of resistance of oxidizing bacteria to these surfactants and toxicity to other microorganisms.

The addition of natural materials into the tailings to induce changes in the microbial community might be an environment-friendly and long-term treatment of tailings. By generating H$_2$S, S$_2$, Fe$^{2+}$, and/or other metal ions, both sulfate-reducing bacteria and dissimilatory iron-reducing bacteria play an important role in sulfide formation and have great potential for immobilizing metals. A strategy to promote the growth of sulfate-reducing bacteria and dissimilatory iron-reducing bacteria in tailings has been proposed for environmental and ecological bioremediation (Nancucheo and Johnson 2011). The addition of straw to tailings can produce efficient sulfate reduction and thus favor the immobilization of heavy metals. A field-scale experiment monitored for four years indicated that the amendment of tailings with a small and dispersed mass of organic carbon can result in remarkable decreases in Zn, Sb, As, and Tl concentrations in pore water and in the precipitation of Fe–S and Zn–Fe–S phases (Lindsay et al. 2009).

**Constructed Wetlands for Downstream Treatment**

The construction of anaerobic wetlands by introducing organic waste into the wetlands is another low-cost strategy for the remediation of heavy metal contamination. Constructed wetlands are complex systems in which biological, chemical, and physical processes interact to remove contaminants from AMD and from the lateral drainage from the bottoms of tailing impoundments. The wetlands can absorb or bind the heavy metals from the effluent and immobilize them in the sediments (Sheoran and Sheoran 2006). The mechanism of heavy metal removal is complex, involving adsorption, precipitation and coprecipitation, oxidation and reduction reactions, and biosorption. Precipitations of sulfides, hydroxides, and carbonates are the predominant mechanisms. The most important processes are the bacterial and chemical sulfate-reduction reactions, in which H$_2$S, CO$_3^{2-}$, and HCO$_3^-$ are produced to sequester heavy metals by mineral precipitation (Konhauser et al. 2011; Southam 2012). Normally, the activity of sulfate-reducing bacteria is a rate-limiting factor. As two moles of carbon are consumed to reduce each mole of sulfate, a sustainable carbon supply is necessary to maintain the removal capability of a constructed wetland (Sheoran and Sheoran 2006). In environments with slightly acidic to neutral pH, adsorption of dissolved metals onto organic substrates and minerals is another important mechanism for immobilizing toxic metals. Whitehead and Prior (2005) found that a wetland for treating AMD in England removed 55–92% of Fe and reduced the concentrations of target metals, such as Cd, Cu, and Zn, to below detection limits. The sediments can retain metals continuously and release them into the water only when the environmental conditions are drastically changed. In practice, it is possible to obtain long-term, successful performance from wetlands. For example, a natural wetland outside an abandoned lead–zinc mine in Ireland has apparently been functioning unattended for over 120 years (Sheoran and Sheoran 2006).

**CONCLUSIONS**

At nearly every metal mine site, large volumes of sulfide-containing tailings are being discharged and disposed of in impoundments or ponds. The chemical and microbial oxidation of residual sulfides in tailings produces acid mine drainage or sulfate- and metal-rich pore water and results in the release of heavy metals. These metals may be discharged into surface water and groundwater systems or be precipitated in secondary minerals. Various microbe-mineral interactions, such as bacteria-mediated oxidation of sulfides and microbial reduction of sulfate and iron oxides/oxyhydroxides, occur in tailings impoundments. Secondary minerals can play an essential role in the natural attenuation of heavy metals via adsorption or coprecipitation, as long as the redox and pH conditions are maintained. To mitigate the negative impacts of mining activities, a variety of passive treatments, such as the construction of wetlands and the use of bactericides, have been proposed and applied. But the permanent fixation of heavy metals in tailings is still a challenging problem.

The huge environmental problems caused by the increasing volume of tailings stimulate the development of new remediation technologies and the improvement of existing techniques, especially bioremediation treatments. For
example, an alternative to inhibiting the oxidation of sulfides in tailings is to promote the biooxidation and release of heavy metals by regulating the local microorganism community, allowing us to obtain a metal-enriched solution. Another strategy is to backfill tailings into underground mine workings. Backfilling into an anoxic environment can prevent the contact of sulfide with oxygen and oxidizing bacteria, thus suppressing heavy metal release. But the most important alternative is to put tailings to good use by applying recycling technologies, as is done in the production of ceramics, building materials, and so on.

ACKNOWLEDGMENTS

We thank guest editors Hailiang Dong and Anhui Lu for inviting this contribution. The editors and anonymous reviewers made many beneficial comments and suggestions. We appreciate financial support from the National Basic Research Program of China (program no. 2007CB815603, 2007CB815601) and the National Natural Science Foundation of China (grant nos. 40930742, 41072253, and 10979018).

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Interactions between Semiconducting Minerals and Bacteria under Light

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A synergistic reaction pathway has been identified between semiconducting minerals and bacteria. Such reactions sustain electron and energy flow from light to nonphototrophic bacteria via semiconducting minerals, which act as a catalytic shuttle. Understanding this pathway may shed light on a unique ecosystem that potentially carries out phototrophic metabolism without the involvement of phototrophic organisms. Four key natural elements of this system are sunlight, semiconducting minerals, nonphototrophic bacteria, and water. This pathway also suggests a “self-cleansing” mechanism that may exist in nature, whereby both oxidative and reductive degradation of contaminants can occur.

**Keywords:** bioelectrochemical processes, environmental remediation, nonphototrophic bacteria, semiconducting minerals, photocatalysis

**INTRODUCTION**

Microbial activity in the environment is governed by several different metabolic pathways that provide energy to microbial cells. In general, the mechanism of these metabolic pathways involves microbes, such as bacteria, oxidizing organic or inorganic compounds (electron donors) to acquire electrons. These electrons are transferred to other compounds or elements (terminal electron acceptors), resulting in reduction. The type of compounds or elements that donate or accept electrons is determined by the species of microorganisms and the environmental conditions. In aerobic environments, dissolved oxygen serves as the electron acceptor. In anaerobic environments, other dissolved compounds or elements are utilized as electron acceptors, such as nitrate, sulfate, Fe(III), and Mn(IV). Most bacteria rely on dissolved electron acceptors, although certain species can use electron acceptors in solid phases.

Insoluble minerals containing elements sensitive to oxidation and reduction (redox) reactions, such as iron [Fe(III)] and manganese [Mn(IV)], can serve as terminal electron acceptors to support the growth of certain bacteria living in anaerobic environments (e.g. *Shewanella* spp., *Geobacter* spp.) (Moser and Nealson 1996; Lovley et al. 2004). Bacterial transfer of electrons to solid minerals can take many forms, including the formation of conductive “nanowires” (Reguera et al. 2005), direct cell-mineral contact via outer-membrane cytochromes (Arnold et al. 1988; Lower et al. 2001), and production of soluble redox-active shuttles (compounds that facilitate electron transfer from cells to electron acceptors) (Newman and Kolter 2000). Bacteria that can carry out diverse extracellular (outside the cell wall) electron-transfer processes have been used for many practical purposes, such as the remediation of organic, radionuclide, and toxic metal contaminants (Lovley 2006; Fredrickson and Zachara 2008). These applied studies have in turn helped scientists find additional mechanisms of extracellular electron transfer.

Microbial populations have the capability to adapt rapidly to environmental changes, as exemplified by bacteria that use several different electron acceptors and/or donors under different environmental conditions (Moser and Nealson 1996; Lovley et al. 2004; Nielsen et al. 2010). In complex environments, microorganisms are able to obtain energy resources by operating multiple strategies simultaneously. Considering such physiological flexibility, the probability of finding alternative pathways linking minerals and microbes is high. One such pathway is the capture of solar energy by nonphototrophic microorganisms with semiconducting minerals as mediators.

Semiconducting minerals, the characteristics of which are described below, are a unique but widely distributed class of minerals in nature. They play critical roles in near-surface geological processes, including the formation of prebiotic organic molecules (Schoonen et al. 2004). Photocatalysis involving semiconducting minerals can control the availability of electrons in the environment, thereby affecting, both directly and indirectly, many redox-based geochemical and biogeochemical processes. The surfaces of semiconducting minerals are, therefore, a very important site for natural redox reactions (Rosso 2001).

The diversity of microorganisms that are able to use a wide range of substances, including minerals, as electron donors or acceptors has led to speculation that extracellular electron transfer between nonphototrophic microbes (microbes that do not use light in their metabolisms) and minerals in the presence of light may be occurring through some pathways that may have been overlooked previously. In this regard, semiconducting minerals are of particular interest due to their multiple roles in harnessing sunlight, exciting electrons, and creating holes on their surfaces that support both oxidative and reductive reactions in micro-environments (Li et al. 2009; Lu et al. 2010).

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The principal goal of this paper is to demonstrate a possible long-existing yet previously unidentified mechanism that involves integrated reactions among solar energy, semiconducting minerals, nonphototrophic microorganisms, and water. The role of each constituent and the potential energy flow in the form of electron transfer are considered, although they are not yet fully understood. We shall also discuss the practical applications of this interactive pathway. However, the long-term impact of such a mechanism in the environment and its application to solving contemporary environmental contamination problems remain to be determined.

**NATURAL SEMICONDUCTING MINERALS**

Semiconducting minerals have a distinctive electronic structure characterized by a filled valence band (VB) and an empty conduction band (CB). The valence band electrons can be excited to the conduction band upon absorption of photons with energy equivalent to or higher than the band gap ($E_g$), which is the energy difference between the top of the VB and the bottom of the CB (Fig. 1a). This process yields negatively charged electrons and positively charged holes in the CB and VB, respectively. These electron–hole pairs then migrate to the semiconductor–solution interface to induce redox reactions (photocatalysis) (Serpone and Salinaro 1999; Fig. 1a). In effect, semiconducting minerals can serve as electron conduits for redox reactions.

There are hundreds of semiconducting minerals on Earth, some of which are common phases near the Earth’s surface: Fe and Mn oxides [e.g. hematite ($\text{Fe}_2\text{O}_3$), goethite ($\text{FeOOH}$), pyrolusite ($\text{MnO}_2$)], other oxides [e.g. rutile ($\text{TiO}_2$), ilmenite ($\text{FeTiO}_3$)], and sulfides [e.g. sphalerite ($\text{ZnS}$), pyrite ($\text{FeS}_2$), chalcopyrite ($\text{CuFeS}_2$)]. The band structure, structural defects, and other physical characteristics of natural semiconducting minerals were systematically studied in the 1970s (Shuey 1975). Xu and Schoonen (2000) compiled the absolute energy positions of conduction band and valence band edges for about 50 semiconducting metal oxide and metal sulfide minerals. Based on their work, we know that impurities and defects, such as substituting ions, interstitial ions or atoms, and vacancies, result in major changes in the electronic structures of semiconducting minerals. In most cases, the band gap of a natural semiconducting mineral is narrower than its synthetic “pure” counterpart, which makes it more susceptible to excitation when exposed to visible light, thereby generating electron–hole pairs.

Semiconducting minerals have been identified as photocatalysts of redox reactions in natural environments (Xu and Schoonen 2000; Schoonen et al. 2004; Zhang et al. 2004) and have been studied in engineered systems designed to degrade hazardous chemicals, such as halohydrocarbons and azo dyes (Lu et al. 2004; Lu et al. 2007; Li et al. 2008; Yang et al. 2011). Photocatalysis by semiconducting minerals under natural conditions and in industrial applications warrants further exploration due to its fundamental and applied significance.

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**Figure 1**  
(A) A scheme of semiconductor photocatalysis.  
(B) Two hypothesized synergistic pathways between semiconducting minerals and microorganisms. The orange line represents electron transfer from minerals to microorganisms, while the blue line represents an alternative pathway of electron transfer from microorganisms to minerals. Direct transfer is shown by solid lines, and indirect transfer is shown by dotted lines.  
(C) Scheme of a device to investigate semiconducting mineral–microorganism synergistic actions.  
(D) View of a lab-scale device. CB = conduction band, $E_g$ = band gap energy, $e^-$ = electron, $h\nu$ = radiation energy, $h^+$ = positively charged hole, LUMO = lowest unoccupied molecular orbital, HOMO = highest occupied molecular orbital, PEM = proton-exchange membrane, which allows the migration of protons ($H^+$) between the anodic chamber and the cathodic chamber, VB = valence band.
**SYNERGISTIC PATHWAY BETWEEN SEMICONDUCTING MINERALS AND MICROORGANISMS**

**Photoelectrochemical Systems**

The lifetime of photogenerated electron–hole pairs is very short (<10^{-12} s) during photocatalysis. The electron–hole pairs rapidly recombine and dissipate the absorbed solar energy as heat, which disrupts electron transfer pathways and reduces the photocatalytic efficiency (Linsebigler et al. 1995). Based on natural photosynthesis, separation of the photoinduced electrons from holes favors the subsequent catalytic redox processes and improves the photocatalytic efficiency (Linsebigler et al. 1995). In order to achieve this improved efficiency, the holes involved in catalytic oxidation and the electrons involved in catalytic reduction need to be physically separated. In pioneering work, Fujishima and Honda (1972) used a photoelectrochemical system for water “splitting” in which the photogenerated electrons on a UV-irradiated titanium oxide anode move through an external electrical circuit to a platinum cathode, allowing the generation of O_{2} and H_{2} at the anode and cathode, respectively.

**Bioelectrochemical Systems**

Bioelectrochemical systems are an emerging technology that utilizes microorganisms and solid electrodes to catalyze oxidative reactions at an anode or reductive reactions at a cathode (e.g. Rabaey et al. 2007). The operation of a bioelectrochemical system generally requires the presence of a primary electron donor (the substrate) at the anode and a terminal electron acceptor at the cathode. So, two half-cell reactions (oxidation of an electron donor and reduction of an electron acceptor) are physically separated at two electrodes and catalyzed by microbial or abiotic species. One of the most widely studied types of bioelectrochemical systems is the microbial fuel cell (MFC). In an MFC, microorganisms serve as bioelectrocatalysts to extract electrons through biodegradation of substrates (electron donors); they then transfer the electrons through a circuit containing a solid-state anode to a cathode exposed to a terminal electron acceptor (e.g. oxygen).

**Coupling a Photoelectrochemical Half-Reaction with a Bioelectrochemical Half-Reaction in an Integrated System**

Theoretically, any anodic reaction can be coupled to a cathodic reaction to form an electrochemical system by combining a photocatalytic half-reaction with a biocatalytic half-reaction. The physical separation of the two catalytic reactions at a photocatalyzed anode (photoanode) and at a biocatalyzed cathode (biocathode), or at a biocatalyzed anode (bioanode) and at a photocatalyzed cathode (photocathode), would allow each half-reaction to be optimized independently. The efficiencies of the two reactions can be improved by suppressing the recombination of photogenerated electron–hole pairs and accelerating the electron-energy turnover for microbial metabolism. Such a system is illustrated in Fig. 1b, in which semiconducting minerals and bacteria are integrated into a photobio-catalytic system. As an example, a semiconducting mineral is utilized as the photoanode to catalyze electron transfer from the primary electron donor to a circuit, and then the bacteria on the biocathode catalyze electron transfer from the circuit to the terminal electron acceptor (see pathway 1 in Fig. 1b). Alternatively, electron transport from a bioanode to a photocathode represents a synergistic pathway linking microorganisms and minerals (see pathway 2 in Fig. 1b). A laboratory system based on the design shown in Figure 1c can be used to understand the synergies between semiconducting minerals and microorganisms in the natural environment. An example of a laboratory system is shown in Figure 1b, where a xenon lamp simulates solar irradiation on the mineral surface and provides the energy to drive the overall reaction.

**SEMICONDUCTING MINERALS STIMULATE GROWTH OF NONPHOTOTROPHIC BACTERIA**

Organisms known to harness energy from solar radiation have thus far been limited to the phototrophs that use light as their energy source and CO_{2} as their carbon source. Nonphototrophic microorganisms, such as chemolithoautotrophs (bacteria that use inorganic compounds or elements for energy and CO_{2} as a carbon source) and chemoorganotrophs (bacteria that use organic compounds both for energy and as a carbon source), lack photosensitive cellular constituents. These organisms also lack the metabolic pathways within their cells to convert light energy into organic macromolecules. However, this deficiency does not necessarily prevent them from deriving energy from sunlight through inorganic mediators such as semiconducting minerals. Semiconducting mineral–mediated energy transfer from photons to electrons (Fig. 1c) provides just such a possibility for nonphototrophs to acquire solar energy indirectly. For example, a photoactive semiconducting material (e.g. rutile) used as a photoanode can stimulate the growth of chemolithoautotrophs at a cathode when the photoanode is irradiated by a light source. Based on the preliminary results reported by Lu et al. (2012), Fe^{3+} at a cathode was reduced to Fe^{2+}, which, in turn was reoxidized to Fe^{3+} by the chemolithoautotroph Acidithiobacillus ferrooxidans. The light-induced photocatalysis of natural rutile resulted in rapid growth of A. ferrooxidans, with concomitant oxidation of Fe^{2+} (Fig. 2a). A positive correlation between net cell growth and the number of photoelectrons transferred was also observed (Fig. 2a), and microbial growth closely corresponded to the light absorption spectrum of rutile (Fig. 2c, d). In this system, solar energy is converted by rutile photocatalysis and stored in the form of electrons in chemical bonds, thus enabling the recycling of the soluble redox-active carrier Fe^{2+}–Fe^{3+} to support the growth of A. ferrooxidans (Fig. 2a). A separate test, in which a simulated-sunlight source (xenon lamp) was used to excite mineral photocatalysis and generate photoelectrons at the anode, yielded an increased population of the chemoorganotroph Alcaligenes faecalis at the cathode (Lu et al. 2012).

Nonphototrophic microorganisms have been found in a number of extreme environments, ranging from the driest desert (Dong and Yu 2007) to very acidic systems (Baker and Banfield 2003). In these environments, organic matter is usually scarce and generally produced by certain chemolithoautotrophic microorganisms; however, semiconducting minerals, such as metal sulfides and metal oxides, are abundant (Baker and Banfield 2003). Under such conditions, mineral photocatalysis could be an important energy-yielding pathway to sustain nonphototrophic bacteria.

