Mine Wastes: Past, Present, Future
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Mine Wastes
Guest Editors: Karen A. Hudson-Edwards, Heather E. Jamieson, and Bernd G. Lottermoser

Mine Wastes: Past, Present, Future
Karen A. Hudson-Edwards, Heather E. Jamieson, and Bernd G. Lottermoser

Geochemistry and Mineralogy of Solid Mine Waste: Essential Knowledge for Predicting Environmental Impact
Heather E. Jamieson

Waste Streams of Oil Sands: Characteristics and Remediation
Kim L. Kasperski and Randy J. Mikula

Mine Waters: Acidic to Circumneutral
D. Kirk Nordstrom

Mine Wastes and Human Health
Geoffrey S. Plumlee and Suzette A. Morman

Recycling, Reuse and Rehabilitation of Mine Wastes
Bernd G. Lottermoser

DEPARTMENTS
Editorial – Prediction is Hard... .............................................................. 363
From the Editors – Thematic Topics in 2012 .............................................. 364
Triple Point – The Globalization of Chinese Science .................................. 367
People in the News – Dingwell, Geochemical Journal Award... ..................... 368
A Life in Science – Trying to Write .......................................................... 370
Meet the Authors ..................................................................................... 372

Society News
Association of Applied Geochemists ......................................................... 411
Società Italiana di Mineralogia e Petrologia .............................................. 412
The Clay Minerals Society ......................................................................... 413
Geochemical Society ................................................................................. 414
Meteoritical Society .................................................................................. 416
Société française de Minéralogie et de Cristallographie ......................... 417
International Association of Geoanalysts ................................................. 418
Deutsche Mineralogische Gesellschaft ...................................................... 419
Mineralogical Society of America ............................................................ 420
Mineralogical Society of Great Britain and Ireland ................................. 422
Sociedad Española de Mineralogía ............................................................. 423
Mineralogical Association of Canada ....................................................... 424
International Association of GeoChemistry ........................................... 425
AIPEA ......................................................................................................... 426
Mineralogical Society of Poland ............................................................... 426

Book Reviews – Advances in the Characterization of Industrial Minerals; Atlas of Non-Silicate Minerals in Thin Section ......................................................... 427
Calendar ..................................................................................................... 429
Meeting Report – EAG Short Course ......................................................... 430
Parting Shots – Spoiled Land ..................................................................... 431

Advertisers in This Issue ............................................................................ 432
"PREDICTION IS HARD—PARTICULARLY ABOUT THE FUTURE"

—Attributed to Yogi Berra

Back in 1989 I put together a model for the chemical evolution of a pit lake in a gold mine as part of an environmental-impact statement. It was a primitive affair that said basically that if you had a lot more calcite than pyrite in the wall rock the lake would not be acid and if you had a plausible amount of pyrite undergoing oxidation, adsorption would take care of the heavy metals and arsenic. Calcium and sulfate concentrations would depend on the depth to which pyrite in the wall rock underwent oxidation (for which I made an arbitrary guess) and on evaporation, which was the main control on other major solutes. I used the same general approach to estimate the composition of runoff/recharge from mine waste dumps.

When I look at recent models in permit applications, I realize that the world has changed. For pit lakes, hydrologic models of inflows and outflows have become more sophisticated, there’s a model for oxygen diffusion into the pit wall, there’s a model for oxygen diffusion into altering pyrite grains, there’s a model for circulation and turnover in the pit lake as it fills, and there are predictions to two decimal places of the concentration of every solute over time for the next century or two. In one example, uncertainty was evaluated using Monte Carlo simulations—attributes that underlie the models and provide a sound basis for political decisions. We also need to be able to communicate the basic concepts that underlie the models and provide a real, if qualitative, constraint: if there’s much more calcite than pyrite the water will not be acidic; radioactive contaminants will not move much faster than groundwater; carbon dioxide is indeed a greenhouse gas. We should not get hung up on specific numbers, which we know are, paraphrasing Donald Rumsfeld, subject to unknown uncertainties.

James I. Drever

What have we gained and what have we lost? On the positive side, I am sure the predictions of the more sophisticated modeling are likely to be more accurate than those of the primitive model. On the other hand, we have lost transparency—there’s no realistic way an outsider can repeat the calculation as a check. The most important thing that gets lost in the process is an understanding of the uncertainties associated with the predictions. We presumably have our doubts about the two decimal places, but how confident are we in the overall prediction? In the example above, the Monte Carlo approach assumed that the only source of uncertainty in the final prediction was the estimated composition of the inflowing groundwater, which is clearly an unreasonable simplification. There are uncertainties in hydrologic models, in the models for oxygen diffusion and pyrite oxidation, in the distribution of minerals in the wall rock, in the assumptions of chemical equilibrium, in the thermodynamic database, and so on.

So do we throw up our hands and say the predictions are unreliable and should be ignored? We can’t predict accurately what the composition of the pit lake will be, so should we stop issuing permits until we can be 100% sure? Or should we say that permits should be issued unless we are 100% sure there will be a problem? I have talked about pit lakes here to illustrate an issue that faces us all as scientists and citizens. Modeling a pit lake is a vastly simpler problem than modeling the performance of a radioactive-waste repository such as Yucca Mountain (although our modeling does not include the vagaries of politics!) or modeling the response of climate to inputs of carbon dioxide. These models have in common that they are enormously complex, have uncertainties that are hard to quantify, and potentially guide enormously important policy decisions. I would argue that even though there are uncertainties that are hard to quantify in model predictions, these predictions represent the best estimate we have of what will happen in the future, and it makes sense to use them as a starting point for policy decisions. There is no such thing as absolute certainty about the future. This is something of a public relations challenge for us geochemists: yes, we know that the predictions have their limitations, but yes, we recognize that they are almost certainly qualitatively correct and provide a sound basis for political decisions.

To me the route to greater confidence in the model predictions is not—at least in the examples of pit lakes, mine wastes, and radioactive-waste disposal—through ever more sophisticated mathematical modeling. I think our skills at modeling have run ahead of our understanding of some of the underlying physical processes and our ability to test the models against real data from the field. Improvements will come from better understanding of the underlying physical processes, exemplified by detailed characterization of the mineral reactions that release contaminants, as discussed in this issue, and from field tests of model assumptions. We also need to be able to communicate the basic concepts that underlie the models and provide a real, if qualitative, constraint: if there’s much more calcite than pyrite the water will not be acidic; radioactive contaminants will not move much faster than groundwater; carbon dioxide is indeed a greenhouse gas. We should not get hung up on specific numbers, which we know are, paraphrasing Donald Rumsfeld, subject to unknown uncertainties.

James I. Drever (drever@uwyo.edu)*

* James I. Drever was the principal editor in charge of this issue.
FROM THE EDITORS

THIS ISSUE
This issue on mine wastes is most timely and well illustrates a conundrum faced by our society: we consume more and more resources, and at the same time we condemn the exploitation, and sometimes even the exploration, of these same resources. On the news recently were stories about protests against the proposed construction of the Keystone XL pipeline (to transport oil from the Alberta oil sands to several locations in the United States), and against the exploitation of the Alberta oil sands in general. As Kim Kaspersky and Randy Mikula explain in their article, Alberta sits on enormous oil resources in its oil sands. Their exploration and exploitation have created great wealth and have contributed significantly to this Canadian province’s booming economy. But the benefits have come at an environmental cost, with increasingly stiff opposition from environmental groups and the public.

ABOUT THEMATIC ISSUES
It’s hard to believe, but with this issue we have covered 41 topics in the Earth sciences. Some issues have been devoted to single minerals (diamond, zircon, bentonite, gold), elements (arsenic, platinum-group elements, sulfur), societal issues (e.g. global water sustainability), and frontier topics (e.g. mineral magnetism, cosmochemistry) of wide appeal to our community. The skeptics who pronounced that we would soon run out of topics have worried needlessly: 2012 is fully booked (see our preview in the next two pages), some topics are already slated for 2013, and there is a steady stream of interesting proposals coming our way.


A question the editors were asked frequently at Goldschmidt 2011 in Prague was “What percentage of proposals is accepted?” Very few proposals are actually turned down—most proposals have merit—but very few are accepted as is. Once we receive a proposal, a dialogue starts that might lead to several revisions before the proposal is accepted. The most common request from the editors is to enlarge the scope of the proposal to take into account Elements’ broad audience. Sometimes we will say, “Not at this time; please consider resubmitting in a couple of years,” in order to let a frontier field mature.

How long does it take before an issue is slated? At least a year and a half— a comfortable amount of time to schedule an issue and work through all the steps. But it might take up to three years if we have to wait for the right timing to schedule an issue. In a one-year lineup, we strive to include a mix of mineralogy, petrology, and geochemistry topics. Potential guest editors (i.e. proposers) often send out a “feeler” e-mail asking, “Would you be interested on an issue devoted to topic X?” Early dialogue with the editors can be very helpful and can ensure the success of a proposal with a minimum amount of revision. So some advice for proposers is this: If you are interested in being guest editor for an issue, send your proposal promptly. Remember that your proposed issue might be scheduled two or three years later. The more lead time you have, the more likely it is that you will be able to get your first choice of authors.

As editors, we try to nurture the guest editors and impress on them the need for broad representation in terms of authorship, geography, and gender. Most of the themes covered in Elements have been the subject of review volumes, special journal issues, or textbooks. In Elements, guest editors are allotted 36 pages of thematic content. They therefore need to choose a focus, an angle. We also ask them to cover the topic in 5 papers, along with a more general introductory article that sets the stage and perhaps fills in briefly on some aspects not covered in the other papers. Every expert on a given topic would probably choose a different focus for an issue.

From time to time, we are asked why Dr. So-and-so, a world-class specialist on a given topic, is not an author. Perhaps Dr. So-and-so was approached but could not fit the writing into his or her busy schedule. We ask guest editors to distribute authorship geographically and to look for persons best able to write for a broad audience. We also ask that papers have no more than 3 authors and ideally 1 or 2 authors, giving 18 authors at most per issue. With all these constraints, it is unlikely that all leaders in a given field can be authors.

Are there specific themes we would like to see published for which we have received no proposal? Yes—we would like to include an “Ocean” issue in our 2013 lineup. If you have ideas for such an issue, please contact Tim Drever (drever@uwyo.edu) with your suggestions.

Pierrette Tremblay, Managing Editor

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IMPACT!

Guest Editors: Fred Jourdan (Curtin University) and Wolf Uwe Reimold (Humboldt University Berlin)

Impact processes are central to the formation and evolution of the Solar System and the modification of planetary surfaces. On Earth, asteroid impacts played a critical role during Earth history; they delivered the constituents of our planet, were responsible for the formation of major ore deposits, and affected life on Earth. Studying impacts and their effects is a very active field at the crossroads of many scientific disciplines, from mineralogy to environmental science. This issue will focus on the mineralogical, geochemical, and petrological aspects of terrestrial impact structures, and in particular on the latest developments in the relevant fields.

- Impact! Wolf Uwe Reimold (Humboldt University Berlin) and Fred Jourdan (Curtin University)
- The impact cratering process Gareth S. Collins (Imperial College London), H. Jay Melosh (Purdue University), and Gordon R. Osinski (University of Western Ontario)
- Shock metamorphism of minerals Falko Langenhorst (Friedrich-Schiller-Universität Jena) and Alex Deutsch (Westfälische Wilhelms-Universität Münster)
- Geochemistry of impactites Christian Koeberl (University of Vienna and Natural History Museum, Vienna), Philippe Claeys (Vrije Universiteit Brussel), Lutz Hecht (Natural History Museum, Berlin), and Iain McDonald (Cardiff University)
- Distal impact ejecta layers: Spherules and more Billy P. Glass (University of Delaware) and Bruce M. Simonson (Oberlin College)
- Dating terrestrial impact structures Fred Jourdan (Curtin University), Wolf Uwe Reimold (Humboldt University Berlin), and Alex Deutsch (Westfälische Wilhelms-Universität Münster)
- Local and global environmental effects of impacts on Earth Elisabetta Pierazzo (Planetary Science Institute) and Natalia Artemieva (Russian Academy of Science)

FROM THE EDITORS

Volume 8, Number 1 (February)

THETMATIC TOPICS IN 2012

MINERALS, MICROBES, AND REMEDIATION

Guest Editors: Anhui Lu (Peking University) and Hailiang Dong (Miami University)

Studies of mineral–microbe interactions lie at the heart of the emerging field of geomicrobiology, because minerals are the fundamental Earth materials with which microbes interact. Microbes are found in a number of the Earth’s extreme environments and also in extraterrestrial materials. In spite of the diverse geological environments in which microbes are found and the various approaches taken to study them, a common thread—mineral–microbe interactions—connects all these environments and experimental approaches and places them under the same umbrella: geomicrobiology. Minerals provide microbes with energy and living habitats, and microbes impact mineral weathering and diagenesis. The recognition of mineral–microbe interactions has revised the traditional discipline of mineralogy, and microbes discovered in various habitats have provided microbiologists with unique opportunities for study. This issue considers microbiologically mediated mineral dissolution, precipitation, and transformation, and the synergistic relation between minerals and microbes for energy acquisition. These interactions have important implications for contaminant remediation.

- Metal oxides, bacteria, and base metals Gordon Southam (University of Western Ontario)
- Chromium and uranium mineralization as mediated by microbial activity Yangjian Cheng (Chinese Academy of Sciences), Hoitong Holman (Lawrence Berkeley National Laboratory), and Zhang Lin (Chinese Academy of Sciences)
- Mineral transformations associated with clay–microbe interactions and implications for environmental remediation Hailiang Dong (Miami University)
- Microbial oxidation of sulfide tailings and its environmental consequences Olli H. Tuovinen (Ohio State University), Xiancai Lu (Nanjing University), and Hongmei Wang (China University of Geosciences)
- Synergy between semiconducting minerals and microorganisms: Implications for environmental remediation Anhui Lu (Peking University), Yan Li (Peking University), and Song Jin (University of Wyoming)

Volume 8, Number 3 (June)

FUKUSHIMA DAI-ICHI: ONE YEAR LATER

Guest Editors: Takashi Murakami (University of Tokyo) and Rodney C. Ewing (University of Michigan)

On March 11, 2011, an earthquake and tsunami hit Japan, killing more than 20,000 persons, displacing tens of thousands, and causing havoc in the infrastructure and economy of the country. In the aftermath of this tragedy, the cooling systems of three of the operating reactors at the Fukushima Dai-ichi nuclear power station failed and meltdown of the reactor cores occurred. Over the following days, a series of hydrogen gas explosions took place. Radionuclides (mainly 131I and 137Cs) were released to the atmosphere and transported over many tens of kilometers from the site, contaminating soil and water. Seawater was used to cool the damaged reactor cores, and water contaminated with radioactivity was released to the ocean. Considerable amounts of used fuel were stored in nearby pools, and with the loss of water, the pools contributed to the release of radioactivity. One year after the tragedy at Fukushima, this issue of Elements provides a summary of what is known about the environmental impact of this nuclear accident.

- The earthquake Jeroen Ritsema (University of Michigan), Thorne Lay (University of California–Santa Cruz) and Hiroo Kanamori (Caltech)
- The anatomy of the Fukushima nuclear accident Edward Blandford (Stanford University), Wataru Mizumachi (JNES), and Joohong Ahn (University of California, Berkeley)
- Radioactive dispersion in the atmosphere Anne Mathieu (Institute of Radiation Protection and Nuclear Safety) and coauthors
- Contamination of the geosphere: Effects on soils and water Naohiro Yoshida (Tokyo Institute of Technology) and coauthors
- Radioactive dispersion in the ocean Yukio Masumoto (Japan Agency of Marine-Earth Science and Technology)
- Long-term changes and corrosion of spent fuel Bernd Grambow (Université de Nantes) and Christophe Poinssott (CEA)
GRANITIC PEGMATITES: SCIENTIFIC WONDERS AND ECONOMIC BONANZAS

GUEST EDITORS: David London (University of Oklahoma) and Daniel J. Kontak (Laurentian University)

Nothing that geoscientists learn as students prepares them for interpreting rock textures as complex as those found in pegmatites. Understanding the textures and mineral zonation of granitic pegmatites is tantamount to understanding the fundamental process of crystallization. It is a challenge to our ability to discern, beyond reasonable doubt, what is igneous and what is hydrothermal. This is the context that has drawn many professional geoscientists to the study of pegmatites for all or part of their careers. In addition, granitic pegmatites are important to our society as sources of raw materials for glasses and ceramics, silicon for microprocessors, and specialty metals including Li, Cs, Be, Nb, Ta, Sn, REE, and U. A very few pegmatites provide some of the most highly prized mineral specimens and colored gems found in national museums and personal collections around the world. No other rock type presents such a diversity of economic commodities in such concentrated fashion.