**SYNERGISM BETWEEN MICROORGANISMS AND SEMICONDUCTING MINERALS IN ENVIRONMENTAL REMEDIATION**

The development of bioelectrochemical systems for the in situ remediation of contaminated materials (e.g. wastewater, soils, sediments) exploits the biodegradation potential of bacteria to extract electrons by oxidizing organic pollutants, which act as electron donors, and transferring those electrons to a terminal electron acceptor through a
man-made circuit. Since oxygen is the most thermodynamically favorable electron acceptor, bioelectrochemical systems have been employed to indirectly facilitate the transport of electrons from an otherwise anaerobic environment to oxygen and achieve enhanced biodegradation of a variety of environmental contaminants, such as phenol (Luo et al. 2009), petroleum hydrocarbons (Morris et al. 2009a), and domestic wastewater (Liu and Logan 2004). The energy potentials of electrons are gradually decreased along the electron-transport chain, which thermodynamically limits the electron acceptors. From an environmental perspective, in most bioelectrochemical system technologies, such as MFCs, either an oxidative or a reductive reaction is used in treating contaminants. For example, the anode of an MFC was used by Morris et al. (2009a) to enhance the degradation of petroleum hydrocarbons through microbially mediated (biocatalytic) oxidation, while the cathode served to close the MFC circuit, acting as the destination for electrons and protons to reduce oxygen and produce water ($O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$). In other studies, the cathodic chamber of an MFC system was used to release electrons and reduce compounds of higher oxidizing potential (e.g. nitrate, trichloroethene), while the anodic chamber collected electrons to complete the circuit (Morris et al. 2009b; Jin and Fallgren 2009).

As illustrated in Figure 1b, electrons released from the microbial oxidation of substrates could also be transferred to a solid conductor and then to photoexcited semiconducting minerals if the redox potential presented by the microorganisms matches the band edge positions of the semiconducting minerals. This would allow solar energy to provide additional potential to drive the overall electron-transport process, therefore enhancing the reaction rates. In a system in which natural rutile was used as the cathode material, a significant enhancement of electron-transfer efficiency was observed, as well as improvements in efficiencies of Cr(VI) reduction (Li et al. 2009) and azo dye degradation (Ding et al. 2010). As illustrated in Figure 3a, the characteristic absorption peak of a model azo dye, methyl orange (MO), disappears after being placed in a synergistic system, and less MO is degraded if microorganisms are absent or if there is no rutile photocatalysis (Ding et al. 2010). As a result of the enhanced electron transfer from the photocathode to the terminal electron acceptors, the anodic oxidation kinetics is also improved due to an “electron hunger effect” imposed on the anodic microorganisms. Because the electrode competes for electrons that are released from the microbial oxidation of substrates, microbes are deprived of those electrons that flow to the electrode and the subsequent conductive circuit. The
photocatalysis of cathodic reactions creates a feedback effect on the anodic bacteria that can help promote the biodegradation of organic substrates and the substantial development of cellular conductive mechanisms, such as protein- or flagella-based conductors (i.e. “nanowire-like materials”) (Fig. 3b). In another example, the COD (chemical oxygen demand, an indicator of the mass of oxygen consumed during the oxidation of organic material) in the bioanodic chamber exposed to light was shown to be more than 3.5 times greater than in the dark (Li et al. 2010; Fig. 3a). In summary, the synergistic cooperation of anodic biocatalysts and cathodic semiconducting minerals and the subsequent photobiocatalytic processes tend to be neglected. In the rutile–A. ferrooxidans system (as previously described), the photon-to-biomass conversion efficiency is in the range of 0.13–1.90‰ (Fig. 4) (Lu et al. 2012), suggesting that such light-induced microbial growth is an inefficient process, at least under controlled laboratory conditions. Schoonen et al. (2004) stated that “a tree with one leaf may still be engaged in photosynthesis, but its yield is small since it can capture only a small amount of light.” Thanks to the abundance of both naturally occurring minerals and microorganisms, semiconducting-mineral photocalysis can still yield a substantial number of photoelectrons and cause observable impacts on nonphototrophic organisms over time, despite the presumed low efficiency of the process. Theoretically, we believe such a pathway may benefit a certain number of nonphototrophic microorganisms.

Although the mechanisms involved in the proposed biogeo-catalytic pathway are not fully understood, we have initiated practical applications of such a synergistic system in environmental remediation by establishing systems containing both biocatalysis and photocatalysis (e.g. Li et al. 2009, 2010). Future research should focus on investi-
gating the semiconducting mineral–oriented electrons in microbial metabolism and the genetic regulatory mechanisms that might be involved, as well as the regulation of energy distribution between semiconducting minerals and microorganisms to accomplish a desired reaction.

REFERENCES

ACKNOWLEDGMENTS
Financial support for this study was provided by the National Basic Research Program of China (973 Program) (2007CB815602). We thank Patricia J. S. Colberg, James Drever, Hailiang Dong, and Paul H. Fallgren for their editorial assistance.

Drever, Hailiang Dong, and Paul H. Fallgren for their editorial assistance.
FROM THE PRESIDENT

On January 1, 2012, I succeeded Paul Morris as president of the Association of Applied Geochemists. I am a graduate of the University of Colorado and the Colorado School of Mines, USA. For more than 30 years, I have worked for the U.S. Geological Survey, based in Denver, Colorado, beginning with geologic mapping and exploration geochemistry in Arizona, Colorado, and Sonora, Mexico. In the early 1990s, my work took me to western and northern Alaska, where I focused on exploration geochemistry and mineral resource assessment. In 1995, I broadened my interests to include the environmental geochemistry of both undisturbed and historically mined mineral deposits in the national forests of Idaho and in the Wrangell-St. Elias and Denali national parks in Alaska. Currently, I am part of a USGS team evaluating exploration geochemical methods at the undisturbed, giant Pebble porphyry Cu–Au–Mo deposit in southwestern Alaska. I am an AAG fellow and have served as councilor, vice-president, and website coordinator for AAG.

As I begin my two-year term as AAG president, I look forward to leading the organization. However, the proactive and stellar leadership of our past president, Paul Morris, is a tough act to follow. In his December 2011 Elements message, Paul detailed the successful 25th International Applied Geochemistry Symposium (IAGS), held in Rovaniemi, Finland, in August 2011. The biennial IAGS is AAG’s flagship meeting, routinely bringing together several hundred geochemists from around the world to exchange ideas, network, go on field trips, and see the latest developments in applied geochemistry, typically with a strong focus on mineral deposits. Coming up in November 2013 is the 26th IAGS, to be held in Rotorua, New Zealand (www.gns.cri.nz/iags/index.html). Early discussions are under way to select the country and venue for the 27th IAGS in 2015. Proposals are being solicited; see AAG’s website (www.appliedgeochemists.org) for symposium guidelines and details.

AAG now brokers and fosters two methods for students in geochemistry to gain research funding: the ioStipend, and In-Kind Analytical Research Funding. Both geochemical consulting and analytical laboratory companies are involved in providing the student funding. A list of companies and application details for these opportunities can be found on AAG’s website under “Students.” These are great funding opportunities, which students and advisors should carefully consider. In addition, AAG initiated a program in 2011 offering subsidized membership to qualified scientists from developing countries. With student funding opportunities, subsidized memberships, and financial assistance available to help students attend IAGS, we hope to see continued growth in applied geochemistry and in the Association of Applied Geochemists.

AAG members are active in organizing conference sessions and workshops in 2012. For the June 2012 Goldschmidt Conference (www.vmgoldschmidt.org/2012/index.htm) in Montreal, Canada, AAG members John Carranza and Cliff Stanley are convening the session “Vectoring towards Mineral Deposits: Integrated Spatial Analysis of Geochemical and Other Mineral Exploration Datasets.” Planning is well underway for the 34th International Geological Congress (www.34igc.org) in Brisbane, Australia (August 2012), of which AAG is an institutional supporter. AAG members are involved in a workshop ("Geochemistry in Mineral Exploration,” coordinated by David Cohen) and in organizing several sessions: “Advances in Geochemical Exploration” (David Cohen, Ravi Anand, Ryan Noble, David Lawie, Graham Closs, Andrew Rate, and Mark Arundall), "Global Geochemical Mapping: Understanding Chemical Earth” (Dave Smith, Xueqiu Wang, and Patrice de Caritat), “Environmental Aspects of Mining” (Bernd Lottermoser and Kirk Nordstrom), and “Advances in the Evaluation and Interpretation of Geochemical Data at the Continental Scale” (Eric Grunsky and Patrice de Caritat).

Bob Eppinger (eppinger@usgs.gov) U.S. Geological Survey, AAG President

RECENT ARTICLE PUBLISHED IN EXPLORE

CHARLES MAURICE and DANIEL LAMOTHE (2012)
An appraisal of Québec’s extensive geochemical database. EXPLORE 154 (March 2012)

The Province of Québec (Canada) covers an area exceeding 1.5 million km², most of which is composed of remote Precambrian glaciated terrain. With a geochemical database hosting more than 753,000 analyses, geochemical surveys are a key component of Québec’s geoscientific program. More than 243,000 of these are rock analyses acquired during geological mapping surveys and exploration programs, and over 510,000 samples were obtained during surficial geochemical surveys (lake, till, stream, soil and water surveys). The article showcases Québec’s geochemical database to the applied geochemists community and shows how geoscience data available in the Geominining Information System (SIGEOM) may be accessed. It also reports on new results from recent surveys in Québec and from the reanalysis of archival samples. In addition, the authors demonstrate how the data can be used to produce first-order exploration targets as part of a comprehensive assessment of the mineral potential of Québec.

Charles Maurice (Charles.Maurice@mrnf.gouv.qc.ca) Bureau de l’exploration géologique du Québec, Val d’Or, Québec

SPECIAL ISSUE OF GEEA

Volume 11 of AAG’s journal, GEOCHEMISTRY: EXPLORATION, ENVIRONMENT, ANALYSIS (November 2011), is the first to be devoted to surficial sediment indicator mineral techniques applied to mineral exploration. In this issue, papers describe the application of indicator minerals to exploration for base metals, gold, platinum-group elements, and diamonds.

Beth McClennagham (bmcclena@NRCan.gc.ca) Geological Survey of Canada
FRANK PODOSEK TO BE MADE LIFE MEMBER

The Council of the Meteoritical Society has elected Frank Podosek as a Life Member of the Society to honor him for his outstanding service to the community as executive editor of *Geochemica et Cosmochimica Acta*. During his 12-year term, Frank Podosek showed exemplary dedication, bringing GCA to the highest standards of scientific publication and helping authors improve the quality of their papers.

In his letter to the associate editors announcing his retirement as executive editor, Podosek wrote, “I have helped to implement changes in the mechanics of how papers are submitted, evaluated and published, but also sought to maintain GCA’s scientific preeminence while serving authors, reviewers, Associate Editors and society governance with cordiality and responsiveness. I have been impressed with the energy and conscientiousness that some very talented people have volunteered in service to our societies and our community. I would like particularly to commend and thank GCA’s Associate Editors, who have provided both the expertise and the attention that have brought the journal to its current state.”

Frank Podosek originally intended to retire as executive editor of GCA at the end of 2012, but he agreed with the publisher to step down at the end of last year when the editorial office at the University of Washington was closed. He has retired from teaching and is now living in Texas. GCA is jointly sponsored by the Geochemical Society and the Meteoritical Society.

Ed Scott (President) and Greg Herzog (Secretary)
The Meteoritical Society

JAMES R. ARNOLD (1923–2012)

James R. Arnold, a fellow of the Meteoritical Society and recipient of the Leonard Medal for 1976, died on January 6, 2012. He was the founding chairman of the chemistry department at the University of California, San Diego, and the first director of the California Space Institute. His contributions to science ranged from the study of cosmic rays to the future of manned space flight.

As a longtime consultant to NASA, Jim helped to set science priorities for missions, including the Apollo flights to the Moon. He first served on a NASA committee in 1959, just three months after the space agency was established. He became the principal investigator for gamma ray spectrometers on Ranger and Apollo. Aware of the importance of water in all aspects of human operations in space, Jim revived and talked widely about earlier ideas for water/ice in the polar regions of the Moon.

Jim was in Houston for the arrival of the first lunar samples and carried some of them back to his laboratory at UC San Diego. Gathered around a television, he and his group watched astronauts on subsequent missions collecting the rocks that they would study next. It was an exciting time. Candace Kohl was then a graduate student, and part of her project was focused on a NASA committee in 1959, just three months after the space agency was established. He became the principal investigator for gamma ray spectrometers on Ranger and Apollo. Aware of the importance of water in all aspects of human operations in space, Jim revived and talked widely about earlier ideas for water/ice in the polar regions of the Moon.

Worried about the threat of nuclear fallout, he was a thoughtful contributor to the *Bulletin of Atomic Scientists* from its foundation. Out of concern for global issues, he took on a student in environmental studies in the early 1970s, a subject that was avant-garde at the time.

In 1970, NASA recognized Jim’s work with an Exceptional Scientific Achievement Medal. He also received the Department of Energy’s E. O. Lawrence Award in chemistry and metallurgy and was a member of the National Academy of Sciences and the American Academy of Arts and Sciences. In 1980, Eleanor Helin and Eugene Shoemaker named an 8-mile-wide asteroid that they discovered 2143 Jimarnold.

Mark Thiemens, Candace Kohl, and Bob Reedy

SOCIETY NEWS

TRAVEL GRANTS AVAILABLE FOR ANNUAL MEETING

The 75th Annual Meeting of the Meteoritical Society will be held in Cairns, in the far north of Queensland, Australia, at the Cairns Convention Centre on August 12–17, 2012. Thanks to generous contributions from the Barringer Crater Company, the National Aeronautics and Space Administration Cosmochemistry Program, the Planetary Studies Foundation, and the International Meteorite Collectors Association (which sponsors the Brian Mason Award), travel grants will be available for qualified students and recent PhDs who are members of the Meteoritical Society. In addition, funds from the Meteoritical Society Endowment Fund will be provided to scientists from low-income countries.

The travel grants will be awarded on the basis of the quality of the submitted abstract, other sources of support available to the recipient, and previous travel grants provided to attend annual meetings. The home institution of the awardee is expected to cover part of the costs. Applicants must be the sole or first author of an abstract to be presented at the meeting. They should also complete an application form and submit a current résumé before May 29, 2012.

MetSocCom is a new electronic discussion group for Society members. It allows subscribers to send and receive messages via their e-mail inboxes. It can be used for meeting announcements, job opportunities, fellowship announcements, student opportunities, and discussions about research or education topics relevant to the Society’s goals. Large data files cannot be posted: only text. Participation in MetSocCom is voluntary, but we encourage members to join as we believe it will be a useful tool. To avoid overwhelming e-mail inboxes, subscribers can choose to have messages combined into a single daily e-mail. You can also unsubscribe at any time.

MetSocCom cannot be used for advertising or for personal e-mail unrelated to Society purposes. Users must obey national and local laws concerning telecommunications. More information, including complete ground rules and links to the subscription page, can be found on the Society website at https://metsoc.meteoriticalsociety.net/lists.html.

To subscribe, visit http://lists.meteoriticalsociety.net/mailman/listinfo/metsoccom, input your name and e-mail address, and choose a password. After you join, you will receive an e-mail explaining how to post messages and manage your subscription. Address questions to MetSocCom’s manager, Jon Friedrich (friedrich@fordham.edu). We hope that members will find MetSocCom useful and interesting and look forward to seeing how this new adventure turns out.

Jon Friedrich (Fordham University)
and Greg Herzog (Rudgers University)

SOCIETY ONLINE DISCUSSION GROUP STARTED

MetSocCom

http://meteoriticalsociety.org

JAMES R. ARNOLD (1923–2012)
Many thanks to all those members who are serving on the Society’s committees this year. We have listed their names below, with the names of the committee chairs in bold. Without the generous help of these members, the Society could not function. We greatly appreciate their help.

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Congratulations to Hap McSween on winning the J. Lawrence Smith Medal of the National Academy of Sciences (page 86)
FROM THE PRESIDENT

I am delighted to take over the presidency of the Mineralogical Society which has been so impeccably nurtured by outgoing president Richard Pattrick. I find a society that is vibrant, overseen by an especially dynamic and youthful Council. During my first term on the MinSoc Council five years ago, I joined wondering about the Society’s role and relevance. I have gradually learned what they are, and now I believe we have an opportunity in steering the Society to make a real contribution to the mineralogical sciences. Among the issues we hope to address in the next two years are:

■ More integration of our special interest groups. Our SIGs are particularly important as they are a strong voice for our early-career researchers, including undergraduate and postgraduate students. Supporting their activities is essential.

■ Exploring the idea of “training workshops” in areas like thermodynamics, textural analysis, mineralogical modelling, and mass spectrometry. Many of my contemporaries will fondly remember the national training opportunities available to UK postgraduate students in the 1980s, which served as a basis for learning skills and networking with peers.

■ Raising the profile of the Earth and mineral sciences in schools and to the public. A particular worry has been the erosion of the definition of our subject. Terms like geology, geography, environmental science and environmental studies are fused together, with the result that students arriving at university are unsure about what they are signing up for, and underprepared for the maths, physics, chemistry and biology needed for a modern geoscience degree.

I’m looking forward to a busy couple of years!

Jon Davidson, President
Mineralogical Society

NEW WEBSITE

The Society’s long-awaited new website has been launched. The URL is the same, but the site has been completely overhauled and much of the content rewritten and rearranged. Visit now and send any comments to kevin@minersoc.org.

The new content-management system will allow us to give permission to interested parties, e.g. special interest group secretaries, to make immediate changes to pages of concern to them. This will allow for a more dynamic site, with less reliance on a central webmaster. The website facilitates seamless linking to our membership module and to our online bookshop.