- Granitic pegmatites: Scientific wonders and economic bonanzas
  David London (University of Oklahoma) and Daniel J. Kontak (Laurentian University)
- The pegmatite puzzle
  David London (University of Oklahoma) and George B. Morgan VI (University of Oklahoma)
- Pegmatite: The industrial minerals storehouse
  Alex Glover (Active Minerals LLC), Bill Rogers (NYCO Minerals, Inc.), and Jim Barton (Martin Minerals)
- Granitic pegmatites as sources of strategic metals
  Robert Linnen (University of Western Ontario), Marieke van Litherveld (Universitat Hannover), and Petr Černý (University of Manitoba)
- Granitic pegmatites as sources of gem materials
  William B. "Skip" Simmons (University of New Orleans), Federico Pezzotta (Natural History Museum Milan), Harmut Burlein (Universidade Federal de Pernambuco), and James Shigley (Gemological Institute of America)
- Granitic pegmatites as complex isotope systems
  Daniel J. Kontak (Laurentian University), Fang-Zhen Teng (University of Arkansas), and Robert B. Trumbull (GZF Potsdam)
- Granitic pegmatites as reflections of their sources
  David London (University of Oklahoma), Milan Novak (Masaryk University, Brno), and Petr Černý (University of Manitoba)

Volume 8, Number 4 (August)

URBAN GEOCHEMISTRY

GUEST EDITORS: W. Berry Lyons (The Ohio State University) and Russell S. Harmon (U.S. Army Corps of Engineers)

By 2030, about 60% of the human population will live in cities. Clearly, anthropogenic activities in urban environments affect geochemical cycles, water resources, and the health of ecosystems and humans globally. Past practices are still having biogeochemical impacts today, and in many cases remediation is needed. Both natural and man-made disasters greatly change the geochemistry of urban areas. Understanding past impacts can aid in future disaster planning. An increased awareness of the geochemical and mineralogical effects of urbanization on geochemical cycling will aid urban planners in the effort to make urban development sustainable.

- Geochemistry and the sustainable urban environment
  W. Berry Lyons (The Ohio State University) and Russell Harmon (U.S. Army Corps of Engineers)
- Urban geochemistry: The legacy problem
  Stefano Albanese (Università degli Studi di Napoli) and Domenico Cicchella (Università del Sannio)
- The impact of urban development on hydrology and geochemistry
  Corinne Wong (University of Texas at Austin) and co-authors
- Ecological and biogeochemical dynamics in urban settings: Lessons from long-term ecological research
  Dan Bain (University of Pittsburgh), Wil Wollheim (University of New Hampshire), and Rebecca Hale (Arizona State University)
- Urban geochemistry and human health
  Gabriel Filippelli (IUPUI), Deborah Morrison (Indiana School of Medicine), and Domenico Cicchella (Università del Sannio)
- Greenhouse gas emissions from urban settings
  Francesco Bellucci, Jean Bogner, and Neil Sturchio (University of Illinois at Chicago)
- Environmental and medical geochemistry in urban disaster response and preparedness
  Geoffrey S. Plumlee (USGS) and co-authors
Recently, I attended the 50th birthday party of a colleague and friend. The party brought together a dozen faculty members at Indiana University who specialize in fields ranging from English literature and law to nuclear physics. Our conversation mostly involved joking about the topic “What is your plan for the next 50 years?”, but at one point the host pulled me aside and asked me questions about China. “Where do you think China will go?” and “Is China a threat to the power of the United States?”

We have known the host and his family for years—our children have practically grown up together. We have discussed and debated many social and family issues, but these hard questions about China had not come up before. What triggered the questions now?

While my friend was referring to economic and military issues, China is also catching up in science. A report from The Royal Society of Great Britain, published on March 28, 2011, shows that China could overtake the United States as the world’s dominant publisher of scientific research by 2013 (Fig. 1). China is now second only to the US in terms of its share of the world’s scientific research papers written in English. In the geosciences, China is third in the number of articles published in English between January 2001 and June 2011, behind the United States and Great Britain (Thomson Reuters 2011).

**Figure 1** Country shares of total world article output in peer-reviewed international journals. Dotted lines are linear extrapolations.

**Source:** The Royal Society (2011)

My geochemist colleagues coming back from the Goldschmidt Conference in Prague last August could not possibly have missed noticing that 5% or so of the participants were from China (144 out of 3711 delegates). Over the past five years, the number of Chinese scientists at Goldschmidt conferences has increased (there were just 67 in Vancouver in 2008). Are they a welcome expansion or a threat to the quality of programs? In some years, conferencegoers have expressed concerns about the disproportionate number of cancelled talks by Chinese geochemists. How many were due to the denial of visas, and how many abstracts were submitted by those who were only interested in the publication and had no intention of attending? There is a cultural clash here. While conferences are planned way ahead of time in the West, Chinese conferences are organized on ridiculously short notice by Western standards. The uncertainties with visas also make planning extremely challenging: the Czech embassy in China did not recognize invitation letters for the 2011 Goldschmidt because they were issued from England!

The Chinese geoscience community could benefit tremendously from international exchange and exposure. Economic development in China has made travel to Prague affordable for student delegates, but the provincial mindset of some citizens of the Middle Kingdom has not been transformed as the economy has grown and globalized. The shiny new instruments recently installed in so many institutions in China do not automatically go hand in hand with a new culture of scientific inquiry. The idea that the pursuit of science comes from an inner thirst for knowledge and that the pursuit of knowledge is itself a reward is as foreign to most Chinese students as Czech food. Without this climate of intellectual inquiry taking root in China, one will just see an increasing volume of low-quality research that will overwhelm the review process. For example, Elsevier claims that 80% of manuscripts submitted from China to Elsevier journals were rejected between 2006 and 2010 (Kamalski and L’Huillier 2011). The Goldschmidt Conference, arguably the highest-quality venue in the field of geochemistry, is the best opportunity for Chinese scientists to see firsthand the high-quality research.

Historically, geology has occupied a much more prominent role among the sciences in China than it has in the United States and Europe. This is particularly true today. Sustained economic development depends upon continual and secure supplies of natural resources, which has translated into substantial government investment in the field of geology, unseen in the West. It also helps that geologists in China have a sympathetic ear in the highest place: the current premier, Wen Jiabao, was not only trained as a geologist but also worked as one for a good part of his life. Geology is booming in China.

In some subdisciplines, Chinese geologists have already made serious impacts, such as in ultrahigh-pressure metamorphism and in paleontology. Will the substantial investment in China translate into advances in the geological sciences, not only in China but in the world as a whole?

I notice that many scientists in the West have explored collaboration with Chinese scientists. The abundant supply of research funds and eager students should provide opportunities for meaningful interactions, especially because of the difference in demography. Because the Cultural Revolution closed the universities from the mid-1960s to the mid-1970s, Chinese scientists are mostly young. Collaboration with and mentoring of young Chinese geologists by senior scientists in the West could be productive for both, since excessive competition and dwindling research resources in the West have prevented many scholars from reaching their full potential.

I think the common ground should be the pursuit of science and service to humanity. Better integration of Chinese Earth scientists into the international geological communities is needed for meaningful collaborations that will find solutions to the global challenges we all face. Tackling widespread environmental contamination in China, a product of the rapid economic expansion, could use expertise and experience from the West. And problems with a global dimension, like global warming, need global collaboration and cooperation.

The European Association of Geochemistry has recently launched an annual Distinguished Lecture Program, which aims to introduce scientists and students from underrepresented regions of the world to emerging research areas in geochemistry. The Goldschmidt Conference has an outreach opportunity at its own door, and in the future could provide more specific programs for delegates from less developed countries, such as short courses and workshops on specific science subjects, new frontiers, scientific writing, ethics, curriculum development, and editing.