MEETINGS

Any reader who has ever tried to organize a scientific meeting will know the effort required: choosing a team, a theme, a venue and suppliers; inviting speakers; doing the advertising; setting up the website and online registration system; and then making sure they all work and are updated as you build to the event itself. Delegate numbers are the least controllable aspect of most meetings, and therefore there is always an inherent risk in running events. The calendar of conferences, national and international, makes it increasingly difficult to find a slot for your meeting that allows you to achieve a sufficient number of delegates to ensure that you can pay the bills created by your conference! And all this in an environment where there is less and less money available to cover delegate travel, subsistence and registration costs at meetings.

So, many groups have taken to collaborating with others for their meetings. This helps with the organizational and financial aspects, but the greater benefit is that it facilitates multi-disciplinary meetings where delegates can step outside their usual comfort zones to learn new things.

The theme of collaboration has been a growing one within the MinSoc for several years. In 2012, we will have two collaborative meetings. The EMC2012 meeting, being held in Frankfurt, is a follow-on and extension of previous meetings in Cambridge (2007) and Edinburgh (2009) and involves ten national mineralogical societies. The conference website (http://emc2012.uni-frankfurt.de) lists 35 sessions arranged in 11 themes where it is possible to submit an abstract. A large gathering is expected for this event, so sign up before May 15 to ensure you get the early-bird rate.

The meeting “Geomicrobiology and Its Significance for Biosphere Processes” will have been held, or will be about to be held (19–20 April 2012), when this copy of Elements lands on your desk. This is the first time the Mineralogical Society (through the Environmental Mineralogy Group) has collaborated with the Society for General Microbiology to co-host an event for the growing number of people interested in this topic. Visit www.minersoc.org/pages/meetings/EMG-SGM.html for details of the meeting. Follow-up events are planned. The convenors are Jon Lloyd, Geoff Gadd and Joanne Santini.

Two more collaborative meetings have been planned for 2013. The first is “Volcanism, Impacts, and Mass Extinctions: Causes and Effects,” co-organized by the Volcanic and Magmatic Studies Group (26–29 March 2013). This event will be held in London. Visit http://massextinction.princeton.edu/ for details.

The other event is the Society’s main meeting for 2013: “Minerals for Life”. Already we have agreed to collaborate with colleagues at the Geological Society, IoM², the British Zeolite Association and the Ceramics Society. A venue and dates will have been selected by the time of the next issue of Elements. The chairman of the organizing committee is Dr Mark Tyrer.
SOCIETY NEWS

Other Forthcoming Events


SEDI is an international scientific organisation dedicated to the study of the Earth’s deep interior. The ultimate goal of SEDI is an enhanced understanding of the past evolution and current thermal, dynamical and chemical state of the Earth’s deep interior and of the effect that the interior has on the structures and processes observed at the surface of the Earth (website: http://sed12012.leeds.ac.uk/).

Joint High-Pressure Mineral Physics Seminar and COMPRES Annual Meeting – Lake Tahoe, California, 9–13 July 2012

The international High-Pressure Mineral Physics Seminar has been held every five years since 1976 and gives researchers an opportunity to present their latest results and cutting-edge techniques in high-pressure mineral science. The resulting publications have been seminal works. This year the eighth High-Pressure Mineral Physics Seminar is joining with the tenth annual COMPRES meeting. This four-day meeting will explore all aspects of high-pressure mineral physics in its broadest sense. The meeting will be held at the Granlibakken Conference Center and Lodge in Lake Tahoe, California (website: http://compres.us/).

Fieldtrip: Magmatic Processes in the Shallow Crust, Adamello Massif, Italy, 26 August–1 September 2012

This field trip will explore the magmatic processes and products of a sub-volcanic feeder system and shallow-level intrusions in northern Italy. Cost: students, £350; non-students, £450; flights not included. A deposit of £100 is payable by 31 April 2012. Leader: Jon Blundy. More information at www.vmsg.org.uk.

SOCIETY OFFERS CHARTERED STATUS

Chartered Scientist (CSci) is a mark of achievement in science. The use of the title promotes public confidence in scientists by ensuring a common high standard of education, training and continued competence. In October 2003, the designation Chartered Scientist was added to the now familiar list of chartered professions: biologist, accountant, surveyor and so on.

“Chartered” is an internationally recognized benchmark of quality and excellence, and it will do much to improve the profile of science and scientists. Although not all mineral scientists will wish to achieve the level of qualification necessary to earn the title, its existence confers chartered standing on the profession as a whole. Chartered status will become the cornerstone of the Society’s professional qualification framework and is a prestigious achievement for ambitious professionals in mineral science (sensu lato).

The designation Chartered Scientist was made possible by a Royal Charter issued to the Science Council on 14 October 2003. The Science Council cannot confer Chartered Scientist status on individuals directly but only through professional member bodies that have been awarded a license. The term for such a member organization is Licensed Member Body, and such a body can charter individual members who meet certain criteria. The Mineralogical Society was awarded Licensed Body status in 2011, and so we now seek our first CSci applicants.

If you wish to apply for Chartered Status, please visit the Society’s website at www.minersoc.org/chartered.html. Application in year 1 costs £50. CSci will cost £45 per year thereafter, in addition to regular membership fees.

Landmark Papers: Granite Petrogenesis

The latest volume in our Landmark Series has been published. Landmark Papers: Granite Petrogenesis (edited by J. D. Clemens and F. Bea) is organized into a number of sections that represent what the editors regard as the main research fields in which progress has been made in understanding granites and their genesis. The origin of granitic magmas is part of the cycle that unites tectonic processes with the generation of mantle magma, crustal growth, the transfer of mantle heat to the crust, high-grade regional metamorphism, crustal melting and crustal differentiation. The extended subject area is far too wide to deal with in a single volume and, therefore, the selection has been limited to papers dealing with the formation, physical behaviour and chemical evolution of granitic magmas; the book just touches on the matter of associated ore deposits. John Clemens and Fernando Bea are world experts on the subject of granite petrogenesis. Clemens’ most important work has been on the origin and evolution of granites and silicic volcanic magmas, experimental studies and modelling of partial melting, and the ascent and chemical evolution of granitic magmas, and these continue to be his main interests. Bea’s research interests have been in the petrology and geochemistry of granitic rocks and the mechanisms of generation of granitic magmas, and he has studied in detail the role of heat-producing elements.

The book is available at the Society’s online bookshop. Go to www.minersoc.org and click on “Online shop”.

Rock-Forming Minerals

Mineralogical Society members can now buy a copy of one of the volumes of Rock-Forming Minerals by Deer, Howie and Zussman (published by the Geological Society) at a reduced price (50%). Contact the Sales Department (sales@geolsoc.org.uk) to secure your discount. Go to www.minersoc.org and follow the link to the site.

And finally, remember that the MinSoc is the only society to offer a year’s free membership to students. Please encourage your students to join, and they will receive their own copy of Elements for a year. They will also be eligible to apply for Society bursaries and to pay reduced rates for Society publications and conferences.

Act now!

Kevin Murphy, Executive Director

Prof. R. A. Howie, an Honorary Life Fellow of the Society, passed away on March 10. Prof. Howie was the long-time editor of Mineralogical Abstracts and one of the authors of the Rock-Forming Minerals series (Deer, Howie and Zussman). He was engaged with the mineralogical community and still working (on the third edition of Introduction to the Rock-Forming Minerals) right up until the time of his death. He will be sadly missed. An obituary will be published in Mineralogical Magazine in due course. See also page 84.

Elements

APRIL 2012
IAGC AWARDS FOR 2012

The IAGC is proud to announce a first round of recipients of its awards for 2012: new IAGC Fellows and recipients of the Certificate of Recognition. The recipients of the Distinguished Service Award, the Vernadsky Medal, and the Elsevier Student Research Grants will be profiled in the next issue of Elements. Congratulations to the winners!

Fellows

The honorary title of IAGC Fellow is bestowed on scientists who have made significant contributions to the field of geochemistry. Susan Brantley, for fundamental research contributions to the understanding of geochemical processes within the critical zone. IAGC member Susan Brantley received a PhD from Princeton University in 1987 and is currently a professor of geosciences at the Pennsylvania State University, director of the Earth & Environmental Systems Institute, and director of the Center for Environmental Kinetics Analysis at PSU. As one of the leading aqueous geochemists of her generation, Professor Brantley has explored important questions like the chemical-weathering rates of silicate minerals, the kinetics of water–rock interaction, soil-forming processes, and the effects of microbial processes on mineral dissolution and soil development. She is widely published in the top-tier geochemical journals, including Applied Geochemistry.

Norbert Clauer, for outstanding research on the geochemistry of clay minerals. IAGC member Norbert Clauer received his PhD from the Université Louis Pasteur in Strasbourg in 1976 and currently is emeritus research director of the French National Research Council (CNRS) and scientific director of the French Nuclear Waste Repository National Agency. As documented through more than 170 research publications, Dr. Clauer is a recognized international authority on clay minerals. Over the course of a distinguished research career, he has used the tools of chemistry and isotope chemistry to understand the mechanisms of clay crystallization and recrystallization; the behavior of detrital and authigenic clay minerals during deposition, diagenesis, low-grade metamorphism, and weathering; and the geochemistry of sedimentary brines.

Certificates of Recognition

The Certificate of Recognition is awarded to IAGC members for outstanding scientific accomplishment in a particular area of geochemistry, for excellence in teaching or public service, or for meritorious service to the Association or the international geochemistry community.

Olle Selinus, for significant contributions to the fields of environmental geochemistry and medical geology. IAGC member Olle Selinus is a PhD geologist with the Geological Survey of Sweden. During the 1960s and 1970s, he worked in mineral exploration, and since the beginning of the 1980s his research work has dealt with environmental geochemistry, including research on medical geology. Dr. Selinus has more than 100 research publications in environmental geochemistry. He has also served as the organizer of several international conferences in this field and was vice-president of the International Geological Congress in Oslo in 2008. He served as editor-in-chief for the book Essentials of Medical Geology and as president of the International Medical Geology Association, which began as an IAGC working group. He has received several international awards and was appointed Geologist of the Year in Sweden for his work in medical geology.

Suzanne Prestrud Anderson, for organizing and leading the 9th International Symposium on the Geochemistry of the Earth’s Surface (GES-9), in Boulder, Colorado, in June 2011. IAGC member Susan P. Anderson is an associate professor of geography in the Department of Geography at the University of Colorado and a fellow of the Institute for Arctic and Alpine Research. She received a PhD from the University of California at Berkeley in 1995. Her research interests are focused on the field-based, mechanistic understanding of the chemical and physical processes that shape the Earth’s surface and control denudation rates.

Neus Otero, for coorganizing the 9th International Symposium on Applied Isotope Geochemistry (AIG-9), in Tarragona, Spain, in September 2011. Dra. Otero received her PhD from the University of Barcelona in 2004 and is currently a tenure-track lecturer in the Department of Crystallography, Mineralogy and Ore Deposits at the Universitat de Barcelona and coordinator of the environmental projects of the Mineralogia Aplicada i Medi Ambient (Applied Mineralogy and Environment) research group. She uses isotopic tools to evaluate the fate of contaminants in the environment, with a special focus on natural and induced attenuation of groundwater pollution.

Albert Soler Gil, for coorganizing the 9th International Symposium on Applied Isotope Geochemistry (AIG-9), in Tarragona, Spain, in September 2011. Dr. Soler received his PhD from the University of Barcelona in 1990 and is a full professor of mineralogy in the Department of Crystallography, Mineralogy and Ore Deposits at the Universitat de Barcelona. He is the coordinator of the Mineralogia Aplicada i Medi Ambient research group, and his research interests center on the use of isotopic tools to identify contamination sources, evaluate the evolution of the contaminants, and foresee natural attenuation processes.

OBITUARY

Ignacio S. Torres (1964–2012)

Our friend and colleague Ignacio Torres passed away unexpectedly on January 15, 2012, after a routine medical checkup at the age of 47. Ignacio S. Torres Alvarado—Nacho to his friends—leaves his wife Gaby and two children. We are deeply shocked by this tragic incident. Ignacio was born in November 1964, in Torreón, State of Coahuila, in northern Mexico. In 1988, he graduated as a geologist from the Instituto Politécnico Nacional in Mexico City, and then as permanent professor (2003–2012). Ignacio was appointed on January 15, 2012, after a routine medical checkup at the age of 47. Ignacio S. Torres Alvarado—Nacho to his friends—leaves his wife Gaby and two children. We are deeply shocked by this tragic incident. Ignacio was born in November 1964, in Torreón, State of Coahuila, in northern Mexico. In 1988, he graduated as a geologist from the Instituto Politécnico Nacional in Mexico City, and then as permanent professor (2003–2012). Ignacio continued his academic career in Germany, where he concluded a one-year-specialty program at the Eberhard Karls University of Tübingen (1988–1989). From November 1989 to October 1990, he was a junior researcher at the Institute for Electrical Research in Cuernavaca, Mexico. He returned to Tübingen in 1996 to complete his doctoral studies with M. Satır and P. Metz at the Institute for Mineralogy, Petrology and Geochemistry. Ignacio returned to Mexico to start a thriving academic career in geothermal studies at the Centro de Investigación en Energía (CIE) of the UNAM in Temixco, Morelos State, central Mexico, first as associate (1997–2002) then as permanent professor (2003–2012). Ignacio received awards from several societies throughout his career, including the Gabino Barreda Medal from UNAM, selection as member of the Mexican Academy of Science and the National System for Scientists, and election as president of the Mexican Institute for Geochemistry from 2002 to 2004. In recognition of his active participation in IAGC’s Water–Rock Interaction Working Group, in 2010 he received the Friend of Water–Rock Interaction Award. During his short career, he published several dozens journal papers, book chapters, extended abstracts, and registered patents, mostly related to mineralogical, geochemical, and isotopic issues in hydrothermal systems.

Nacho was anxious to support and enhance the use of renewable energy in Mexico, which is also reflected in the establishment of the bachelor’s program in renewable energy at CIE. He was known for his open manner of interacting with people. His international network of contacts and professional collaborators is an exceptional example for productive worldwide relations. Ignacio will be missed especially by his Mexican and German friends.

Thomas Kretzschmar, CICESE, Mexico
I wish to state that the Italian Society of Mineralogy and Petrology will remain committed to its fundamental mission as defined in 1940 by the founding members, namely, “to promote, organize, and develop advancing knowledge in the different fields of mineral sciences, in their broadest sense.” Activities pursued by SIMP will be devoted, as ever, to organizing meetings, sponsoring PhD courses, allocating grants and awards, fundraising, participating in scientific journals and magazines (European Journal of Mineralogy and Elements), establishing and strengthening national and international relationships with allied societies, and making the public, policy makers, and stakeholders more aware of the value of our science.

The SIMP 2012 annual meeting will be held during the upcoming European Mineralogical Conference (EMC2012) in Frankfurt. SIMP is actively endorsing the launch of a tradition for a joint European conference of mineral sciences in their broadest sense. Dedicated travel grants from the Geotabella Foundation will be awarded by SIMP Council to facilitate the participation of students. The next outstanding event, with SIMP strongly supporting the local organization chaired by Massimo Coltorti, is the 2013 Goldschmidt Conference, to be held in Florence. Other recent initiatives include the launching of a new prize dedicated to the late Enzo Michele Piccirillo, made possible by a generous donation from a SIMP member. It will support young Italian researchers eager to improve their scientific skills in other countries.

The commitment of SIMP to strengthen links with allied societies in crystallography, geochemistry, and volcanology, and with the Italian Geological Society, will continue in an effort to provide our community with more impact in the political arena, while maintaining the diversity of our disciplines.

Just as has been reported by other members of the Elements family, mineralogy and mineral sciences in the broadest sense are facing financial austerity and an identity crisis in both Italy and Europe. This situation requires an immediate reaction from individuals and scientific societies. Great potential still exists to show that our disciplines can contribute to societal issues, including the environment, natural hazards, renewable energies, CO$_2$ capture and sequestration, the understanding and modeling of the deep-Earth engine, the design of new mineral-inspired materials, the preservation of cultural heritage, raw materials, the interplay of the geo- and biospheres, and the like. If our scientific community does not provide substantial input on these issues, who will? So let’s all join our efforts, and in doing so, allow our vision of the future to be more optimistic!

Giuseppe Cruciani (cru@unife.it)
SIMP President

REFERENCES
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 society awards. The awards were presented at the Society’s annual meeting in Mito, Japan, on September 10, 2011. The Japan Association of Mineralogical Sciences Award for Young Scientist is awarded annually to a maximum of two scientists under 37 years of age for exceptional contributions to the mineralogical and related sciences. The Japan Association of Mineralogical Sciences Award for Applied Mineralogy is awarded once a year to one scientist who has made remarkable contributions to applied mineralogy. The recipients of the Japan Association of Mineralogical Sciences Award, the Manjirō Watanabe Award, and the Japan Association of Mineralogical Sciences Research Paper Award will be announced in the next issue. Congratulations to all the winners!

JAMS Award for Young Scientist to Hiroaki Ohfuji and Satoko Ishimaru

Hiroaki Ohfuji is an associate professor at the Geodynamic Research Center, Ehime University. He received his PhD degree from Cardiff University, UK, where he studied the self-organization mechanism of framboidal pyrite, a raspberry-like micrometer-sized cluster of several microcrystals, under the guidance of Prof. David Rickard. Through detailed electron microscope observations of many framboids from various localities, he discovered that the pyrite microcrystals are in icosahedral packing. This finding is significant because it not only changes our perception of framboidal pyrite as a “spherical” cluster, but it is also the first report of a dense multiparticle icosahedral material in nature. He also described a variety of microcrystal packings in framboidal pyrite—icosahedral, face-centered cubic, and random packing—and revealed that self-organization is achieved by the nucleation of monodisperse microcrystals, followed by the aggregation and reorientation of individual microcrystals driven by the minimization of surface free energy. His study is the first systematic mineralogical and crystallographic investigation on framboidal pyrite, and it contributes greatly to the understanding of the origin and nature of this form of pyrite, which have remained a mystery for more than half a century. Currently, he is expanding his research to the investigation of the formation of microtextures and to the phase-transition mechanism and kinetics of synthetic diamond and other high-pressure minerals.