Cont’d on page 368
**DINGWELL NAMED 3rd SECRETARY GENERAL OF THE EUROPEAN RESEARCH COUNCIL**

Donald Bruce Dingwell will serve as the Secretary General of the European Research Council (ERC) for 24 months, starting 1 September 2011. The Secretary General is the permanent representative of the Scientific Council in Brussels. In this position he will be a vital link between the governing scientific council and the executing ERC agency. With Dingwell as the third Secretary General, a Canadian-trained geoscientist follows the geneticist Ernst-Ludwig Winnacker and the economic Andreu Mas-Colell in this post.

Set up in 2007 by the European Union, the ERC is the first pan-European funding organization for frontier research. It aims to stimulate scientific excellence in Europe by encouraging competition for funding between the very best, creative researchers of any nationality and age. The ERC also strives to attract top researchers from anywhere in the world to come to Europe. The ERC, which is the newest, pioneering component of the EU’s Seventh Framework programme (‘Ideas’ Specific Programme), has a total budget of €7.5 billion from 2007 to 2013.

Dingwell holds the Chair of Mineralogy and Petrology at Germany’s leading research university, the Ludwig Maximilian University of Munich, and is on partial leave of absence from his duties there. With experience as an external expert, a panel member and a grant research holder, he brings a unique background to the job. Combined with a decade of participation in European and national evaluation systems, he is preparing to embark on a campaign of internationalization of the granting system.

**GEOCHEMICAL JOURNAL AWARDEES**

The Geochemical Journal Award recognizes the most outstanding research article published during the current year, based on originality, quality, and the advancement of science, particularly geochemistry. Recipients of this year’s Geochemical Journal Award are Dr. Jun-Ichi Matsuda of Osaka University and his colleagues, Dr. Takuya Matsumoto and Mr. Akihisa Suzuki. They published an “Express Letter” entitled “Helium in Old Porcelain: The Historical Variation of the He Isotopic Composition in Air.” The paper deals with a long-standing debate on whether there is a variation of the atmospheric $^3$He/$^4$He ratio due to the anthropogenic release of radiogenic $^4$He contained in exploited fossil fuels. To confirm the temporal variation, capsules of paleoatmospheric helium need to be found and investigated. This is what the authors of this paper did. They nicely showed that vesicles in old porcelain could preserve old atmosphere. This paper provides additional insights into the anthropogenic effects on the chemistry and volatile content of the atmosphere. For the quality of the data, the significance of the results, and the novelty of the approach, this paper well deserves the Geochemical Journal Award of the Geochemical Society of Japan.

**TRIPLE POINT Cont’d from page 367**

As for my friend’s questions, I, like most people, cannot foresee where China will be more than 3 to 5 years down the road. But I do not believe that China will be a threat or challenge to the United States, militarily, economically, or scientifically. China has made a lot of progress, but unshackling the country from the burden of 2000 plus years of history is a challenge no less great than “moving the mountains.”

Chen Zhu (chenzhu@indiana.edu)
University of Indiana

**REFERENCES**


**Chen Zhu** is a professor of geological sciences at Indiana University, USA, and an adjunct professor at the University of Oslo, Norway. He received his PhD from Johns Hopkins University and completed a postdoctoral fellowship at Woods Hole Oceanographic Institution. He was a guest professor at the Swiss Federal Institute of Technology, Switzerland, in 2004 and 2008, and was a Fulbright Scholar at the University of Oslo in 2009. Zhu coauthored with Greg Anderson the textbook Environmental Applications of Geochemical Modeling. He has served as an associate editor for Geochimica et Cosmochimica Acta since 2005.

**Triple Point** raises issues of broad interest to the readers of *Elements*, and explores different themes of our science (teaching, publishing, historical aspects, etc.), our societies, funding, policy, and political issues. Contact Bruce Yardley (B.W.D. Yardley@leeds.ac.uk) if you have an issue you would like to write about.
A hypothetical question of course! But even if we could ask them, the SPECTRO MS makes the question redundant. This novel ICP mass spectrometer analyzes the entire relevant mass spectrum completely simultaneously; faster and more precisely to boot.

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As I sit down to write this piece, I feel great trepidation. Writing is the “currency” of scientists, but my pile of unwritten articles is much larger than I’d like. Various thoughts pass through my mind: This article may take me lots of time. Maybe I should get a cup of coffee first? Actually, another room is better. Then, there is that e-mail reply waiting—perhaps I should do that first. **Why is it so hard to write?**

Writing is important for advancing science and our careers. The process of writing forces us to improve our ideas, and those ideas are further improved through the review process. Publications make our ideas accessible to a larger audience, they provide deliverables for granting agencies, and they advance our careers. Therefore, for science and our careers to flourish, it is important that we become effective writers.

Research informs us that there is a solution to the dilemma of writing. Basically, we need to “try to write,” rather than “try not to write.”

**Trying Not to Write**

One of my favorite books on writing is *How to Write a Lot*, by Paul Silvia (2007). Dr. Silvia identifies several common “specious” barriers to writing; that is, barriers that we pretend are real. Some of these specious barriers are:

- Only writing when there is “enough time”
- Only writing when inspired
- Saying that you have writer’s block (although there is no such condition)
- Distracting yourself or wanting a different work space (like my shenanigans)
- Not writing until you have more analyses or more papers to cite
- Needing a perfect first draft or being afraid of criticism
- Pursuing a poorly conceived project that is not publishable or suffered from a lack of testable hypotheses or appropriate methods
- Pursuing a project that you hate

**Only Writing When There Is Enough Time or When You Are Inspired**

Studies show that two of the most successful ways to “try not to write” are (1) only writing when there is sufficient time to write and (2) only writing when you are inspired. Both of these methods are known as “binge writing.” Binge writers wait to sequester themselves to write.

Boice (1990) illustrates some of the pitfalls of binge writing and provides some successful strategies. He outlines a study of 27 faculty members who had reported difficulty in finishing their writing, even though each had a manageable writing project to complete. The faculty members were assigned to three groups and were studied for 10 weeks. The first group was told not to write except in the case of an “emergency.” The second group was given 50 scheduled writing sessions, but only required to write if inspired. The third group was given 50 scheduled writing sessions but, if they did not write at least three pages each session, they were required to send money to a distasteful organization. The group that was obliged to write was significantly more productive than the other groups (Fig. 1). Furthermore, this group had a creative or novel idea each writing day (Fig. 1). In contrast, the group that wrote only in emergencies had the lowest level of productivity and the least frequent creative ideas. Binge writing is ineffective: to write more productively, the best approach is to write regularly. In fact, some authors say that increasing scheduled writing time by as little as two hours a week convinces most writers that scheduled writing is the most effective approach.

**Tips on Trying to Write**

1. **Make a schedule for writing.** Treat writing like teaching a class or going to a meeting: schedule it, make the time sacrosanct, and do not allow disturbances. Try to write every day for 20–90 minutes.
2. **Prioritize your writing tasks.** Do the most important things first (Fig. 2).
3. **Set goals and reward yourself upon completion.** Set clear, measureable goals that may be tested, for example “write 200 words.” Goals and rewards provide motivation.
4. **Keep track of your work or enlist friends to help you keep on target and reward yourself.** Some people like to keep track of their work themselves, but others like to use a taskmaster (a peer) or a writing group (e.g. Silvia 2007).

Now, it is time for me to do some scientific writing. But, that cup of coffee sounded great...

**Penny King** (penking@unm.edu), University of New Mexico

**REFERENCES**

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Meet the Authors

Karen A. Hudson-Edwards is a reader in environmental geochemistry and mineralogy at Birkbeck, University of London. Her research focuses on understanding contaminant, nutrient, and water cycling in Earth-surface environments. Specific topics of interest include the cycling of contaminants in mining-affected environments, mechanisms of arsenic and manganese pollution of groundwater, formation and stability of biogenic sulfate minerals, and processes and products of weathering. She is on the editorial boards of *Journal of Geochemical Exploration* and *Mineralogical Magazine*, and currently serves as publications manager for the Mineralogical Society of Great Britain and Ireland.

Heather E. Jamieson is a professor in the Department of Geological Sciences and Geological Engineering at Queen’s University. She also holds an appointment and teaches courses in the School of Environmental Studies at Queen’s. Her expertise is in the area of environmental geochemistry, particularly the mineralogical controls on the mobility of metals and metalloids (notably arsenic) in mine waste and the application of synchrotron-based X-ray experiments and other microanalytical methods to metal speciation in mine tailings, soils, sediments, and household dust. Much of her fieldwork is in the Canadian Arctic, but she has also conducted research in Nova Scotia, California, Montana, Spain, and Australia.

Kim L. Kasperski is a senior research scientist with Natural Resources Canada, a Canadian government department. She holds a PhD in physical chemistry from the University of Alberta and has worked in research related to oil sands for over twenty years. In the past ten years, her research team has worked mainly on problems related to water and tailings in oil sands mining and more recently in water issues associated with in situ operations. She has appeared before House of Commons committees as an expert witness on oil sand water issues and has written several reviews on oil sand topics.

Bernd G. Lottermoser is New Star Professor in environmental geochemistry at the University of Tasmania, Hobart, Australia. In his varied career, he has worked in the mining industry and also in research and teaching at Australian, German, and British universities. His work has been recognized by a German Humboldt Research Fellowship, an Erasmus Mundus Fellowship of the European Union, and, from the Australian government, an Endeavour Executive Award and the Michael Daly Award for Excellence in Science Communication. His current research interests focus on mineralogical and geochemical aspects of degraded lands, mine-site rehabilitation, and mine wastes, areas in which he has written an acclaimed textbook and original papers.

Randy J. Mikula is the former leader of the Canadian federal government’s Natural Resources Canada research effort on oil sands tailings. With over 25 years in oil sands research, his work has ranged from the development of more efficient extraction processes to mitigating the environmental impact of oil sands development. He is currently principal scientist at Kallium Research, a new company devoted to responsible development of Canada’s oil sands resource. Randy has a BSc in chemistry (magna cum laude) from the University of Saskatchewan and a PhD in chemistry from the University of British Columbia. In 2003 Randy was elected as a Fellow of the Canadian Institute of Chemistry.

Suzette A. Morman is a research geologist with the U.S. Geological Survey in Denver, Colorado. Suzette began her professional career as a registered nurse. She received a BS in geology from the University of South Florida, an MS in geology from the University of Alabama, and a master’s degree in public health from the University of Colorado. Her current research focuses on the use of simulated biofluids to elucidate and estimate health risks to humans from exposure to geogenic materials (soils, dusts, wildfire and volcanic ash). Other research interests include linking geological and public health databases to assess morbidity, and the effects of climatic variability on dry lands and the implications for human health.

D. Kirk Nordstrom is a senior scientist with the National Research Program of the U.S. Geological Survey at Boulder, Colorado. He has been a USGS project chief for the last 31 years, concentrating on mine waste geochemistry, arsenic geochemistry, radioactive waste geochemistry, geothermal chemistry, thermodynamic-data evaluation, aqueous redox geochemistry and microbiology, and geochemical modeling of water-rock interactions. He has coauthored (with Jim Munoz) a popular text, *Geochemical Thermodynamics*; has documented the occurrence of negative-pH mine waters; and has consulted with numerous state, federal, and foreign agencies on water-quality issues. He has been recognized with the GSA Birdsall-Dreiss Lecture Award, the DOI Meritorious Service Award, and the DOI Cooperative Conservation Award, and he is a Fellow of the GSA and the MSA.

Geoffrey S. Plumlee, a research geochemist with the U.S. Geological Survey since 1987, received his BS in geology from the University of New Mexico (1980) and PhD in geochemistry from Harvard University (1989). Growing upon his early research in economic geology and the environmental geochemistry of mineral deposits, his current research applies geochemistry to the understanding of problems in human health and environmental disaster response/preparedness. He is an adjunct clinical assistant professor at the University of Colorado School of Public Health, is chair of the American Geosciences Institute Environmental Geoscience Advisory Committee, and was the 2008 chair of the Geological Society of America’s Geology and Health Division.
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Mine Wastes: Past, Present, Future

Karen A. Hudson-Edwards1, Heather E. Jamieson2 and Bernd G. Lottermoser3

Mine wastes are unwanted, currently uneconomic, solid and liquid materials found at or near mine sites. Volumetrically they are one of the world’s largest waste streams, and they often contain high concentrations of elements and compounds that can have severe effects on ecosystems and humans. Multidisciplinary research on mine wastes focuses on understanding their character, stability, impact, remediation and reuse. This research must continue if we are to understand and sustainably manage the immense quantities of historic, contemporary and future mine wastes, given the trend to exploit larger deposits of lower-grade ores.

Keywords: mine wastes, tailings, metals, metalloids, radionuclides, acid mine drainage, dust

INTRODUCTION

Iconic treasures such as the gold funeral mask of King Tutankhamen and the Koh-I-Noor Diamond would not exist today without mining. Since the dawn of civilization, humans have exploited metals, coal, industrial minerals and rocks for the production of goods, energy and building materials. These mining activities have created great wealth: the Chalcolithic (Copper) Age, for example, took its name from the exploitation of copper ores and the production of copper-based tools, and the “Golden Age” of Spain in the 16th and 17th centuries was built on the gold and silver extracted from mines in the Americas. The importance of mining was recognized by Gregor Reisch in 1503 in his book *Margarita Philosophica* (*The Philosophical Pearl*), in which he illustrated his section on natural objects with a woodcut showing “Mining for Metal” (Fig. 1).

These treasures and associated wealth have come at an environmental cost, because mining has produced colossal quantities of solid and liquid wastes, known collectively as “mine wastes”. Nearly every country has or has had a mining industry and, therefore, has a legacy of mine waste. Thus, the large-scale production of mine wastes and their secure disposal or sustainable remediation represent problems of global importance. It has been estimated that, annually, the production of solid mine wastes now matches the amount of Earth materials moved by global geological processes – several thousand million tonnes per year (Fyfe 1981; Förstner 1999). Many of these wastes contain components, such as arsenic, lead and cyanide, in concentrations that may pose serious hazards to ecosystem and human health. The control and mitigation of acid mine drainage (AMD) mine wastes alone is considered to be one of the major environmental challenges facing the mining industry worldwide (International Network for Acid Prevention 2011). The estimated costs for total worldwide liability associated with the current and future remediation of acid drainage are approximately US$100 billion (Tremblay and Hogan 2001).

**WHAT ARE MINE WASTES?**

In this issue of *Elements*, we define mine wastes as “those waste products originating, accumulating and present at mine sites, which are unwanted and have no current
economic value” (Lottermoser 2010) (see glossary for this and other terms). Mine wastes are heterogeneous materials consisting of ore, gangue, industrial minerals, metals, coal or mineral fuels, rock, loose sediment, mill tailings, metallurgical slag and wastes, roasted ore, fly dust, ash, processing chemicals and fluids. This definition is illustrated by the Kalgoorlie “Super Pit” gold-mining operation (Fig. 2), one of the largest in the world. The mine is surrounded by waste dumps and tailings ponds, the latter of which also contain processing chemicals such as cyanide (Griffiths et al. 2009). The footprint of the Super Pit is greatly exceeded by that of its wastes, mainly because so much rock is mined to extract the parts per million amounts of gold within its ores. For every tonne of metal ore extracted, at least a tonne of waste is generated, and usually orders of magnitude more (Lottermoser 2010).

Figure 2: The “Super Pit” gold mine at Kalgoorlie, Western Australia, with its attendant grey waste dumps and grey-white tailings ponds. The town of Kalgoorlie abuts the mining area. Photo taken 15 February 2010, courtesy of NASA

STORAGE, REDISTRIBUTION AND ENVIRONMENTAL IMPACT OF MINE WASTES

Solid mine wastes are stored in piles or in tailings impoundments around or near mine sites (Fig. 2). In the past, tailings were discharged to rivers or wetlands. Currently, tailings are used as backfill underground, stored in open pits, dried and stacked, or pumped into tailings impoundments ranging from a few hectares to thousands of hectares in area. In some cases, the tailings are thickened with a flocculant to increase surface tension and maintain saturation during storage. In impoundments, tailings may be exposed to the atmosphere or stored below a water cover. Figure 3 shows the tailings-disposal site at Kidd Creek in northern Ontario, Canada. One of the world’s largest and richest volcanic massive sulfide deposits, Kidd Creek has produced silver, cadmium, copper, indium, sulfuric acid and zinc since 1966 (InfoMine 2011). By the time the site closes in 2023, more than 130 million tonnes of tailings will be stored in the pond (InfoMine 2011). Global estimates of tailings production are similarly high: in the 1960s, tens of thousands of tonnes of tailings were produced each day, but by 2000, that amount had risen to hundreds of thousands of tonnes per day (Jakubick and McKenna 2003).