Satoko Ishimaru is an assistant professor in the Faculty of Science, Kumamoto University. She obtained her PhD degree from Kanazawa University under the supervision of Professor Shoji Arai. She revealed the petrographical and geochemical characteristics of peridotite xenoliths from Avachinsky (Avacha) volcano on the volcanic front of the Kamchatka arc through detailed microscopic observations and chemical analyses. She used this information to unravel the mantle wedge processes beneath the volcanic front. The Avacha peridotites were metamorphosed by silicic melts and fluids, forming secondary orthopyroxenes at the expense of olivine. The peridotites occasionally contain highly silicic glasses associated with euhedral to subhedral secondary orthopyroxenes, indicating the activity of these melts and fluids within the mantle wedge. She also found several specific metasomatic modifications of the mantle peridotite. The presence of Fe–Si alloys and metallic phases within the mantle wedge suggests the activity of reducing fluids. The presence of “Ni-rich spots” (the highest NiO content in olivine is 5.3 wt%) in a fine-grained peridotite indicates the activity of a S–Ni-rich metasomatic agent, possibly a peculiar melt. These metasomatic events are apparently unusual, but they are possibly characteristic of the subfrontal upper mantle. Her work has provided a glimpse into processes in this part of the mantle, and she plans to substantiate her hypotheses by carrying out further research.

JAMS Award for Applied Mineralogy to Akira Monkawa

Akira Monkawa is a researcher at Tokyo Metropolitan Industrial Technology Research Institute. He started his research in the field of applied mineralogy after obtaining his PhD degree from the University of Tokyo under the supervision of Professor Masamichi Miyamoto. Hydroxylapatite (HAp) is a major inorganic component of bone and teeth tissues, and it has excellent biocompatibility and high osteoconductivity. The HAp-related bioceramics have various applications such as bone substitute, coating substance of metal implants, inorganic-polymer composites, and cell culture. Akira Monkawa devised (1) a method for surface modification of HAp using an organosilane and (2) a method for fabricating an ultrathin HAp layer on a gold surface for protein adsorption analysis by the QCM-D (quartz crystal microbalance) technique. The interfacial interaction between collagen and HAp in a nanoregion was controlled by depositing an organosilane, n-octadecltrimethoxysilane (ODS: –CH3) or aminopropyltriethoxysilane (APTS: NH2) by chemical vapor deposition. The morphologies of the collagen adsorbed on the surfaces of HAp and HAp deposited by APTS were similar, but the morphology of the collagen adsorbed on the ODS-deposited HAp surface was apparently different, because of the hydrophobic interaction between the organic head group of –CH3 and the residual groups of collagen. Monkawa’s group also developed a method for coating a gold QCM-D sensor with an ultrathin layer of HAp nanocrystals, such that the nanocrystals cover the surface evenly and bind tightly to the surface. The HAp sensor operated in liquid media with high stability and sensitivity. The HAp sensor can be used for the qualitative and conformational analysis of protein adsorption.


Ehimeite, NaCa2Mg6(CrSi3Al3O12)(OH)2: The first Cr-dominant amphibole from the Akaishi Mine, Higashi-Akaishi Mountain, Ehime Prefecture, Japan

Daisuke NISHIO-HAMANE, Masayuki OHNISHI, Tetsuo MINAKAWA, Jun-ichi YAMURA, Shohel SAIITO, and Ryo KADOTA

Hydrous and anhydrous melting experiments of an alkali basalt and a transitional tholeiite from the Oginosen volcano, southwest Japan: The possible influence of melt depolymerization on Ca-Na partitioning between plagioclase and the melt

Ushio HONMA

Secondary tungsten minerals in quartz veins from the Ishidera area, Wazuka, Kyoto Prefecture, Japan: Anthoinite, mpororoite and Fe-free hydroknoelnsmoreite

Norimasa SHIMOBAYASHI, Masayuki OHNISHI, and Kenji TSURUTA

The eruption history and silicic magma systems of caldera-forming eruptions in eastern Hokkaido, Japan

Takeshi HASEGAWA, Mitsuhiro NAKAGAWA, and Hiroshi KISHIMOTO

Carbonic fluid inclusions in amphibolite-facies pelitic schists from Bodonch area, western Mongolian Altai

Oyun-Erdene ZORIGTKHUU, Toshiaki TSUNOGAE, and Bat-Uzliz DASH

Annular fluid inclusions from a quartz vein intercalated with metapelites from the Besshi area of the Sanbagawa belt, SW Japan

Kenta YOSHIDA and Takao HIRAJIMA
THE PRESIDENT’S CORNER

Last fall’s headlines, at least in science-oriented publications, read, “Daniel Shechtman Awarded the Nobel Prize in Chemistry for Discovering Quasicrystals.” Shechtman, a researcher at Technion (the Israel Institute of Technology in Haifa), started on the road to a Nobel Prize back in 1982 when he first observed atomic-packing patterns in rapidly cooled metal alloys that did not and could not have three-dimensional periodicity. Conventional crystallographic wisdom at the time said such structures were impossible, and Shechtman’s peers, egged on by none other than Linus Pauling, accused him of disordered thinking. But Shechtman persisted, finding support in pure mathematics, Penrose tiles, and the aperiodic mosaics of the Alhambra Palace, until at last his critics were humbled. What he had discovered were three-dimensional “crystal” structures that followed mathematical rules but never repeated, a concept that strikes at the very heart of what it means to be a crystal.

The appreciation of disordered quasicrystalline structures is also at the heart of clay mineralogy. Clay mineralogists have long recognized “short-range ordered” mineral phases such as allophane, imogolite, and ferrihydrite. The term quasicrystal was in fact coined by Lance Aylmore and James Quirk1 to describe smectites, which have two-dimensional periodicity but lack ordered structure along the c crystallographic axis due to turbostatic stacking of the individual 2:1 phyllosilicate layers. In preceding publications, Aylmore and Quirk and other clay mineralogists struggled with the term crystal as they came to realize that smectite layer stacking is random from the dearth of hkl peaks in X-ray diffraction patterns.

I once prepared an oriented specimen of Ca-saturated synthetic flurohectorite on a ceramic heating tile and mounted it in the X-ray diffractometer. Analysis of the specimen at ambient temperature and humidity revealed a pronounced 15 Å 001 peak with over 50,000 cps. I then passed a little current through the heating tile without otherwise touching or changing the specimen. At 90 °C, I reran the diffractometer. Analysis of the specimen at ambient temperature and humidity revealed a pronounced 15 Å 001 peak with over 50,000 cps.

I then passed a little current through the heating tile without otherwise touching or changing the specimen. At 90 °C, I reran the diffractometer. Analysis of the specimen at ambient temperature and humidity revealed a pronounced 15 Å 001 peak with over 50,000 cps.

I then passed a little current through the heating tile without otherwise touching or changing the specimen. At 90 °C, I reran the diffractometer. Analysis of the specimen at ambient temperature and humidity revealed a pronounced 15 Å 001 peak with over 50,000 cps.

I congratulate Daniel Shechtman for his well-deserved Nobel Prize and for being the first to recognize three-dimensional nonrepeating crystalline structures in metal alloys and related solids! But despite the headlines, disorder in crystalline solids is nothing new to clay mineralogists. We long ago struggled with the word crystal and coined the word quasicrystal in recognition of the fact that three-dimensional periodicity was often lacking in quasicrystalline clay minerals, nature’s nanoparticles.

David Laird, president
The Clay Minerals Society
dalaird@iastate.edu


STUDENT RESEARCH SPOTLIGHT

Congratulations to Keith Morrison for winning a CMS Student Research Grant award. Keith is a PhD candidate in geochemistry at Arizona State University. He received his BS in environmental toxicology and MS in Earth sciences at the University of California, Riverside. His current research is focused on antibacterial clays that have the ability to kill antibiotic-resistant strains of bacteria. Keith has recently begun investigating the antibacterial mechanism using scanning transmission X-ray microscopy at the Advanced Light Source (Berkeley, California) to map the uptake and redox chemistry of soluble transition metals interacting with fully hydrated bacteria and biofilms.

STUDENT RESEARCH GRANTS AND TRAVEL AWARDS

The research grant program is designed to provide partial financial support (up to $3000) to graduate students in clay science and technology doing master’s or doctoral research. The travel grant program provides partial financial support to graduate students to attend the annual meeting of the Clay Minerals Society and present results of their research. All student members of the Clay Minerals Society are eligible to apply for a travel grant. See the CMS website for more information: www.clays.org. The application deadline is 30 April 2012.

6th BIENNIAL REYNOLDS CUP COMPETITION

The 6th biennial Reynolds Cup competition for quantitative mineral analysis is now open. You can register your interest for the contest by sending an e-mail to ReynoldsCup2012@csiro.au. Information about the competition, including guidelines and previous winners, can be found at www.clays.org. The competition is free for all to enter; however, those who are not members of the CMS are encouraged (but not obliged) to become members. Results must be submitted by 15 May 2012.

“SHALES AND IMPOSTERS”

The 49th Annual Meeting of

The Clay Minerals Society

July 7-11, 2012
Colorado School of Mines
Golden, Colorado, USA

Workshop (July 7) and field trip (July 8):
• Organic Shales: Pore-Systems
• Organic Shales: Clay Diagenesis and Organic Maturity
• Multiscale Modeling of Clays and Layered Minerals
• Clays and Human Health
• Industrial Clays
• Soil Clays and Environmental Science

Abstract Deadline: April 30
Early Registration Deadline: May 1
More details at www.clays.org
As President Rick Carlson announced in the previous issue of Elements, Geochemical News has been reinvigorated as a weekly newsletter. GN contains highlights of news of interest to the geochemical community; advertisements from suppliers of geochemical instrumentation, equipment, and supplies; and breaking news from the Geochemical Society. GN is available via e-mail and as a mobile application, for your reading pleasure while waiting in airports on the way to the field or a geochemical conference. We hope you enjoy the information presented. GS members are subscribed as a member benefit. View past issues at www.multibriefs.com/briefs/gs/.

GEOCHEMICAL CAREER CENTER

The Geochemical Society’s Geochemical Career Center (http://jobs.geochemsoc.org/jobs) is a web-based service open to the entire geochemical community offering an easy-to-use and highly targeted resource for online employment connections.

Employers can use the Geochemical Career Center to reach qualified candidates. For a nominal fee, employers can post job openings, search for qualified candidates based on specific job criteria, and create an online resume agent to e-mail qualified candidates.

For job seekers, the Geochemical Career Center is a free service that provides access to employers and geochemistry jobs. In addition to posting resumes, job seekers can browse and view available jobs based on their criteria and save those jobs for later review if they choose. Job seekers can also create a search agent to provide e-mail notifications of jobs that match their criteria.

If you are looking for a job or have a job you want to post, come to the Geochemical Career Center.

REVIEWS IN MINERALOGY & GEOCHEMISTRY

MINERALOGICAL SOCIETY OF AMERICA AND THE GEOCHEMICAL SOCIETY


Following an overview in chapter 1, this volume is divided into 4 parts: (1) Analytical and Spectroscopic Methods – chapters 2 and 3; (2) Physical and Chemical Properties of S-Bearing Silicate Melts – chapters 4–7; (3) Constraints from Natural and Experimental Systems – chapters 8–11; and (4) Natural and Technical Applications – chapters 12–16.

For more description, a table of contents of this book, and online ordering, visit www.minsocam.org or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110, USA; phone: +1 (703) 9950; fax: +1 (703) 652-9951; e-mail: business@minsocam.org.

2013 AWARD NOMINATIONS

The V.M. Goldschmidt Medal is awarded for major achievements in geochemistry or cosmochemistry.

The F.W. Clarke Medal is awarded to an early-career scientist for a single outstanding contribution to geochemistry or cosmochemistry.

The C.C. Patterson Medal is awarded for a recent innovative breakthrough in environmental geochemistry.

The Alfred Treibs Medal is awarded for major achievements in organic geochemistry.

The GS/EAG Geochemical Fellows Award is bestowed upon outstanding scientists who have made a major contribution to geochemistry.

Make a nomination at www.geochemsoc.org/awards/makeanomination.htm.

Nomination Deadline: October 15, 2012

Why Nominate?

Geochemists want and need recognition for their work. Awards help to inspire individuals to do their best. Awards set the bar for others to match and/or exceed. Your participation in the awards program by being a nominator or writing a supporting letter of recommendation not only benefits the nominee, it benefits the geochemical community.

Please take the time to highlight the accomplishments of your valued colleagues by nominating them. With your help, we can ensure that the award committees have a diverse and deserving pool of candidates.

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“Like” us on Facebook!
www.facebook.com/geochemsoc
The V.M. Goldschmidt 2012 Conference will be held at the Palais des Congrès in Montréal, June 24–29, 2012, under the general theme “Earth in Evolution.” Nearly 2900 abstracts have been submitted for 167 sessions within 23 diverse themes, such as “Evolution of the Solar System,” “Geomicrobiology,” “Earth Resources,” and “Geoengineering and Remediation.”

### Plenary Speakers at Goldschmidt 2012

- **Bernard Bourdon** (ENS Lyon, EAG President)
- **Robert Howart** (Cornell University)
- **Terry Engelder** (Pennsylvania State University)
- **Lee Kump** (Pennsylvania State University)
- **Larry Cathles** (Cornell University)
- **Patrice Christmann** (BRGM)
- **Ros Rickaby** (University of Oxford, 2012 Gast Lecturer)

### Awards to Be Presented at Goldschmidt 2012

#### GEOCHEMICAL SOCIETY

2012 Goldschmidt Medal: **Edward M. Stolper** (California Institute of Technology)

2012 Patterson Medal: **Stefan Schouten** (Royal Netherlands Institute for Sea Research)

2012 Clarke Medal: **David T. Johnston** (Harvard University)

#### EUROPEAN ASSOCIATION OF GEOCHEMISTRY

2012 Urey Medal: **Alexander Halliday** (University of Oxford)

2012 Houtermans Medal: **Frédéric Moynier** (Washington University in St. Louis)

2012 Science Innovation Award in Biogeochemistry (Lowenstam Medal):

- **Katherine Freeman** (Pennsylvania State University)
- **Andrew Gleadow** (University of Melbourne)
- **Daniel Sigman** (Princeton University)
- **James Farquhar** (University of Maryland)

#### GS/EAG

2012 Gast Lecturer: **Ros Rickaby** (University of Oxford)

2012 Geochemical Fellows:

- **Bjørn Jamtveit** (University of Oslo)
- **Hans Keppler** (Universitat Bayreuth)
- **Lee R. Kump** (Pennsylvania State University)
- **Andrew Putnis** (Universität Münster)

#### INTERNATIONAL ASSOCIATION OF GEOCHEMISTRY

2012 IAGC Fellowship: **Susan L. Brantley** (Pennsylvania State University)

2012 Vernadsky Medal: **Robert A. Berner** (Yale University)

2012 Shen-su Sun Award: **Di-Chen Zhu** (China University of Geosciences – Beijing)

#### MINERALOGICAL SOCIETY OF AMERICA

2012 Dana Medal: **Roberta L. Rudnick** (University of Maryland)

#### OTHER AWARDS

- **Fabiola Giordano** (University of California, Los Angeles)

#### AWARDS TO BE PRESENTED AT GOLDSCHMIDT 2012

- **2012 Goldschmidt Medal: Edward M. Stolper** (California Institute of Technology)
- **2012 Patterson Medal: Stefan Schouten** (Royal Netherlands Institute for Sea Research)
- **2012 Clarke Medal: David T. Johnston** (Harvard University)
- **2012 Urey Medal: Alexander Halliday** (University of Oxford)
- **2012 Houtermans Medal: Frédéric Moynier** (Washington University in St. Louis)
- **2012 Science Innovation Award in Biogeochemistry (Lowenstam Medal):**
  - Katherine Freeman (Pennsylvania State University)
  - Andrew Gleadow (University of Melbourne)
  - Daniel Sigman (Princeton University)
  - James Farquhar (University of Maryland)
- **2012 Gast Lecturer: Ros Rickaby** (University of Oxford)
- **2012 Geochemical Fellows:**
  - Bjørn Jamtveit (University of Oslo)
  - Hans Keppler (Universitat Bayreuth)
  - Lee R. Kump (Pennsylvania State University)
  - Andrew Putnis (Universität Münster)
- **2012 IAGC Fellowship: Susan L. Brantley** (Pennsylvania State University)
- **2012 Vernadsky Medal: Robert A. Berner** (Yale University)
- **2012 Shen-su Sun Award: Di-Chen Zhu** (China University of Geosciences – Beijing)
- **2012 Dana Medal: Roberta L. Rudnick** (University of Maryland)
2012 EAG MEDALLISTS

Alex Halliday, FRS, Recipient of the Urey Award

Alex is currently the head of the Mathematical, Physical and Life Sciences Division at Oxford University. Through his development of MC-ICPMS technology, Alex pioneered a revolution in the determination of natural isotope systems. He identified and exploited a series of short-lived radionuclides, including Hf–W, to provide powerful new constraints on the early evolution of the inner solar system, and he is responsible for renewed worldwide interest and activity in cosmochemistry. He has made major contributions to understanding oceans and climate through the study of coral and ferromanganese crusts. His enthusiasm, support and promotion not just of geochemistry but of the geosciences at large have done much to raise the profile of our field within the wider scientific community. The Urey Award is bestowed annually by EAG for outstanding contributions advancing geochemistry over the recipient’s career.

Frédéric Moynier, Recipient of the Houtermans Award

The EAG is proud to announce that Frédéric Moynier has been selected as the 2012 Houtermans medallist. Frédéric is originally from Provence, France. He received his bachelor’s degree and a PhD from the École Normale Supérieure de Lyon. After graduation in 2006, he did a post-doc at the University of California, Davis, before being appointed as assistant professor at Washington University in St Louis. Frédéric has made major contributions towards improving our understanding of the early solar system, the early differentiation of the Earth, the origin of the volatile elements in terrestrial planets, mass-independent isotope fractionation mechanisms, and nucleosynthesis and stellar environments during the birth of our solar system. The Houtermans Award is bestowed annually on a scientist no more than 35 years of age or within 6 years of the PhD for a single exceptional contribution to geochemistry.

Kate Freeman and Daniel Sigman, Co-recipients of the Science Innovation Award

Katherine H. Freeman and Daniel M. Sigman are the 2012 co-recipients of the EAG Science Innovation Award, a medal named in honour of Heinz Lowenstam for his contributions to biogeochemistry.

Kate Freeman is a professor of geosciences at the Pennsylvania State University, USA. She has been recognized for her role in the development of compound-specific isotope analysis and the subsequent application of this technique to a diverse range of problems, including topics in biogeochemistry, microbial geochemistry, palaeo-oceanography, and palaeobotany.

Danny Sigman is the Dusenbury Professor of Geological and Geophysical Sciences at Princeton University, USA. He has been recognized for his innovations in the development of techniques for the determination of nitrogen and oxygen isotopes in nitrogen-bearing compounds in nature and, importantly, the application of these techniques to understanding the dynamics of the carbon cycle through glacial/interglacial intervals.

Both individuals stand out in their generation of biogeochemists; their contributions and scholarship have profoundly shaped their field of research and have provided exciting opportunities for the next generation of biogeochemists.

Full details are available at www.eag.eu.com/awards

COMING SOON!
Volume 1, number 3 | July 2012

The sculpting of rocks by reactive fluids produces many interesting and often beautiful patterns. Examples range from botryoidal aggregates and stromatolites grown from stagnant fluids to travertine terraces and karst morphologies shaped, at least in part, by flowing fluids. Intimate coupling among growth, dissolution, transport and stress, generating volume changes, is often important in porous rocks, and these coupled processes also produce fascinating replacement patterns that provide valuable information about fluid–rock interactions at depth. This issue emphasizes similarities between patterns formed in a wide range of fluid–rock systems and focuses on the controlling role of processes rather than materials.
Leaving the institute and the students for ten days in November! At first this sounded like a dreadful idea. However, the Distinguished Lecture Tour organized by the EAG has been a wonderful experience that will long stand out in my mind. This was a unique opportunity for unforgettable encounters with scientists, now friends, around Europe. Taking this time to meet scientists abroad, exchange experiences, and share our not-so-different points of view on diverse research systems was refreshing, valuable and very instructive.

The trip started in Prague, Czech Republic, the scene of the last Goldschmidt Conference. Martin Mihaljevic and Martin Novak organized my stay there. I gave two talks: one at Charles University and one at the Geological Survey. I will remember from Prague the interesting visit to the facilities of the mineralogy department of Charles University; the pleasant dinners and lunches with Czech colleagues (do they always involve that much beer?); and the romantic streets and bridges of Prague.

After the Prague weekend, I flew to Budapest, Hungary. Csaba Szabó kindly welcomed me at the airport late in the evening. The next day, after my talk, I visited the Eötvös University. After my talk in a huge room that was completely different from our Budapest or Bucharest evenings but equally thrilling.

I then flew to Bucharest, Romania. This was my first time there. I have always been curious about Romania because of the close historical connections between France and Romania. Madalin Enache welcomed me at the airport. I was hosted like a king in a beautiful hotel facing the Romanian Academy. The next day, I gave two talks in a row at the Academy in a beautiful lecture room, which I would guess dated from the late 19th century or so. Madalin took me for lunch and then for a walk around Bucharest. I discovered a restless city with a very unique appeal: Orthodox churches with a very evocative atmosphere inside; some very old, degraded but charming buildings cohabiting with huge grey buildings from the Communist period.

My last stop was in Bratislava, Slovakia. Here, I had a unique and wonderful welcome by Bronislava Lalinska. Bronislava, together with Peter Sottnik and their partners and friends, took me for dinner in a kind of pub-restaurant. After a very enjoyable dinner, I attended a concert by a Czech funk band: JAR. This was of course completely different from our Budapest or Bucharest evenings but equally thrilling. The next day, after my talk, I visited the Comenius University and the geology and mineralogy departments. Noticeably, because of Science Week, there were dozens of high school students in the halls of the university presenting their science projects, dealing with topics as diverse as the formation of bone or a robot able to move around obstacles. This is definitely a nice way to introduce high school students to the university for a week, and I promise that I will someday suggest a similar event here in Paris.

Despite the difficulties that everybody recognizes when coming back to the office after several days of absence, the sweet memories of all these encounters provided me with serenity and detachment for almost a week. I am sure that I will see again each of these persons, maybe for future collaborations or just a dinner at a conference or in Paris. For all of this, I wish to thank the EAG Council and Marie-Aude (EAG business manager): my tour was a humanistic and enriching adventure.

Karim Benzerara
EAG Distinguished Lecturer 2011
PRESIDENT’S LETTER

MSA and AGU: A Very Important Partnership Begins

We are exceptionally pleased to announce that Alex Speer and I, on behalf of the Mineralogical Society of America, have signed a Memorandum of Understanding (MOU) with the American Geophysical Union (AGU) and its president, Michael McPhaden, and executive director, Christine McEntee. AGU is the largest geophysical society in the world, with a membership well in excess of 50,000 from roughly 135 countries. Its fall meeting attendance is now in excess of 20,000 and has doubled in less than 10 years. This is by far the largest annual meeting of geophysical scientists in the world and is arguably the most diverse gathering among all geoscience meetings.

How did this union come about, and what does it mean? Many of us have wanted to consummate a formal agreement between MSA and AGU for some time. The actual breakthrough for this MOU started last May when then MSA Past-President John Brady contacted former AGU President and MSA Fellow Tim Grove of MIT. Tim was very receptive to a formal agreement between the societies and put John in contact with Christine McEntee. David Bish was MSA president at that time, and he shepherded the connection along until I became MSA’s president at the 2011 GSA meeting in Minneapolis. Over the last few months, we have had detailed discussions with several AGU section and focus group officers, which resulted in the creation and signing of our MOU.

The MOU acknowledges that joint activity between AGU and MSA fosters the further development of science and provides opportunities for the memberships of both societies. The agreement formally opens the door to cooperation involving scientific conferences, educational opportunities, student programs, and professional services. It specifically stipulates that each organization will offer members of the other organization registration at member rates at its annual meeting. For AGU, this would be the fall meeting in early December each year in San Francisco, and for MSA, it would be short courses that we sponsor. MSA and AGU leaders will meet each year to discuss issues of mutual interest and cooperation, and their business offices will now seek collaboration wherever needed or useful.

A specific opportunity that we are currently pursuing with the Volcanology, Geochemistry, and Petrology (VGP) Section and the Mineral and Rock Physics (MRP) Focus Group of AGU is to move MSA’s Dana Medal presentation and lecture to the fall AGU meeting. We feel that the Dana Medal deserves a consistent home, much like the Roebling Medal and MSA Award have enjoyed for many decades at the GSA annual meeting. We are also looking for ways to hold joint AGU-GS-AGU short courses and ways to bring Elements magazine to a wider audience. Sessions cosponsored by AGU and MSA, as well as joint social events, now become a distinct possibility at fall AGU meetings.

MSA has worked with AGU before. In fact, MSA cosponsored AGU’s spring meeting, which was held in Baltimore for many years before moving around North America and Europe starting in 1998. I remember fondly: I was awarded the 2002 Dana Medal at a spring AGU meeting in Washington, DC. But those days are long gone. The spring meeting has morphed into the Joint Assembly, and in August 2012, that meeting combines AGU with the Asia Oceania Geosciences Society in Singapore.

Full membership in AGU is only $20 per year. Personally, I am a long-time member and a fellow of that society, and, like many of you, I can attest to the fact that EOS alone is easily worth the cost of membership.

EOS has a weekly circulation in excess of 60,000 and is considered by many to be the premier international newsletter/newspaper for Earth scientists.

It is most important to emphasize that MSA’s highly productive, long-term relationship with the GSA annual meeting will not change as a result of this AGU-MSA agreement. In fact, AGU and GSA have already enacted a highly cooperative MOU between them. GSA boasts a still-growing membership from around the world, and its members have shown remarkable loyalty and cohesiveness. Most MSA members know GSA very well, as the majority of GSA’s 17 divisions have something to do with minerals. I am also proud to be a long-time member and a fellow of this great society.

As I have written before, mineralogy should not exist in a vacuum. We are the keepers of the core science that underlies nearly all areas of the Earth and planetary sciences. As such, it is a privilege that we can associate with and have formal ties to great societies like GSA and AGU. The opportunities that this provides us are nearly endless.

Michael F. Hochella

NOTES FROM CHANTILLY


[Vote 2012 MSA Elections]

MSA members will be sent voting instructions by e-mail in April. Make sure MSA has your current e-mail address! Those who do not wish to vote online can request a paper ballot from the MSA business office. As always, the voting deadline is August 1. Individuals elected to office decide on the direction of the Society. Voting is an important job for all MSA members.

- There is a new virtual special issue of the American Mineralogist on the theme “Minerals in the Human Body” (http://amin.geoscienceworld.org/site/misc/asbestos_health.xhtml), which will examine the interaction, formation, and alteration of minerals in the human body. Manuscript submissions are welcome, and the special issue will remain open for submissions until at least the end of 2013. The associate editors of this special issue are Mickey Gunter (Department of Geological Sciences, University of Idaho) and Gregory Meeker (U.S. Geological Survey). They hope to demonstrate how mineralogists, petrologists, and geochemists can aid in this area, while including papers from other specialists outside the geosciences and involved with this theme (e.g. medical researchers and workers in the regulatory fields).

- MSA workshops have returned. There will be a joint Deutsche Mineralogische Gesellschaft (DMG) short course and Geological Society of America workshop on the theme “Application of Diffusion Studies to the Determination of Timescales in Geochemistry and Petrology,” on 1–5 October 2012 at the Institut für Geologie, Mineralogie und Geophysik, Ruhr Universität Bochum, Germany. Details are available at www.minsocam.org/MSA/SC/#diffusion.

**J. Alex Speer**, MSA Executive Director  
(jasper@minsocam.org)

**INVITATION TO REQUEST A 2012–2013 MSA DISTINGUISHED LECTURER**

The Mineralogical Society is again offering a Distinguished Lecturer program for the 2012–2013 academic year, with the arrangement that the MSA will pay travel expenses of the lecturers and the host institution will be responsible for local expenses, including accommodation and meals. The program will include three lecturers, one of whom resides in Europe. Depending on the response, one or more lecture tours will be arranged outside North America.

The 2012–2013 Distinguished Lecturers are **Julia Baldwin**, **Matt Kohn**, and **Hans-Peter Schertl**, and their affiliations and lecture titles are as follows:

**Julia A. Baldwin**
Department of Geosciences, University of Montana, Missoula, MT, USA

*Metamorphic Phase Diagrams and Geochronology: You Can’t Have One Without the Other*

*When the Continental Crust Gets Really Hot: The Petrology of Ultrahigh-Temperature Metamorphism*

**Matthew J. Kohn**
Department of Geosciences, Boise State University, Boise, ID, USA

*How to Become a Fossil: A Geochemist’s Guide*

*Making the Himalaya: Oozing, Squashing or Sliding?*

**Hans-Peter Schertl**
Institut für Geologie, Mineralogie und Geophysik, Ruhr Universität Bochum, Bochum, Germany

*A Time Machine for Rocks: Cathodoluminescence Microscopy of Metamorphic and Magmatic Minerals*

*How Do Mountains Form? The Critical Evidence from Small-Scale Petrological Observation*

If your institution is interested in requesting the visit of an MSA Distinguished Lecturer, e-mail your request to the lecture program administrator, Prof. Steven R. Dunn, Dept. of Geology & Geography, Mount Holyoke College, 50 College St, South Hadley MA 01075-6419, USA; e-mail: sdunn@mtholyoke.edu; tel.: +1 (413) 538-2531; fax: +1 (413) 538-2239. The Distinguished Lecturer Program will run from September 2012 through April 2013. Lecturer requests received by May 4, 2012, will be given priority. Late applications will be considered on a space-available basis. In making your request please include (1) the distance and travel time from the airport to your institution, (2) the name of a contact person at your institution for the months of May and June (when lecturer schedules will be assembled), (3) contact e-mail addresses and phone numbers, (4) your flexibility on the chosen lecturer, and (5), for schools outside the U.S., the starting and ending dates of academic terms. Because of travel and schedule constraints, it is normally not possible to satisfy requests for tightly constrained dates such as seminar days.

**NOMINATIONS FOR 2013 AWARDS**

Remember the 1 June 2012 deadlines for 2013 MSA awards and honors: **Roebling Medal**, **Dana Medal**, **Mineralogical Society of America Award**, **Distinguished Public Service Medal**, and **Fellowship**. Submissions requirements and procedures: http://www.minsocam.org

**Mineralogical Society of America and Geochemical Society**

**SHORT COURSE ANNOUNCEMENTS**

**Applied Mineralogy of Cement and Concrete**
21–22 June 2012 (after ICDC 2012)
Trondheim, Norway

**Convenors:**
Maarten A. T. M. Broekmans,
Geological Survey of Norway
Herbert Poellmann,
Martin Luther Universität

The course will be held in conjunction with the 1st International Congress on Durability of Concrete (ICDC), Trondheim, Norway, June 18–21, 2012. The course will cover the mineralogical and geochemical aspects of clinker and cement production, cement hydration, and concrete damage. Selected topics represent both “hot issues” (reduction of CO₂ emissions, alternative cements) as well as “long-standing problems” (rebar corrosion and “deleterious alkali–silica reaction”), first described in 1940.

Information and registration: www.minsocam.org/MSA/SC/#concrete

**Environmental Arsenic Mineralogy, Geochemistry and Microbiology**
5 August 2012 (preceding 34th IGC)
Brisbane, Australia

**Convenors:**
Rob Bowell, SRK Consulting, Dave Polya, University of Manchester, Dave Craw, University of Otago, Jack Ng, University of Queensland, Petr Drahota, Charles University

The short course will provide a comprehensive understanding of arsenic geochemistry in the near-surface environment. It will follow on from recent arsenic conferences, such as the Aquatrain series, the most recent being in July 2010 in Manchester, and the EPA conference on arsenic in Denver in 2001. The short course will cover the mineralogy and geochemistry of arsenic and their implications in assessing arsenic geochemistry in natural groundwater, mine-associated impacts, the interaction of arsenic with biological cycles and its consequences, and the management and mitigation of arsenic related impacts in the environment.

Information and registration: www.minsocam.org/MSA/SC/#arsenic

**THE MINERALOGICAL SOCIETY OF AMERICA**

2013 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 as judged from a written proposal, and the likelihood of success of the project. There are three US$5000 grants with no restrictions on how the funds may be spent, as long as they are used in support of research. Application instructions and online submission are available on the MSA website, www.minsocam.org. Completed applications must be submitted by June 1, 2012.
Matthew Izawa completed a BSc in the Department of Physics at the University of Western Ontario in 2006. He then moved on to an MSc degree in geology (completed in 2008) with Dr. Roberta Flemming and Dr. Penny King. He is currently working towards his PhD, supervised by Dr. Flemming and Dr. Neil Banerjee. An important objective of his PhD research is to better understand the shock and thermal metamorphic history of the enstatite chondrites (EC), an important class of primitive solar system material that may be analogous to the precursors of Earth. He aims to quantify shock metamorphic effects in EC minerals at scales ranging from a few unit cells to features visible in the optical microscope. Thus far, he has helped to develop an X-ray diffraction–based technique to quantify the degree of misorientation within shocked mineral grains and has investigated a meteorite that may represent a partial melt residue of EC parentage. His ongoing efforts include mapping the distribution of lattice misorientation within individual mineral grains using electron backscatter diffraction and focused ion beam sample preparation for transmission electron microscopy. He has always had a fascination for the fundamental nature of “stuff,” and he is happy to have found a niche in mineralogy where he can explore some of nature’s little puzzles.

Melissa Anderson completed a BSc degree in geology (Hon.) with a minor in physics at Brandon University, Manitoba. She then enrolled in a master’s program in geology at the University of New Brunswick, Fredericton, under the supervision of Dr. Dave Lentz and Dr. Chris McFarlane. Her MSc study comprises a detailed examination of the Moose II pegmatite, located 115 km southeast of Yellowknife, Northwest Territories. This zoned pegmatite forms a north-trending dike, approximately 430 m long and up to 61 m wide, and belongs to the spodumene subtype of the rare-element pegmatite family. This pegmatite was selected for detailed geochemical investigations due to its accessibility, exposure, and production history for lithium and tantalum (1946–1954). Melissa is examining how the pegmatite formed, the mechanisms of emplacement, and the processes leading to mineralization. In addition, she is using the trace element geochemistry of muscovite to develop a geochemical exploration tool for pegmatites in the area. Rare-metal granitic pegmatites are important hosts for the rare lithophile elements, including Ta, Li, Cs, Nb, Be, and Sn. These elements are fundamental for current and emerging technologies. Melissa loves doing geological field work and has found a passion for economic geology.

New Councilors

At its last meeting, the MAC Council welcomed three new councilors:

David London is the Stubbeman-Drace Presidential Professor, the Norman R. Gelphman Professor of Geology, and the director of the electron microprobe laboratory at the University of Oklahoma. London also acts as chair and managing editor for the Pegmatite Interest Group of the Mineralogical Society of America. London’s research pertains to the chemical evolution of silicic magmas. His work combines experimental studies with research on the chemical attributes of common and rare minerals in granites and pegmatites. He is the author of Pegmatites, which was published in 2008 as Canadian Mineralogist Special Publication 10, and he received the Hawley Medal in 2010 for his paper “The Origin of Primary Textures in Granitic Pegmatites” (Canadian Mineralogist 47: 697-724). London is a member of the Mineralogical Association of Canada and the American Geophysical Union, and a fellow of the Mineralogical Society of America. He is the namesake of the mineral londonite, CsAlBe$_4$[B$_2$Be]O$_{28}$ (Canadian Mineralogist 39: 747-755).