Although impoundments are useful and necessary repositories for tailings, they can create environmental problems. Air and soil can be contaminated by the generation and dispersal of dust, and groundwater and surface water can be contaminated by seepage through embankments or through the base of the tailings pile. Most dramatically, tailings dams can fail. Since 1970, over 70 major failures of impoundments have occurred around the world. Many of these have resulted in short- and long-term damage to ecosystems, in significant impact on communities that live beside them and rely on impacted lands for food and livelihood, and most seriously, in the loss of over 1000 lives (WISE 2011). An example is provided by the Aznalcollar–Los Frailes dam failure in southwestern Spain on 25 April 1998 (Fig. 4). The flood of tailings and acidic water spread out in the flatter, lower reaches of the catchment but was impeded by walls constructed to protect the Doñana National Park, the largest reserve for birds in Europe and a UNESCO Reserve of the Biosphere. These walls, and the emergency removal of the tailings back to the open pit beginning on May 3, 1998, considerably reduced the medium- and long-term impacts on vertebrate wildlife (Guitart et al. 2010). Nonetheless, 37 tonnes of fish, 40 tonnes of amphibians, 20 tonnes of birds and 8 tonnes of mammals were killed by the spill, and agricultural products had to be destroyed (Grimait et al. 1999). Soils and groundwaters in the area retain considerable quantities of potentially toxic metals resulting from the spill and historical contamination, and the clean-up operations severely destabilized the river channel and floodplain, accelerating erosion and sedimentation downstream (Turner et al. 2008). Such observations have been made in other areas affected by spills of impounded tailings, and the long-term environmental consequences in many of these areas remain unknown.

Mine wastes have been, and still are, discharged directly into marine environments, rivers and lakes, and indirectly through erosion of tailings and waste-rock piles (Lewin et al. 1977). This can cause increased turbidity and sedimentation, and can contaminate suspended, channel, floodplain and lake sediments with metals, metalloids and radionuclides. For example, more than two million cubic metres of metal-contaminated mine waste sediment are stored in the floodplains of the Clark Fork River basin in the United States (Moore and Luoma 1990). In northern England, an estimated area of 12,000 km² of river catchments is polluted by historic waste, mainly generated during lead and zinc mining in the 19th and early 20th centuries (Macklin et al. 2006). Of pressing concern is the potential for remobilization of mining-contaminated alluvial sediment from these areas, either by in situ biogeochemical weathering or by physical erosion during
Both processes have the potential to contaminate groundwater and surface waters through dissolution or desorption of contaminants from sediment surfaces. Nagorski et al. (2003), for example, showed that concentrations of arsenic, copper, iron, manganese and zinc in the water of a mining-impacted stream in Montana, USA, were highest following spring runoff and short-term storm events. The greater frequency and severity of floods due to climate change may, in turn, contribute to increasing mobilization of riverborne mine wastes (Goudie 2006).

Surface and subsurface mine waters used in the extraction and disposal of mine wastes, which include mill and process waters, are themselves considered mine wastes. At well-managed mines sites, such mine waste water is stored in settling ponds and used as recycle water in mill processes and open pit and underground operations. At abandoned or improperly managed sites, however, water is discharged deliberately or inadvertently as a result of seepage, run-off or flooding, often spreading several kilometres from the source. In most countries, regulations prohibit the release to the environment of water that does not meet specific water-quality standards. Perhaps the most famous example of mine waste water concerns the Río Tinto (“red river”) in southwestern Spain. There, long-term natural weathering and at least 5000 years of mining of massive sulfide orebodies have delivered both natural acid rock drainage (NARD) and AMD to the river, giving it a characteristic red colour and high acidity (pH = 1.7–2) extending some 60 km downstream from the mining area (López-Archilla et al. 1993). The reason for the persistence of such low pH, which is not seen in other AMD rivers, is due to factors such as the constant input of low-pH water from mine workings, waste dumps and waste-lined railway and road bases, abundant pyrite-oxidizing microorganisms and the dissolution of acid-producing secondary sulfate salts (e.g. Hudson-Edwards et al. 1999). The latter are common, if ephemeral, products of the precipitation of AMD waters.

In addition to acidity, they also contribute pulses of metals and metalloids when they dissolve during rainfall or flood events.

The uptake of toxins from mine waste–affected soils and waters can lead to their bioaccumulation and biomagnification in terrestrial plants and aquatic algae. Plants and crops grown on contaminated soils often contain high concentrations of metals (Miller et al. 2004). Animals grazing on alluvial soils often eat this plant material and sediment, especially after flooding when fresh metal-rich sediment is deposited. This poses risks to their health and that of humans who ingest their meat and milk. Some plants and animals, however, are able to survive and even thrive on contaminated soils. Such plants, known as metallophytes, have developed mechanisms to tolerate high levels of metals and metalloids, by either excluding or incorporating them into their biomass. Rapid invasion of abandoned and rehabilitated mine sites by metal-excluding plants is beneficial to their rehabilitation as it leads to the establishment of a green cover that protects wastes and waste repositories from erosion and leaching.

Fauna, too, can develop metal and metalloid tolerance in mining-affected sites: the earthworm Dendrodrilus rubidus, which is native to the mining-contaminated soils at the Coniston copper mine in northern England, was shown to tolerate higher soil copper and exhibit significantly less change in weight than control worms (Arnold et al. 2008). Pathways of metals, metalloids and radionuclides from mine waste to humans include the ingestion of polluted drinking water, soil, and foodstuffs (if grown on contaminated soils), and the inhalation and ingestion of polluted dust (Miller et al. 2004).

**RECYCLING, REUSE AND REHABILITATION OF MINE WASTES**

The legacy of historic mine waste and the piles that accumulate today and will do in the future present both a problem and a benefit to society. To achieve sustainable growth, humankind ideally requires the products of mining to be extracted without negative environmental impact. Consequently, plans for the rehabilitation of mine wastes are incorporated into plans for new extraction operations. This does not, however, address the issue of historic wastes, which were often not disposed of securely. Remining or reprocessing of such wastes, especially those in which ore extraction was not as efficient as with modern technologies, brings potential financial and waste-
reduction benefits. New techniques such as soil amendments and phytoremediation are being explored for mine waste rehabilitation. Some procedures, such as the hydroseeding of slag dumps (Fig. 6), have the added benefits of reducing the visual impact, stabilizing the wastes and preventing waste dispersal.

**MINE WASTES IN THE FUTURE**

Modern society relies on energy and mineral resources, and as a result the volumes extracted are increasing year on year. There are many, however, who think that this rate of extraction cannot continue. Gordon et al. (2006) warned that if all nations consumed the same amount of copper, zinc and platinum as the developed nations, supplies would unlikely be exhausted in the immediate future, but demands might not be met in the long term, even if near-complete recycling and complete extraction of all the lithosphere’s metals were to occur. Studies such as this have led others to coin the term “peak metal” (analogous to “peak oil”, a term used in the energy industry), meaning that humankind has extracted more metal to date than is left to mine. Although controversial, these terms highlight the fact that many of the richest mines and energy resources are being or have already been exploited, and companies are now turning to larger deposits with lower-grade ores. Such deposits, as a consequence, generate more mine waste per unit extracted. Thus, the mine waste–related damage to the Earth’s surface, which is already extensive, is likely to be exacerbated.

New technologies and declining resources have also created new types of mine wastes. Lanthanide (rare earth) elements such as neodymium and europium are used in lasers, solar panels and televisions, but they are mined from deposits that may contain uranium and thorium; therefore, the associated wastes are potentially both radioactive and toxic. The strong demand for lithium-ion batteries for portable electronic devices and other applications has also increased demand for this metal. Lithium is extracted from salt pans such as the Salar del Hombre Muerto in northwestern Argentina (Fig. 7). Here, as elsewhere in the world, lithium is extracted and concentrated into solution by evaporating water from the brine in solar ponds. In addition to the currently unknown human health risks associated with the waste waters and discarded salty sediments, the effects on local water cycles of large-scale brine extraction in these arid environments are not well understood. Also, the environmental impact of oil sand mining, which generates massive quantities of high-salt tailings and airborne volatile organic compounds, is severe (Kasperski and Mikula 2011 this issue).

The risks associated with mine wastes are directly related to the ways in which the potentially toxic components are released, transported and taken up by flora and fauna. These mechanisms, in turn, depend on the nature of the minerals in the mine wastes and the fluids and organisms they encounter. Geoscientists have the knowledge and the tools to better understand these processes. In the example shown in Figure 8, the mineral scorodite (FeAsO$_4$·2H$_2$O) has been identified in weathered, arsenopyrite-rich mill tailings using traditional transmitted- and reflected-light microscopy, together with modern synchrotron radiation-assisted micro-X-ray diffraction. In the future, the synergistic use of these and other emerging techniques, including tomography and CAT scanning, will enable the behaviour of mine wastes to be better understood and predicted.
Similarly, our ability to mitigate the environmental impact of surface-mined oil sands operations will hinge on our ability to characterize particles on the nano scale.

IN THIS ISSUE

The geochemistry, mineralogy, human ecotoxicology, remediation and reuse of mine wastes are explored in this issue. Heather Jamieson discusses the chemistry and mineralogy of solid metallic mine wastes and stresses the need for characterization at the micro- to nanoscale for better behaviour prediction and remediation (Jamieson 2011). This need is echoed by Kim Kasperski and Randy Mikula in their article on the emerging issue of oil sand extraction wastes (Kasperski and Mikula 2011). Kirk Nordstrom discusses the microbiology and geochemistry of acidic to circumneutral mine waters (Nordstrom 2011). Nordstrom discusses the microbiology and geochemistry of acidic to circumneutral mine waters (Nordstrom 2011). Nordstrom discusses the microbiology and geochemistry of acidic to circumneutral mine waters (Nordstrom 2011). Nordstrom discusses the microbiology and geochemistry of acidic to circumneutral mine waters (Nordstrom 2011).

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REFERENCES


Lottermoser provides a comprehensive overview of the recycling, reuse and rehabilitation of mine wastes, and highlights the necessity for making the most efficient use of all mined resources, while protecting the environment (Lottermoser 2011). Although a plethora of studies have contributed to a good baseline understanding of the character, weathering mechanisms, long-term stability, ecotoxicology, remediation and reuse of mine wastes, much still remains to be discovered. Geochemists and mineralogists have a significant role to play in this endeavour, especially with the challenges associated with historic mine wastes and the growing global mass of new, inherently complex mine wastes.


Lottermoser BG (2011) Recycling, reuse and rehabilitation of mine wastes. Elements 7: 405-410


Chemolithoautotrophic bacteria – the potential for the weathering of mine waste to generate low-pH water; usually calculated from the sulfide and carbonate contents of the rock

Acid mine drainage (AMD) – the process whereby low-pH water (pH < 5.6) is formed from the mining-induced weathering of sulfide minerals. The term is also used to describe the low-pH water itself.

Acidophiles – archaea, bacteria and eukarya organisms that thrive in low-pH water (pH < 5)

Calcination (or calcining) – the thermal treatment of ores at temperatures below their melting point to cause thermal decomposition or phase transitions, and thus release the economic materials

Chemolithoautotrophic bacteria – bacteria that gain their carbon from CO₂ and their energy from the oxidation of inorganic substrates (in mine wastes, usually minerals containing reduced forms of Fe and S)

Coal-mine drainage (CMD) – the process whereby low-pH water mine water is formed from the oxidation of sulfide minerals in coal deposits. The term is also used to describe the low-pH water itself.

Efflorescent salts – post-mining oxidation minerals (mainly sulfates), commonly present as cements and crusts in wastes and at or near the wastes’ surfaces

Fines – fine-grained particulates remaining after the crushing and processing of ores

Fine ashes and dusts – fine particulates formed during the metallurgical smelting of ores

Gangue minerals – valueless minerals intergrown with ore minerals

Heap leaching – the process in which metals are dissolved from ores by leaching them with a solution. The ores are crushed and usually heaped onto an impermeable base known as a leach pad.

Hydrosedding – a planting process using a slurry containing seed and mulch to stabilize mine wastes

Industrial minerals – rocks or minerals of economic value, excluding metallic ores, mineral fuels and gemstones

Mature fine tailings (MFT) – a term used in oil sand mining for the material formed by the gradual settling of the minerals in fluid fine tailings over three to five years until they reach a content of 30 to 40 wt% solids

Metallurgical slag – the non-metallic top layer that separates during the smelting of ores

Metallurgical wastes – the residues of the leached or smelted ores whose grade is too low to allow further treatment. These include the wastes from hydrometallurgy (e.g., cyanide leaching of gold ores), pyrometallurgy (e.g., smelting of copper or zinc ores to break down their host minerals and release the metals) and electrometallurgy (e.g., the use of electrolysis to liberate metals such as aluminum).

Mine wastes – solid, liquid or gaseous by-products of mining, mineral processing, and metallurgical extraction that are unwanted, have no current economic value and accumulate at mine sites

Natural acid rock drainage (NARD) – the process whereby natural low-pH water (pH < 5.6) is formed from the weathering of sulfide minerals. The term is also used to describe the low-pH water itself.

Oil sand – sand that contains bituminous organic matter incorporated when the sediment was deposited

Ore – an aggregate of metallic or industrial minerals and gangue minerals that is economically valuable

Ore roasting – a metallurgical process carried out to purify metals extracted from sulfide ores, involving oxidation, reduction, chlorination, sulfation and pyrohydrolysis reactions at high temperatures

Physiologically based extraction test (PBET) – a laboratory leach test that models the release of toxicants from various solid and liquid media (including mine wastes) in simulated gastric, gastrointestinal, lung, and other body fluids

Pressure oxidation – oxidative dissolution of sulfide minerals to remove sulfur and concentrate metals, carried out at high pressures and temperatures

Processing chemicals – chemicals that are added to crushed and sized ore to aid the separation of the sought-after minerals/metals from gangue minerals and unwanted metals

Recycling – the practice whereby new valuable resource ingredients are extracted, or the waste is used as feedstock, thus converting the entire mine waste into a new valuable product or application with some reprocessing

Rehabilitation – measures that alleviate environmental impacts during post-mining waste storage

Remediation – the process of removing mine waste-derived pollutants or contaminants completely from water or soil, reducing their concentrations to comply with regulatory requirements, or making them insoluble or unavailable to biota

Recover – resources that can be economically and legally extracted now

Resource – naturally occurring concentrations of liquids, gases, or solids in or on the Earth’s crust in such form and amount that economic extraction of a commodity is currently or potentially feasible

Reuse – the process that involves the new use or application of the total mine waste in its original form for an identified purpose directly without any reprocessing

Settling pond – a pond used to separate mine waste particles into different grain sizes using gravity and, in some cases, with the aid of a flocculant

Slag – the vitreous product of flux addition during smelting, consisting of metal silicates and oxides, and, in some cases, sulfides and native metals

Smelting – a metallurgical process carried out to extract metal from ore. It involves heating and partial melting of the ore, and the addition of a chemical reducing agent to remove oxygen and a flux to remove the gangue as slag.

Tailings – crushed rock and processing fluids (that may contain xanthate or cyanide) from a mill, washery or concentrator resulting from the removal of the economic metals, minerals, mineral fuels or coal from the mined resource

Waste rock – rock material removed to access and mine ore or coal

Zero waste – the concept of total resource utilization, where all the material mined is put to good use and no waste is generated
Large volumes of waste rock and mine tailings are stored at mine sites. Predicting the environmental impact of these wastes requires an understanding of mineral–water interaction and the characterization of the solid materials at the microscopic scale. The tendency of mine wastes to produce acid or neutral drainage containing potentially toxic metals generally reflects the ratio of primary sulfide to carbonate minerals and the trace element concentrations inherited from the ore deposit, as well as any ore processing that may have created new compounds. Whether potentially toxic elements are released to surface water, groundwater, or bodily fluids (in the case of ingestion or inhalation) depends on the host mineral and the possibility of sequestration by secondary minerals.

**INTRODUCTION**

Senior executives of mining companies have been heard to say that their business is as much concerned with moving and managing solid waste as it is with producing metals. The sheer volume of tailings and waste rock produced is astounding: on a per capita basis, North Americans produce more than 10 times as much solid mine waste as household garbage. Despite opportunities to recycle and reuse this material (Lottermoser 2011 this issue), most of it is simply stored. Aside from the physical issues associated with enormous piles of waste rock and voluminous tailings in impoundments or filling lakes and streams, the chemical reactivity of some mine wastes, specifically the release of potentially toxic and bioavailable elements to natural waters and, if ingested, bodily fluids, causes the greatest environmental damage. It is the geochemical and mineralogical character of solid mine waste that determines the nature of hazardous drainage and harmful dust, the amount of contamination and, ultimately, the risk to human and ecosystem health.