Christopher G. Weihsner is an associate professor at the Great Lakes Research Institute for Environmental Research (GLIER) at the University of Windsor and is cross-appointed to the Department of Earth and Environmental Sciences at the same university. He received his undergraduate degree in geology (1998) and his PhD (2003) from the University of Western Ontario. From 2002 to 2004 he was a postdoctoral fellow at the University of Waterloo, where he investigated metal-contaminant transport in groundwater from mine waste sites. From 2004 to 2005 he continued his postdoctoral training at the University of Windsor, studying microbial metal cycling and applying synchrotron and high-resolution transmission electron spectroscopies to elucidate microbe–mineral interactions. In 2005 he joined the faculty of GLIER as an assistant professor. In 2010 he was awarded an Early Researcher Award by the Ontario Ministry of Research and Innovation for his research into microbe-catalyzed metal mobility associated with mine-impacted watersheds.

Yulia Uvarova received a BSc in geology (2001) from Moscow State University, Russia, and a PhD (2008) from the University of Manitoba. Her PhD research was on the mineralogy, petrology, and geochemistry of rocks from the Kola Superdeep Borehole, Russia, the deepest borehole ever drilled. While working on her dissertation, she was involved in projects that resulted in the description of 8 new minerals. Yulia is currently an NSERC postdoctoral fellow in the Department of Geological Sciences and Geological Engineering at Queen’s University, Kingston. Her research focuses on the geochemistry, mineralogy, petrology, and genesis of economic mineral deposits, uranium in particular; the development of new tools for uranium deposit exploration; the behavior of high-field-strength elements in high-temperature systems; and the geochemistry of nontraditional isotopic systems and the application of these systems to the elucidation of processes responsible for deposit formation.
MAC awarded 12 travel and research grants in 2011, for a total of $8800. We congratulate these deserving students and give highlights of their reports. Several presented their research results at the GAC-MAC-SEG-SGA joint meeting held in Ottawa (GAC-MAC 2011) in May 2011.

Pedro Acosta is a PhD student at the University of Alberta, supervised by Dr. Sarah Gleeson. His project deals with iron oxide–copper–gold (IOCG) mineralization in the Great Bear Magmaic Zone, Northwest Territories. He aims to characterize the nature and geochemistry of the fluids responsible for the multiple mineralizing episodes through detailed petrographic, electron microprobe, fluid inclusion, isotope, halogen, and trace element analyses. He presented his preliminary results at GAC-MAC 2011.

Donnelly Archibald presented a poster at GAC-MAC 2011, related to his MSc thesis at Acadia University, Wolfville, Nova Scotia. The poster was entitled “Revised Bedrock Geology of the Southern Antigonish Highlands, Nova Scotia, Canada.” The purpose of the project is to characterize a recently recognized Ordovician plutonic suite in the Avalonian of northeastern Nova Scotia. Interacting with specialists in his field was the most beneficial aspect of attending the conference.

Neil Fernandes is an MSc student at the University of Alberta. His research on the geology and geochemistry of “barren” barite sequences in the Selwyn Basin, Canada, and their relationship to sediment-hosted lead–zinc occurrences in the same region has resulted in the definition of new exploration vectors. He presented his research at the “Economic Potential of Northern Canadian Sedimentary Basins” session at GAC-MAC 2011.

Anna Hicken, an MSc student at Queen’s University, attended the International Applied Geochemistry Symposium in Rovaniemi, Finland. She presented her research on the glacial dispersal of indicator minerals at the Izok Lake volcanogenic massive sulfide deposit, Nunavut, Canada. She is using till and bedrock to establish a suite of indicator minerals for an amphibolite grade metamorphosed VMS deposit.

Steven Holland, an MSc student at McMaster University, presented a poster at GAC-MAC 2011. He is investigating the influence of iron-reducing bacteria on copper, cadmium, and arsenic sorption to bentonite clays, as well as the bacterial influences on the long-term stability of sorbed metals(loid)s. With the help of the MAC travel grant, he learned much from discussions with other geoscientists.

Darren Lefort, an MSc student at St. Mary’s University, Halifax, attended GAC-MAC 2011 to deliver his talk “Subepithermal Au-Pd Mineralization Associated with an Alkaline Porphyry Cu-Au Deposit, Mt. Milligan, Quesnel Terrane, British Columbia, Canada.” Based on his undergraduate thesis, his presentation discussed the link between alkaline porphyry and subepithermal (epithermal-like deposits occurring outside typical epithermal regimes) deposits as revealed through bulk rock analyses and fluid inclusion studies.

Rhea Mitchell, as part of her MSc thesis at the Memorial University of Newfoundland, conducted nanoscale imaging of granulite facies symplectites and partial melting microstructures using transmission electron microscopy at the GFZ German Research Centre for Geosciences. She found conclusive evidence for static partial melting at the nanoscale, thus increasing understanding of the internal structure of these high-temperature metamorphic minerals and the mineral reactions that took place at grain boundaries.

Daniel Petrasch attended the 2011 Goldschmidt Conference in Prague, where he presented preliminary results of his PhD research at the University of Alberta. He is evaluating the likely contribution of microbial activity to geochemical signatures preserved in the stromatolitic rock record. This conference fostered motivating exchanges with researchers at all levels working in geochemical modeling of microbe–mineral interactions.

Jared Shivak, an MSc student at the University of Western Ontario, traveled to the University of Alberta to perform electron microprobe analyses on a suite of Martian meteorites. Martian meteorites provide the only samples of Martian bedrock available for study on Earth. The geochemical work performed with the help of this grant will be integrated with other analyses to provide a full characterization of these meteorites and a clearer picture of the habitability of the Martian subsurface.

Katie Smart attended the Goldschmidt Conference in Prague, where she presented results from her PhD research in the session “Mantle Redox and the Deep Carbon Cycle.” Her presentation dealt with the formation mechanism of diamonds in the cratonic mantle lithosphere and the potential carbon sources involved in diamond growth. Part of Katie’s research at the University of Alberta focused on determining the process of diamond formation in eclogite xenoliths from the Jericho kimberlite, Nunavut.

Michelle Thompson, of Queen’s University, attended GAC-MAC 2011. She presented the results from her undergraduate project on brecciated ordinary chondrite NWA-869 from the collection of the Royal Ontario Museum. Her travel grant provided her a first opportunity to give a presentation at a scientific conference. Being able to listen to and share ideas with other researchers was invaluable experience and has encouraged her to continue on to graduate studies.

Anne Westhues, a PhD student at the Memorial University of Newfoundland, traveled to Stockholm to carry out analyses at the NordSIMS facility. She collected U–Pb dates of zircon, monazite, apatite, and titanite from the Kiruna iron ore deposits of northern Sweden. Combined with Sm-Nd and Lu-Hf isotope systematics, these dates will give a better understanding of how these deposits form in nature. Her goal is to develop a predictive model for the exploration of similar deposits throughout the world. These deposits are considered to be end-member of the IOCG class of deposits and are a potential source of rare earth elements.
MINERALOGICAL SOCIETY OF POLAND: NEW HONORARY MEMBERS

The Mineralogical Society of Poland (MSP) has recently awarded the title of Honorary Member of the Society to three prominent scientists in the mineral sciences: Professors Maria Borkowska-Lydka, Barbara Kwiecinska, and Anna Maliszewska.

Maria Borkowska-Lydka, professor emeritus of the Polish Academy of Sciences (PAS), Warsaw, is a leading Polish petrologist who is well known for her long and fruitful career as the director of the Institute of Geological Sciences, PAS, and much liked by her colleagues for her friendly personality. Her scientific interests center on the genesis of granite rocks and on the formation and evolution of granite magmas. Her petrological studies on the granitoid masses of the Sudetes (southwest Poland, Central European Variscides), which had been studied half a century earlier by Hans Cloos, have shed new light on Variscan magmatism and significantly influenced the European “granite school.” Her monograph on the Karkonosze Granite (including original and pioneering contributions to the chemistry and structure of feldspars as petrogenetic indicators) is still highly regarded and widely quoted.

Professor Borkowska is also well known among Polish students in the Earth sciences for her excellent handbook (coauthored by Kazimierz Smulikowski), *Rock-Forming Minerals.*

In 1968, Professor Borkowska was among the founders of the Mineralogical Society of Poland. Earlier, she had become a member of the Société Française de Minéralogie et de Cristallographie. During the period when Central European countries were politically isolated, her close links with the French mineralogical community were important for the introduction of modern, international research trends. In recognition of her scientific achievements and international reputation, she was nominated as the scientific secretary of PAS and as a member of the Scientific Council of PAS in Paris. Throughout her career, Professor Borkowska has contributed greatly to the promotion of mineral sciences in society. Her professional activities and outstanding scientific achievements justify her place among the Honorary Members of MSP.

Barbara Kwiecinska, professor emeritus of the AGH University of Science and Technology, Krakow, is an internationally recognized expert in coal petrology. She has published over 150 research papers and four monographs, nearly all devoted to the various types of coal and related organic matter. Her habilitation thesis characterized the numerous structural forms of the hexagonal and orthorhombic polymorphs of natural graphite, which represented various metamorphic facies in deposits around the world.

Professor Kwiecinska has collaborated with many research teams from academic centers worldwide: Newcastle University, Newcastle upon Tyne; INCAR-CSIC Oviedo; the Michigan Technological University (USA); the Geological Survey of Denmark and Greenland, Copenhagen; and the High Mining School Ostrava (Czech Republic). She also participated in the IGCP Project “Organics in Major Environmental Issues.”

Professor Kwiecinska has been a member of the International Committee for Coal and Organic Petrology (ICCP) since 1970, a vice president of this committee from 1995 to 2003, and a honorary member since 2007. She has coorganized and participated in ICCP conferences in many countries. For many years, she was secretary of the scientific board of *Mineralogia Polonica* (now *Mineralogia*). For 25 years beginning in 1977, she was a member of the editorial board of the *International Journal of Coal Geology*. She initiated the Coal Petrology Group of the Polish Geological Society and was a member of the Committee on Mineralogy and the Committee on Geology of PAS. She was a meritorious teacher and coauthored several academic textbooks.

Professor Barbara Kwiecinska joined the MSP at its very beginning. She has always been a very active and enthusiastic member of the MSP, beloved by colleagues and students.

Anna Maliszewska, professor emeritus of the Polish Geological Institute (PGI) – National Research Institute, is a well-known specialist in the fields of petrology, mineralogy, and geochemistry. For more than 50 years, Professor Anna Maliszewska was employed by the PGI in Warsaw. In her professional career, she worked mainly on sedimentary and volcanic rocks ranging in age from Precambrian to Quaternary. She has published ten monographs and books (including the popular *Petrographic Dictionary*, coauthored by Wacław Ryka), 63 reviewed papers, and 75 short papers and abstracts. Most of Professor Maliszewska’s scientific work has involved detailed petrological studies, which have been important in the analysis of sedimentary basins and the reconstruction of diagenetic processes. Her wide-ranging scientific activities have had practical applications in prospecting and mineral and rock exploitation. An important theme of her studies was the mineralogy and geochemistry of soils. She studied soils in Poland and in many other regions of the world (Argentina, Finland, Mongolia, Germany, Syria, and Iraq). Professor Maliszewska created a research group of sedimentary petrologists at the PGI. She also led a Polish–German cooperative project to develop a methodology for mineralogical and petrological studies in sedimentary rocks.

Professor Anna Maliszewska was a founding member and, for decades, an active member of the MSP. From 1970 to 1978, she was the secretary of the Warsaw branch of the Society. Later, she became a member of the Board and vice-president of the branch. From 2005 to 2009, Professor Maliszewska was the president of the Warsaw branch and a member of the Board of the MSP. At present, she continues to act as a member of the Board of the Warsaw branch.

A characteristic common to our new Honorary Members, apart from their scientific achievements and their impressive numbers of high-quality publications, is their ability to attract and inspire people, thus drawing them into the large mineralogical family. This has always been most important for the development of the mineral sciences in our country.

R. Kryza, E. Słaby, K. Jarmołowicz-Szulc, A. Manecki, M. Michalik

Members of the Board, MSP
The First European Mineralogical Conference will be held this year from September 2–6 at the Johann Wolfgang Goethe-University in Frankfurt, Germany. This EMC2012 meeting is intended as the beginning of a biennial series of conferences to be held in different host countries with the goal of furthering the exchange of new results and ideas in the material oriented geosciences at a European level. Ten mineralogical societies are participating in this first meeting:

- DMG Deutsche Mineralogische Gesellschaft
- MinSoc Mineralogical Society of Great Britain & Ireland
- MinSocFin Mineralogical Society of Finland
- ÖMG Österreichische Mineralogische Gesellschaft
- PTMin Mineralogical Society of Poland
- RMS Russian Mineralogical Society
- SEM Sociedad Española de Mineralogía
- SFMC Société Française de Minéralogie et de Cristallographie
- SIMP Società Italiana di Mineralogia e Petrologia
- SSMP Swiss Society of Mineralogy and Petrology

Fourteen symposia themes were agreed upon by these societies under the general conference theme “Planet Earth from Core to Surface”. Together, they cover a broad range of topics in mineralogy. Each theme is comprised of sessions that are listed below together with their designated convenors. The session titles and the support of the convenors fill us with great expectations for an exciting and stimulating conference. Highlights of the scientific programme will be the invited speakers including this year’s IMA award medallist, D.H. Green: “Experimental petrology of peridotites, basalts and C, H, O – a Window on the Earth’s Upper Mantle”; Hilary Downes looks at mantle and core formation including this year’s IMA award medallist, D.H. Green: “Experimental petrology of peridotites, basalts and C, H, O – a Window on the Earth’s Upper Mantle”;

Abstract submission deadline: 15 May 2012

**THEMES, SESSIONS AND CONVENORS AT EMC2012**

**MANTLE PETROLOGY AND GEOCHEMISTRY**
- 1a Nature of the deep lithospheric mantle and interactions at the lithosphere-asthenosphere boundary (Aubach, Klemme, Tommasi)
- 1b Geochemical evolution of the mantle: from the Hadean to modern signatures (Weyer, Ionov)
- 1c Mantle processes as revealed by trace elements, phase relations and redox state (van Vestrenen, Woodland)
- 1d Earth’s deep volatile cycle (Keppler, Demouchy, Bromiley)

**MAGMATISM AND VOLCANOLOGY**
- 2a Magmatic crystals as recorder of pre- and syn-eruptive processes: analysis, modelling and quantification (Troll, Klugel, Wiesmaier)
- 2b Crustal evolution in arc settings: magmatism, geochemical models and field observations (Wörner, Holtz, Münntener)
- 2c Experimental and observational constraints on the abundance and role of volatiles in magmas: from reservoirs to the surface (Ulmer, Scaillet, Slaby)

**METAMORPHISM**
- 3a Deciphering high grade metamorphic processes: trace elements, accessory minerals and isotopes (O’Brien, Harley, Rubatto)
- 3b Fluid release, fluid flow and mass transfer in metamorphic environments: nature and modelling (Scambelluri, Tropper, John)
- 3c Modelling phase equilibria in metamorphism (Polli, Conolly)

**APPLIED MINERALOGY**
- 4a Mineralogical aspects of CO2 storage (Soler, Liebscher, Wilkinson)
- 4b Building materials and mineral processing (Pollmann, de Villiers)
- 4c Medical and Environmental Mineralogy (Fiore, Gualtieri, Posfai, Giéré)
- 4d Natural and synthetic host phases for radionuclides (Pattrick, Bosbach, Yudintsev, Gatta)

**MINERAL PHYSICS**
- 5a Elasticity, plasticity, and rheology of minerals - implications for anisotropy and convection in the Earth (Mainprice, Merkel)
- 5b News from the Earth’s interior: a mineral-physics approach (Bofka-Ballaran, Angel, Figuet)
- 5c Advances in spectroscopy of Earth materials (Wille, McCammon, Stalder)
- 5d Computational mineral physics (Winkler, Jahn)

**MINERALOGICAL CRYSTALLOGRAPHY**
- 6a Handling structural complexity: theoretical and experimental methods applied to unravel structural hierarchies (Balic, Camara, Siidră)
- 6b New minerals, classifications and related issues (Pasero, Galuskin, Pekov)

**PLANETARY MATERIALS**
- 7a Geochemistry and petrology of meteorites (Palme, Folco, Wilkinson)
- 7b Planetary formation in the Early Solar system (Mezger, Wade)
- 7c Evolution of the continental crust (Storey, Zeh)

**MINERAL DEPOSITS AND RAW MATERIALS**
- 8a Ore belts in Europe (Alderton, Palinkas, Tornos, Fontboté)
- 8b PGM and related accessory minerals in mafic-ultramafic rocks and unconventional deposits (Owen, Tzarzarin, Vymazalova)
- 8c Ore-forming hydrothermal processes (Heinrich, Wilkinson)
- 8d Critical raw materials for Europe (Raith, Melcher)

**LOW-T GEOCHEMISTRY**
- 9a Water–rock interactions in natural and contaminated systems (Bogush, Momnin, Zuddas)

**GEOCHRONOLOGY**
- 10a Timing and rates of geological processes - geochronology in action (Finger, Gerdes, Dobson)
- 10b Isotope geochemistry: traditional and non-traditional, mass-dependent and non-mass-dependent (Münker, Fiebig, Pack, Staubwasser)

**GEOBIOCHEMISTRY**
- 11a Biologic mineralization and biomimetic model systems (Schmahl, Rodríguez-Navarro, Benzerara)
- 11b Geobiochemistry and mineralogy of mine waste: perspectives and future goals (Hudson-Edwards, Morales, Majzlan)

**ADVANCED ANALYTICAL TECHNIQUES**
- 12a Exploring the nanoworld: synchrotron and neutrons advances in environmental geochemistry and mineralogy (Benning, Testemate, Rodríguez-Blanco, Artioli)
- 12b Nano- to micro-scale platform in the geosciences: Advances in analytical techniques (Ahmed, Rollinson, Mugnaioli)

**ARCHEOMETRY, CARE AND PRESERVATION**
- 13a Mineralogical sciences and cultural heritage (Greiff, Ionescu, Quartieri)

**OPEN SESSION**
- 14
9th SWISS GEOSCIENCE MEETING
11–13 November 2011, Zürich
The 9th edition of the Swiss Geoscience Meeting was held in the spectacularly renovated Earth Science building of ETH Zürich. The plenary session on Friday, November 11, was devoted to the topic “Life and Planet Earth.” The invited keynote lecturers were A. Halliday (Oxford), L. Kump (Penn State), N. MacLeod (London), A. Boetius (Bremen) and D. Imboden (Bern). These lectures were followed with great interest by an impressive audience that filled the largest lecture hall at ETH. On Saturday, about 700 participants attended 18 symposia (384 oral pre-

sentations) covering all aspects of geosciences in Switzerland. As in previous years, our society offered a “Mineralogy-Petrology-Geochemistry” open session, which was characterized by a breadth of topics and a lively audience. A second session, “Perspectives on Batholith Formation and Evolution in 4-D,” was convened and chaired by doctoral students of the national Swiss doctoral program “Adamello 4-D”; many outstanding talks and lectures by invited keynote speakers from the USA, France, and the UK attracted a large audience. The poster sessions in both symposia were well attended and fostered lively scientific discussions, which were considerably eased by the available drinks.

THE 4-D ADAMELLO FIELD CONFERENCE

Bagolino, Italy, September 5–12, 2012
This field conference will summarize the results of the Swiss doctoral program “Adamello 4-D.” It will feature a 3-day lecture program in the village of Bagolino (UNESCO world heritage site) and 3 days of excursions into the southern part of the Adamello batholith, with overnight stays in mountain huts. The symposium will benefit from invited keynote lectures by T. Sisson (USGS), B. Schoene (Princeton), D. Coleman (North Carolina), B. Dutrow (Louisiana State), J. Blundy (Bristol) and J. Dufek (Georgia Tech). For details, consult www3.unil.ch/wpmu/adamello2012/.

10th Swiss Geoscience Meeting
16–17 November 2012, University of Bern
“Mountains – Up and Down”

Obituary: Prof. Emilie Jäger (1926–2011)

During the summer of 2011, we lost one of the pioneers of radioisotopic dating, Prof. Dr. Emilie Jäger. After a degree in chemistry in her hometown of Vienna, she moved to the University of Bern in 1952. She developed a profound interest in mineralogy, chemistry, and the isotopic chemistry of minerals during her doctoral studies in the Department of Mineralogy, under the direction of H. Huttenlocher, and later in the Department of Physics, under F. G. Houtermans. The late 1950s witnessed a genuine interest in dating minerals, with the advent of new isotopic methods developed in different laboratories around the world. Emilie Jäger’s supervisors therefore decided to send her to the Carnegie Institution in Washington, DC, where she learned the techniques of Rb–Sr dating of minerals; there, she was inspired by the presence of several outstanding isotope geochemists, such as George Tilton and Henry Faul. She returned to the University of Bern and set up an isotopic laboratory in 1959–1960. The first Rb–Sr isotope measurements on minerals were carried out in 1959 using the solid-source mass spectrometry laboratory in the Department of Physics, led by J. Geiss, P. Eberhardt and H. Oeschger. By determining mineral and whole-rock Rb–Sr isotope compositions in the Alpine orogen, she developed the hypothesis that the mineral ages had to be interpreted in terms of cooling ages, a theory summarized in her 1962 paper, “Rb–Sr Age Determinations on Micas and Total Rocks from the Alps,” and further developed over the following decade. She subsequently became involved in many aspects of isotope geochemistry, such as decay constants (Steiger and Jäger 1977), establishing mineral standards for radioisotopic dating (Jäger et al. 1963), dating mineral deposits and dating petroleum migration in reservoirs, and she participated in the establishment of environmental isotope chemistry in Switzerland and neighbouring countries. Towards the end of her career, she became increasingly interested in low-temperature chronometers, such as fission track dating, and optical luminescence.

She leaves behind a large number of former students, who now work at the national and international levels in environmental management and research, ressources, research infrastructure, life-quality services, construction projects in Switzerland and academia. Emilie Jäger’s former students are indebted to her for having shared with them her enthusiasm for science, for her generosity, and for having motivated them to achieve their scientific and professional goals.

Matthias Giger (Thun), Christian Schlüchter (Bern) and Urs Schaltegger (Geneva)

Jäger E (1962); Rb-Sr age determinations on micas and total rocks from the Alps. Journal of Geophysical Research 67: 5293-5306

Jäger E, Niggli E, Baethge H (1963) Two standard minerals, biotite and muscovite for Rb-Sr and K-Ar age determinations, samples Bern 4 B and Bern 4 M from a gneiss from Brione, Valle Verzasca

The most critical aspect in creating a stimulating workshop is that it is designed around a compelling science topic with wide interest.

### Figure 1

Revenues versus expenses for a workshop. For most workshops, the goal is to balance revenues and expenses.

### Science Goals for Workshops

Before running his workshop, it is important for Philippe to decide what he wants to achieve in terms of the scientific goals and what kind of participants he hopes to involve. The most critical aspect in creating a stimulating workshop is that it is designed around a compelling science topic with wide interest. Philippe decides to focus on one exciting new advance in mineralogy and geochemistry and then sends tentative invitations to speakers. He defines the delivery format (e.g., lectures, labs, field trip, etc.) and decides on the level of science output—he considers informal discussions, media (videos, web pages, databases), and a peer-reviewed volume or journal issue with papers or abstracts.

Peer-reviewed volumes have a lasting impact on science and provide a wonderful service to the community, but this avenue would add another dimension to Philippe's job. He chooses to team up with some other scientists and produce a volume. He needs to find authors who are willing to write on appropriate topics in the required timeframe. Then he defines the manuscript and figure format, finds reviewers, obtains funding for printing and shipping the volume, keeps track of authors' and reviewers' responses, and obtains copyright. Philippe is told that preparing a peer-reviewed volume might take 24 months from the initial stages to publication, so he plans to be engaged in the project for 30 months because he knows that there are always unforeseen hurdles.

### Preworkshop Logistics

The budget is one of the most difficult parts of the preworkshop logistics. As shown in Figure 1, most workshops aim to balance revenues and expenses. This means that it is critical to determine the largest revenue and expense items before proceeding with requests for sponsorship and going ahead with the workshop.

For many workshops in geochemistry and mineralogy, most of the revenue comes from the registration fees. From this perspective, estimating the number of speakers, professionals, and students who will attend is essential, because they generally pay different registration fees.

The largest expenses depend on the speaker costs and the workshop location. Many people think that workshop speakers have their costs entirely covered and might even be paid for their appearance. However, more often than not, invited speakers in academic workshops pay their own way or are only partially subsidized. Philippe decides to write a formal letter to each potential workshop speaker, and he places several upper limits on travel reimbursements, which are dependent on the likely registration numbers.

The venue chosen also contributes significantly to the workshop costs. The location defines the cost of travel for the invited speakers, as well as the cost of the workshop room rental, audio-visual equipment, and food. It is helpful to consider site accessibility: if group transportation is required, the costs will be higher for the participants. Philippe tours a large hotel and the local university, looking at possible accommodation and facilities for his workshop, before deciding on a venue.

Once Philippe has confirmed the speakers and a location, he prepares a schedule with an agenda. All of the information that he has gathered up to this point is needed for the workshop-sponsorship proposal he will submit to a nonprofit professional organization. Getting such sponsorship may not mean that Philippe will receive a monetary contribution, but it may mean that he will have support from the organization when it comes to editing, formatting, producing, and distributing a scientific volume. At this stage, it is critical that Philippe communicates with the sponsoring society because they likely include people who have run similar workshops before, and conversations with these “old hands” will help him figure out successful strategies and potential pitfalls in running his workshop. He may also request an example of a spreadsheet to use as a template for his budget.

### Attracting Workshop Participants

As indicated in Table 1, a simple workshop may include a group of researchers who are familiar with each other and may already collaborate regularly. More complicated work-
shops arise when people are brought together with no previous research collaborations and when they come from a range of countries for which visas are required. To attract his target participants, Philippe comes up with a snappy workshop title and sets up a dedicated e-mail address for the workshop.

Philippe remembers back to when he was a student and attended a workshop with a travel grant. He makes inquiries and finds out that there are various options for funding available from his national science funding agency, so he submits an application for student travel grants. He also stops by the local cement company and gemstone distributors to alert them about the upcoming workshop, and they offer to sponsor a student travel grant, too. His plans are going well!

**On-Site Logistics**

Philippe does his homework before the workshop and decides to employ a helper to welcome participants at the registration desk. The helper will give each participant a welcome package, with a map to local restaurants and area attractions, the short course volume, a pad of paper and pen, and name tags. Importantly, this person will also help check that the audio-visual equipment works (with both Macs and PCs), that the presentation files are uploaded for all speakers, and that backup equipment is available.

**Postworkshop**

Philippe’s workshop turned out to be a success because he planned carefully (just like you could, too!). After the workshop, he checked the budget and wrote a report, then sent his volume of papers out for review to further promote the workshop.

**Acknowledgments**

Instructions on how to run a workshop by the Mineralogical Association of Canada and the Mineralogical Society of America were helpful in writing this article. Jim Webster (American Museum of Natural History) provided some insightful comments that were greatly appreciated.

**Penny King**
Australian National University

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<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>SOME VARIABLES THAT AFFECT HOW EASY OR DIFFICULT IT IS TO ARRANGE A WORKSHOP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VARIABLE or GOAL</strong></td>
<td><strong>INFORMAL</strong></td>
</tr>
<tr>
<td><strong>Science</strong></td>
<td></td>
</tr>
<tr>
<td>Scientific output</td>
<td>None or perhaps a summary of the discussions</td>
</tr>
<tr>
<td>Scientific activities during the workshop</td>
<td>Informal discussions</td>
</tr>
<tr>
<td><strong>Organizers</strong></td>
<td></td>
</tr>
<tr>
<td>One or a few</td>
<td></td>
</tr>
<tr>
<td>A large team</td>
<td></td>
</tr>
<tr>
<td><strong>Participants</strong></td>
<td></td>
</tr>
<tr>
<td>Local or close collaborators and students</td>
<td>International researchers and students with no previous collaborations</td>
</tr>
<tr>
<td><strong>Overseas participants</strong></td>
<td>None</td>
</tr>
<tr>
<td><strong>Subsidized invited speakers</strong></td>
<td>None or self-paying invited speakers</td>
</tr>
<tr>
<td><strong>Preworkshop agenda</strong></td>
<td>None</td>
</tr>
<tr>
<td><strong>Workshop advertising</strong></td>
<td>Conversation or e-mail</td>
</tr>
<tr>
<td><strong>Workshop venue choice</strong></td>
<td>Local to the organizer, quiet, and allows participants to mix</td>
</tr>
<tr>
<td><strong>Requirements for the workshop room</strong></td>
<td>Appropriate room (chairs, table, white board/paper), and A/V equipment</td>
</tr>
<tr>
<td><strong>Funding and budget</strong></td>
<td>None or in-house funds</td>
</tr>
<tr>
<td><strong>Registration</strong></td>
<td>None</td>
</tr>
<tr>
<td><strong>Deposits</strong></td>
<td>None</td>
</tr>
<tr>
<td><strong>Helpers (or professional organizers)</strong></td>
<td>Not required or done by people in house (e.g. students)</td>
</tr>
<tr>
<td><strong>Food requirements</strong></td>
<td>Not required or minimal (e.g. coffee/tea breaks)</td>
</tr>
<tr>
<td><strong>Accommodation</strong></td>
<td>None required</td>
</tr>
<tr>
<td><strong>Budget</strong></td>
<td>Not applicable</td>
</tr>
<tr>
<td><strong>Postworkshop</strong></td>
<td>None</td>
</tr>
</tbody>
</table>
The 9th International Eclogite Conference, with associated field trips, was held in Mariánské Lázně, Czech Republic, on August 6–10, 2011. The Organizing Committee was led by Shah Wali Faryad (Charles University, Prague) in cooperation with Gordon Medaris, Emil Jelínek, Ondrej Lexa, Martin Svojtka, Lukáš Ackerman, David Dolež, and Zdeněk Venera. A total of 147 participants from 22 countries participated in the conference. The conference agenda was prepared by the International Eclogitic Committee. The abstract volume and field trip guide can be downloaded from http://petrol.natur.cuni.cz/eclogites/index.php/ice/2011 and http://geolines.gli.cas.cz/. The conference sponsors were Charles University (Prague), the Academy of Sciences of the Czech Republic, the Czech Geological Survey, the Ministry of Environment of the Czech Republic, Task Force IV of the International Lithosphere Program, Tescan Co. (Czech Republic), Oxford Instruments Inc. (UK), Nikon Co. (Czech Republic division), and Agico Co. (Czech Republic). The program was coordinated with the Task Force IV of the International Lithosphere Program.

New achievements in the following fields were discussed in the scientific sessions:

1) **Ultrahigh-pressure (UHP) metamorphic phases and microfabrics in high-pressure (HP) metamorphic rocks.** The session highlighted a new discovery of microdiamonds in granulite of the Bohemian Massif (Czech Republic), garnet peridotite of the Western Alps (Italy), and ophiolites of Tibet (China). The sessions also considered theoretical and experimental aspects of UHP phase transformations, the formation of microfabrics, and the kinetics of breakdown reactions recorded by microstructural features of exsolution products and chemical reactions.

2) **Geotectonic modeling and exhumation of HP-UHP metamorphic rocks.** The session focused on current work and achievements in the field of numerical modeling of rock dynamics in collisional orogenic belts, and the characteristics and evaluation parameters of the rapid rate of exhumation of natural UHP-HP rocks by geophysical, geochemical, and geochronological methods. Original data collected from UHP-HP terranes in the orogenic belts of Siberia, the European Variscides, the Greek Rodopes, and the Scandinavian Caledonides, and from a unique, fast-exhumed terrane containing coesite-bearing eclogite in New Guinea, were presented.

3) **Mantle dynamics and fluid flow in the subduction zone.** Fragments of mantle peridotite involved in subduction zone processes play an important role in understanding the transfer of large amounts of volatiles into the mantle by the subduction of crustal materials. In this context, participants in the session discussed the geochemical, microstructural, and compositional features of garnet peridotites from the Greenland Caledonides and the deep origin of Alpe Arami peridotites from the Ligurian Alps. The theme was extended to the understanding of mass flow in serpentinite-hosted subduction channels, the geodynamic significance of mantle rocks incorporated within UHP-HP metamorphic terranes, carbonate mineral stability, and carbonic fluid activity. Processes related to metamorphic dehydration and partial melting of UHP metamorphic rocks with crustal protoliths and aspects of metasomatic processes were also on the agenda.

The poster sessions presented new findings from HP rocks and brought to the attention of participants original studies on mantle–crust interaction from the petrological, geochronological, and geodynamical perspectives. These studies were conducted in the Alps, the Appalachians, the Bohemian Massif, the Carpathians, central Iran, North Qaidam, Papua New Guinea, the Sanbagawa belt, the Scandinavian Caledonides, the Turides, the Urals, and other orogenic belts.

The Organizing Committee of the conference presented three awards for the best student presentations; the winners were A. Cruz-Uribe (USA), Y. Kouketsu (Japan), and A. O. Mikhno (Russia). Dirk Spengler (Potsdam University, Germany) received the Flinn-Harte Award from the International Eclogitic Committee.

Pre- and postconference field trips to the Bohemian Massif illustrated the geological relations, lithological and geochemical features, and metamorphic evolution of several HP and UHP crystalline segments that formed by subduction and collision during the Variscan orogeny. The participants had a chance to observe the entire orogen, examine the various lithologies, and discuss the pressure-temperature evolution of HP and UHP crustal and mantle rocks. These rocks were exhumed along subduction channels and subsequently reequilibrated under granulite facies conditions in the orogenic root. During preconference field trips, participants crossed the Saxothuringian zone of the Bohemian Massif. They also visited the Saidenbach reservoir area, where they discussed the tectonometamorphic evolution of coesite- and microdiamond-bearing gneisses, the Zöblitz garnet peridotite (both in Germany), and the low-temperature eclogite at Meluzina (Czech Republic). The mid-conference field trip focused on eclogite in ophiolite of the Marianské Lázně Complex. The latter is an example of amphibolite facies metamorphism during an early stage of the Variscan orogeny superimposed on eclogite facies rocks.

Participating in the postconference field trip examined rocks along a >200 km traverse through the Moldanubian zone in the eastern part of the Bohemian Massif. HP granulites, containing lenses of eclogite, garnet peridotite, and garnet pyroxenite, were enthusiastically collected by the participants. The field trip continued into Austria, where garnet peridotite and garnet pyroxenite in granulites were observed at two localities. Garnet peridotite, garnet pyroxenite, and eclogite samples associated with felsic granulites were collected at the Kutná Hora in the central part of the Bohemian Massif, and these samples will be studied later using advanced analytical techniques in various laboratories.

Plans are already underway for the 10th International Eclogite Conference (www.iec2013.unito.it), which will be held in Courmayeur, Aosta Valley, Italy, from September 2 to 10, immediately following Goldschmidt 2013 in Florence.

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A REVIEW AND MUSINGS ABOUT GEOFLUIDS RESEARCH

Frontiers in Geofluids is actually a collection of invited papers published in 2010 to mark the tenth anniversary of the launch of the journal Geofluids. It is composed of 19 research and review articles varying in length from 7 to 32 pages and written by 39 different authors, many of whom are leading authorities in the study of geological fluids. The topics cover a wide range of subjects, including the specification and equations of state of fluids, mineral–fluid equilibria, mineral–fluid reactions and reaction mechanisms, the structural and stratigraphic control of fluid flow, the creation and destruction of permeability, the relation between heat flow and fluid flow, and the relation between earthquakes and groundwater flow. The study methods reported involve theoretical calculations, laboratory experiments, field studies, and the analysis of rock and fluid samples. The latter two methods are applied specifically to sedimentary rocks and sedimentary basins, groundwater flow, seafloor and continental hydrothermal systems, hydrocarbon and ore deposits, metamorphic rocks, and melt inclusions. Individual articles range from a systematic review of a subject (e.g. A. Liesborcher on phase equilibria and physical properties of aqueous fluids) to results of new research (e.g. B. W. D. Yardley, D. E. Harlov, and W. Heinrich on the experimental simulation of retrograde metamorphism), although most articles have more of a mix. The level of Frontiers in Geofluids is similar to that of “Frontiers” papers in Earth and Planetary Science Letters and Reviews in Mineralogy and Geochemistry. The volume has a broader reach than “Frontiers” papers, but is not as comprehensive as RIGM volumes.

The 19 articles can be grouped in a number of ways. The editors chose five subject categories: theory and experiment (4 articles), sedimentary basins (3), ocean crust and upper mantle (4), continental crust (6), and other (2, one each on ore deposits and melt inclusions). A more revealing two-part subdivision, however, can be made in terms of the underlying science discipline: (1) physical aspects of fluids and fluid flow, including rock and fluid mechanics and heat flow (7 articles), and (2) chemical aspects of fluids and fluid flow (12 articles). The two kinds of studies seem to peer at each other across an abyss. The physics articles ignore any chemical reaction between fluids and rocks, while the chemistry articles generally ignore the mechanics of fluid flow or even fluid flow entirely. (A notable exception is the paper by D. Dolejs and C. E. Manning, which models the precipitation of minerals in veins.) The reason that fluids are important in Earth science is because they flow. When fluid flows through rock, reaction between the two is not just possible, but inevitable. Flowing fluids transport heat and mass at kilometer to crustal scales, and they have played a vital role in processes such as the distribution of elements in the crust, the cooling of the planet, the driving of mineral reactions in thousands of cubic kilometers of the crust, the formation of most ore and hydrocarbon deposits, and the evolution of life, if not the origin of life itself. A quantitative understanding of all these (and other) important processes requires integrated studies of the physics and chemistry of fluids and fluid flow, not just a consideration of one or the other by itself.

The title, Frontiers of Geofluids, is appropriate because the volume is an excellent snapshot, of interest to all readers of Elements, of how far studies in geological fluids have progressed in scope and sophistication over the last two decades. The volume, however, could also be considered a kind of manifesto for research opportunities because of its compelling documentation of the gap between studies of the physics and chemistry of fluid flow. Bridging that gap is the next frontier. The foundation of such integrated studies—transport theory—has been known for decades in hydrogeology and chemical engineering. This theory includes statements of the conservation of energy (the heat equation), of mass (the advection-diffusion equation), and momentum (usually Darcy’s Law). As several authors note (e.g. C.-Y. Wang and M. Manga, p. 213), further advances in fluids research will involve new research in theory, laboratory experimentation, and field studies. Some theoretical problems include the incorporation of complex fluid and solid solutions into transport models and the consideration of rock mechanics in modeling the development of permeability in flow systems, for example. Experimental measurements are needed of mineral–fluid equilibria, mineral–fluid reaction rates, intercrystalline and intracrystalline diffusion rates, and permeability in porous media undergoing mineral–fluid reaction. Future field studies will focus on the spatial distribution of minerals, mineral assemblages, and the elemental and isotopic compositions of rocks and minerals, as well as their structural context, in active and fossil fluid flow systems on a spectrum of scales from microns to kilometers. These spatial distributions both record the various processes of heat and mass transport in fluid flow systems that can be decoded by transport theory and serve as tests for transport models that seek to explain the distributions.

To achieve this vision of a quantitative marriage of the physics and chemistry in studies of fluid flow, however, a new educational paradigm is called for. Just as the study of chemical thermodynamics is now considered a requirement in the training of geochemists, petrologists, and mineralogists, so should transport theory. Even a basic understanding of transport theory is a powerful tool for making back-of-the-envelope calculations that can solve the essence of a problem. Likewise, geophysicists need to have more training in phase equilibria. It may be too much to ask that each individual master all aspects of fluid flow, but even collaborative research will require among the partners a broader familiarity of both chemical and physical aspects of fluids and fluid flow than is currently the case.

On the practical side, Frontiers in Geofluids is in an attractive volume printed on heavy glossy paper, perfect for those like myself who enjoy scribbling notes in the margins and marking pages with dog-ears or Post-its for future reference. Typographical errors are remarkably few (e.g. there is an occasional mismatch in numbering between text and figure captions). Oddly, some figures that are in color in the electronic version of Geofluids appear in black and white in the printed version (however, with only minor loss of clarity). It is likely that few will choose to purchase the volume for themselves. Students and professionals whose institutions allow them access to Geofluids on the Wiley-Blackwell website can download any or all of the 19 articles for free. They would only lack the index. For those who do wish to have their own copy, as of December 12, 2011, print copies can be purchased for as low as $75.82 from Amazon; an electronic version for a Kindle is $80.43.

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Crystal twinning has been a fascinating topic of study since the development of modern mineralogy and crystallography. This crystallographic phenomenon is well synthesized in the book published, in French, by Jean-Claude Boulliard under the title Le cristal et ses doubles. Divided into three sections and accompanied by two annexes, the book treats the topic exhaustively. In the first part, the author reviews the various mineralogical, crystallographic, mathematical, and physical theories put forward to explain the nature of twinning. Boulliard uses mostly the discoveries of well-known French scientists to explain how knowledge grew during the 18th, 19th, and 20th centuries. The French and German schools of thought were frequently at odds with each other, and some of our modern theories take all their relevance in this historical context. Boulliard details the contributions to twinning theory made by the great scientists Hauy, Pasteur, and Bravais.

The second part introduces the modern theory of twinning. It shows the different components of current knowledge related to twins, including their geometric description, determination, and recognition. It explains in detail how the structural arrangement of atoms and molecules is the basis for the symmetry operations from which twins are ultimately derived. This section addresses mechanical, transition, and growth twins, and also offers an overview of epitaxy, a crystallographic phenomenon related to twinning. This section of the book requires a good grounding in crystallography to understand the theories presented therein and could have benefited from a more simply expressed section aimed at the amateur.

The third section is where the professional mineralogist joins the amateur and collector. It illustrates numerous remarkable twinned mineral specimens, all from the collection of the Université Pierre et Marie Curie (Paris), where Boulliard is the curator. The specimens are well chosen, and the photographs have generally been taken in view of the natural expressions of twins in minerals, although it takes keen observation to detect some twins. An inventory of deposits containing different twinned mineral species supplements the text and provides a valuable reference. Finally, two appendices, one devoted to the etymology of words and the other summarizing the modern theory of twins, complete the work.

Overall, Boulliard presents ideas effectively, without cluttering the text with unnecessary detail. However, we deplore the absence of computer graphics in the three-dimensional figures and in the photographs, which would have better highlighted the geometry of twins. Moreover, the lack of scale in the captions of mineral photographs is unfortunate. Apart from these few weaknesses, this book is undoubtedly an essential reference on this subject. It is a valuable contribution to the synthesis of information on the science of twins. This book will appeal equally to historians of science and mineral collectors.

François Létourneau, Saint-Nicolas, Québec

**BOOK REVIEW**

**ELOQUENT SCIENCE**

Eloquent Science: A Practical Guide to Becoming a Better Writer, Speaker, and Atmospheric Scientist is an eloquent book and delivers what its subtitle promises. The author, David Schultz, practices what he preaches: he writes in an engaging manner and for his reader. A professor of experimental meteorology at the University of Helsinki and the Finnish Institute of Meteorology and a reader at the University of Manchester, Schultz has extensive editorial and writing experience from which to draw.

Among the writing guides I have read (and there have been several), I would rate this book at the top. It would be well suited for a writing course or as a guide for a young researcher writing his first paper, though experienced writers will also find many gems for improving their writing. Initially I wondered if it would bother me that all examples are related to atmospheric science. But it did not: in fact, because I was not familiar with the jargon, it was clear to me how much improved the revised examples were.

The book comprises 4 parts. Over 200 pages are devoted to part I, “Writing and Publishing Scientific Research Papers.” Part II (25 pages) deals with the peer-review process, part III (90 pages) treats preparing and delivering scientific presentations, and part IV (20 pages) addresses communication in the workplace and with the media. Two annexes (one on commas, hyphens, and dashes, notes, and references complete the book. For the purpose of this review, I will focus on part I.

In part I, after outlining the process of publication and discussing what to take into account before deciding where to submit your paper, Schultz takes us through all the steps and mechanics of writing a paper. In “Motivation to Write,” he explores strategies for overcoming writer’s block and lack of motivation: write a little bit at a time, develop a plan, break your writing project into smaller parts, and make appointments with yourself to write some of the tips he offers. In “Accessible Scientific Writing,” he argues that “scientific writing does not need to be turgid, dense text written for a handful of specialists.” He encourages us to visualize our writing as being more like providing directions to the reader and to imagine that one’s audience is comprised of (1) one’s worst critics, (2) the best scientists in the field, and (3) the authors one is citing. In “Writing an Effective Title,” he states that “the title is your first opportunity to attract an audience to your paper.” Titles should be informative, accurate, concise, and clear, and they should command attention. Avoid starting a title with “The” and “An”; don’t use acronyms in a title. Schultz recognizes that papers in some high-profile journals, like Science and Nature, often have titles summarizing the conclusions of the paper, but he warns that if you choose that approach, your conclusions had better stand the test of time.

Getting down to the text itself, he progressively focuses on effective paragraphs, sentences, and words, giving many examples along the way. Effective paragraphs contain one theme only and are coherent. Their focal point is the “topical sentence,” often placed at the beginning of the paragraph and defining the theme. Schultz tells of writers who write the topical sentence of each paragraph as an outline of their paper. Ideal paragraphs are 4 to 8 sentences long, he says. You can download the chapter “Constructing Effective Paragraphs” as an excerpt of the book at http://eloquentscience.com/2009/11/chapter-8-constructing-effective-paragraphs. In applying the lessons in the chapter “Constructing Effective Sentences”—eliminate redundant words, choose shorter alternatives (e.g. replace “In the event of” by “if”), choose strong verbs, beware of sentences beginning with “it”—you can cut down the number of words in your text by 10 to 20%.

Of course, figures and tables are integral parts of a paper. But creating an effective figure that will be “worth a thousand words” requires many steps. Decide on the type of graphic that will best tell the story behind your data. In choosing font size, take into account the likely final size of the published figure. And of course, follow the instructions of the journal you plan to submit your paper to. “Never skimp on the caption”; every component of a figure needs to be described so that the reader gets the meaning of the figure from the caption alone.

Once you have a first draft of your paper, thesis, or report, celebrate; let it rest for a few days and then move on to the next step: revising. Schultz stresses the importance of this step to produce a high-quality manuscript. He states that some of the authors he admires most will produce up to 50 versions of their manuscript before they finally send it out for publication. Don’t count on editing after the review process: send out your very best effort right from the start.

A full chapter is devoted to second-language authors. All students will benefit from recommendations Schultz makes to ESL (English as a second language) scientists. I was glad to see that scientific ethics and misconduct rated a full chapter. It deals mainly with plagiarism, which accounts for most cases of misconduct in the physical sciences. In defining authorship, he adheres to the rules set out by the International Committee of Medical Journal Editors, which state that all authors of a manuscript must satisfy all three of the following criteria:

- They must have made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data
- They must have participated in drafting the article or revising it critically, thus providing important intellectual content.
- They must have approved the final version to be published

I hope I have by now convinced you that you need this book. It might be the best investment of $45 you will make. As a bonus, it is written in an entertaining, conversational style. I found myself turning page after page. The author maintains a blog and a website where excerpts of the book and a list of writing resources can be accessed (www.eloquentscience.com).

Pierrette Tremblay  
Managing Editor, Elements

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Call for Session Proposals for IMA 2014

Preparations are well under way for the 21st meeting of the International Mineralogical Association (IMA) in South Africa. The overall theme of the IMA 2014 meeting is “Delving Deeper – Minerals as Mines of Information.” The logo is symbolic of South Africa’s rich mineral resources, from which has sprung its dynamic mining heritage, also the backbone of the country’s economy. The meeting will take place on 1–5 September 2014 at the Sandton Convention Centre, in the heart of Johannesburg, the City of Gold.

The IMA 2014 meeting will be held under the auspices of the Geological Society of South Africa and the Mineralogical Association of South Africa, and is already generating sponsorship from the mineral industry, which will enable a professional, vibrant atmosphere for a memorable conference. South Africa’s sizeable community of mineralogists will contribute to the hosting of this first IMA meeting on African soil, and all aspects of mineralogy will be covered. The Organizing Committee is headed by Dr Sabine Verryn as conference chair, along with Dr Desh Chetty as scientific committee chair and Dr Craig Smith as finance chair.

Proposals for sessions and topics to be covered are invited (e-mail: info@ima2014.co.za), and further information is available on the conference website (www.ima2014.co.za). Please register to receive updated information if you are not already on the communications list. The Organizing Committee looks forward to welcoming everyone to South Africa in September 2014.
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For this Parting Shots, I have been ordered by Managing Editor Pierrette Tremblay to break with tradition and show some illustrations from my own research which seem appropriate for this issue. All are secondary electron SEM images of (001) crystal surfaces taken by my long-time and very skilful collaborator, Martin Lee, when we were investigating the complicated character of the surfaces of moderately weathered alkali feldspars. Although the surfaces appear smooth to the unaided eye, at the micrometre scale they are covered by all manner of tiny nooks and crannies\(^1\) that are potential homes for microbes. These defects are not intriguing rarities, but commonplace, albeit sub-optical, features of Earth’s surface. Alkali feldspar is the third most abundant mineral in the continental crust, and crystals originating in granitic rocks almost always develop similar complex surfaces when they enter the weathering zone.

**Figure 1** encapsulates the riot of crystal-structural and chemical processes that leads to nook and cranny formation. The original, centimetre-sized crystal grew from granitic magma 394 million years (Ma) ago at ~750°C as a homogeneous alkali feldspar solid solution with a composition near Na\(_{0.3}\)K\(_{0.7}\)AlSi\(_3\)O\(_8\). Na\(^+\) and K\(^+\) have very different ionic radii, and this imposed severe local distortions on the feldspar’s Al–Si–O framework. In response, at ~670 °C the crystal began to unmix, by solid-state diffusion, forming a lamellar intergrowth (known as film perthite) of Na-rich albite in a matrix of K-rich orthoclase. It is these film lamellae that give the pronounced E–W lineation on the micrograph.

Over the following 10,000 years, the crystal cooled and the lamellae grew longer and thicker, to lower their surface energy. Initially the framework remained completely continuous, but the different cell dimensions of albite and orthoclase led to elastic strains close to the surfaces of the lamellae. As the feldspar cooled and its structure stiffened, these strains became insupportable, and at ~400°C misfit dislocations nucleated to minimize strain energy. The tubular structures in the micrograph shown in **Figure 2**, resembling the perforations on old-fashioned postage stamps, mark the outcrop of these dislocations. Their character is most easily seen on the artificially etched surface in **Figure 2**, where the etch pits occur in pairs at the surfaces of the albite lamellae. Dislocations cannot end within a crystal; they must either reach a surface or form closed loops. Each pair of etch-pits lies on a section through a single dislocation loop, with the shape of a very flattened lens encircling each albite lamella.

For nearly 400 million years, the crystal lurked beneath the surface, at a maximum depth of ~3 km, replete with its inventory of residual elastic strains and energy in the cores of dislocations. Uplift began at ~65 Ma. Some 20,000 years ago, northern Britain was beneath a kilometre of ice, but rapid global warming 15,000 years ago led to fast retreat. Excavated by ice, our feldspar emerged into the light. Great forests developed, to be cut down by Neolithic man beginning 5000 years ago. Peat soils developed, with acid pore waters, currently with a pH of 3.4. The water rapidly became nearly saturated in feldspar components, and dissolution of our feldspar occurred preferentially, at sites of high strain or down dislocation cores, allowing fluid access to crystal interiors. At low temperatures, whenever both Na- and K-rich feldspars are present (as in these perthitic intergrowths), aqueous solutions with which they are in equilibrium are strongly enriched in Na and have fixed compositions that do not depend on the proportions of the two feldspars. So, in our feldspar (Fig. 1), albite has dissolved preferentially, leading to the E–W slots. A residual ‘toast-rack’ of orthoclase remains, flaking off in places to reveal striations where dislocations once occurred.

For well-understood crystallographic reasons, the long axes of the lens-shaped dislocation loops develop in two orientations, one approximately normal to (001), as shown in these micrographs, the other at right angles, parallel to the b-axis. Impregnation in vacuo using a runny type of resin, followed by dissolution of the silicate in HF, showed that the weathered feldspars contain extraordinary, deep, organized honeycombs of etch tubes penetrating many tens of micrometres beneath the surface (Fig. 3). Soil bacteria and other microbes demonstrably inhabit these natural labyrinths, and the tubes and cells are remarkably similar in size (Fig. 4). Aqueous fluids in the tubes will have high Na:K ratios, just like the extracellular fluids in your body, dear reader, while your cellular fluids are relatively rich in potassium. Encouraged by the late J. V. Smith (see *Elements* 1: 151-156), we and others have suggested that these myriad self-organized, cell-sized nooks and crannies may have provided protective containers for the prebiotic reactions that led to the first self-replicating molecules and the emergence of life.

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1 These strange English words may be unfamiliar to some of our international readers. The *Concise Oxford Dictionary* defines a nook to be ‘a corner or recess; a secluded place’. A cranny is ‘a chink, a crevice, a crack’. It is perhaps worth mentioning that the word nooky is U.K. slang for sexual activity, perhaps because it is usually enjoyed in a secluded place.

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Ian Parsons
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