This article will show how the prediction of the risk associated with mine wastes, particularly whether they will produce acid, sulfate- and metal-rich drainage or, alternatively, pH-neutral or even alkaline drainage with potentially toxic elements, is rooted in their geochemical and mineralogical composition. Examples of exciting new microanalytical techniques will illustrate how detailed mineralogical analysis can provide key insights into the transformation of mine wastes through weathering and the implication of these reactions for environmental damage.

**GEOCHEMISTRY OF MINE WASTE**

Since more than 90% of the material handled during most metal mining is discarded, mine wastes are, essentially, geochemically equivalent to the rock mined. Exposure of these wastes to the atmosphere, the hydrosphere and the action of microorganisms generates drainage that may be acid and rich in dissolved metals and sulfate. As explained by Nordstrom (2011 this issue), the chemistry of the drainage is mainly the result of the oxidation of iron sulfide minerals, such as pyrite and pyrrhotite. This reaction generates acidity and sulfate and releases elements such as Cu, Zn, Cd, and Pb from sulfide minerals that are soluble in low-pH water. If sufficiently high amounts of carbonate minerals are present, the drainage may be neutralized, but some potentially toxic elements, such as arsenic and selenium, may still be present in relatively high concentration in these higher-pH waters. The first important attribute inherited from the deposit that governs the chemical reactivity of mine wastes from metal mines is the balance between reactive, acid-generating sulfide minerals (notably pyrite and pyrrhotite) and acid-neutralizing minerals (primarily calcite and other carbonate minerals such as dolomite). This balance is evaluated using acid–base accounting methods (Jambor 2003; Price 2009). These static tests have two parts: (1) determination of the acid-producing potential (AP) based on sulfide content (assumed to be pyrite), and (2) evaluation of the neutralization potential (NP) by titrating the sample with acid, usually sulfuric. Those materials with NP/AP < 1 are considered potentially acid-generating. In modern mining, hundreds of samples are tested, and the results are used to assess the risk that acid mine drainage might be produced from the wastes. Kinetic tests provide additional information on the rate of acid generation and neutralizing processes; using “humidity cells”, crushed rock is exposed to alternating dry and humid air over periods of weeks or months and then rinsed, and the drainage produced is analyzed for pH, sulfate, and other solutes. The second important attribute of mine wastes inherited from the deposit is the trace element association, particularly the potentially toxic elements that are hosted in ore minerals or accompanying sulfides. The potential for the leaching of such elements is evaluated using various types of leaching experiments, including simple field tests—where samples are mixed with water and shaken for several minutes and the solution is then decanted and analyzed—and multyear field bin or column studies designed to simulate mine wastes exposed to weathering conditions (Price 2009).
Both attributes can be predicted, to some degree, by the type of ore deposit mined or prospected. For example, volcanicogenic massive sulfide-base metal deposits are likely to produce acid mine drainage since the ratio of neutralizing carbonates to reactive sulfide minerals is low, and the potentially toxic elements that could be released include Cu, Zn, Pb, and Cd. On the other hand, orogenic gold deposits are less likely to produce acid mine drainage since they have lower concentrations of sulfide minerals and often contain carbonate minerals (Seal and Hammarstrom 2003). However, wastes from orogenic gold deposits may liberate As from arsenopyrite during weathering, and this metalloid can be mobile at neutral pH.

MINERALOGY OF MINE WASTE

The most serious environmental problems associated with solid mine wastes are their tendency to chemically react with air and water to produce contaminated water (Nordstrom 2011) or to be ingested or inhaled by humans and react with bodily fluids (Plumlee and Morman 2011 and recent studies). Airborne dust may also transport metals to soils and surface water. The fundamental processes that control the rate of sulfide oxidation and the nature of the potentially toxic elements released. As an example, Figure 2a depicts the primary ore assemblage at the Geco Cu–Zn deposit in northwestern Ontario, Canada, and Figure 2b shows tailings from the same deposit that have been exposed to the atmosphere for three years. Pyrrhotite, a rapidly oxidizing sulfide (Jambor and Blowes 2003). However, wastes from orogenic gold deposits may liberate As during weathering, and this metalloid can be mobile at neutral pH.

Types of Minerals in Mine Wastes

Minerals and other solid compounds in the mine wastes discussed in this article fall into four groups: (1) primary sulfide minerals, (2) primary non-sulfide minerals, (3) compounds produced by ore processing, and (4) secondary minerals formed by weathering. Tables 1 and 2 show examples of the first and last groups; Alpers et al. (1994) and Lottermoser (2010) have compiled more comprehensive lists.

Primary Sulfide Minerals

The sulfide minerals comprising or accompanying ore affect the degree and rate of sulfide oxidation and the nature of the potentially toxic elements released. As an example, Figure 2a depicts the primary ore assemblage at the Geco Cu–Zn deposit in northwestern Ontario, Canada, and Figure 2b shows tailings from the same deposit that have been exposed to the atmosphere for three years. Pyrrhotite, a rapidly oxidizing sulfide (Jambor and Blowes 2003). However, wastes from orogenic gold deposits may liberate As from arsenopyrite during weathering, and this metalloid can be mobile at neutral pH.

Table 1: Selected primary sulfide minerals found in mine wastes

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrite</td>
<td>FeS2</td>
</tr>
<tr>
<td>Marcasite</td>
<td>FeS2</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>Fe₇S₈</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>CuFeS₂</td>
</tr>
<tr>
<td>Bornite</td>
<td>Cu₃FeS₄</td>
</tr>
<tr>
<td>Sphalerite</td>
<td>(Zn,Fe)S</td>
</tr>
<tr>
<td>Pentlandite</td>
<td>(Fe,Ni)S₈</td>
</tr>
<tr>
<td>Enargite</td>
<td>Cu₃AsS₄</td>
</tr>
<tr>
<td>Galena</td>
<td>PbS</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>MoS₃</td>
</tr>
<tr>
<td>Tetrahedrite–Tennantite</td>
<td>(Cu,FexSb1–xS1)</td>
</tr>
<tr>
<td>Cinnabar</td>
<td>HgS</td>
</tr>
<tr>
<td>Cobaltite</td>
<td>CoAsS</td>
</tr>
<tr>
<td>Stibnite</td>
<td>Sb₂S₃</td>
</tr>
<tr>
<td>Realgar</td>
<td>AsS</td>
</tr>
<tr>
<td>Orpiment</td>
<td>As₅S₃</td>
</tr>
</tbody>
</table>

Table 2: Selected secondary minerals found in mine wastes

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron oxyhydroxides</td>
<td></td>
</tr>
<tr>
<td>Goethite</td>
<td>α-FeO(OH)</td>
</tr>
<tr>
<td>Lepidocrocite</td>
<td>γ-FeO(OH)</td>
</tr>
<tr>
<td>Ferrihydrite</td>
<td>Fe(OH)₃</td>
</tr>
<tr>
<td>Aluminum oxyhydroxides</td>
<td></td>
</tr>
<tr>
<td>Gibbsite</td>
<td>Al(OH)₃</td>
</tr>
<tr>
<td>Böhmite</td>
<td>AlO(OH)</td>
</tr>
<tr>
<td>Sulfate minerals</td>
<td></td>
</tr>
<tr>
<td>Gypsum</td>
<td>CaSO₄·2H₂O</td>
</tr>
<tr>
<td>Jarosite group minerals</td>
<td>(K,Na₂H₂O)Fe₃(SO₄)₁·(OH)₆</td>
</tr>
<tr>
<td>Schwertmannite</td>
<td>Fe₃O₅(SO₄)₂·9H₂O</td>
</tr>
<tr>
<td>Melanerite</td>
<td>FeSO₄·7H₂O</td>
</tr>
<tr>
<td>Copiapite</td>
<td>Fe₁₀Fe₃I⁺(SO₄)₃(OH)₁₂·20H₂O</td>
</tr>
<tr>
<td>Epsonite</td>
<td>MgSO₄·7H₂O</td>
</tr>
<tr>
<td>Angleites</td>
<td>PbSO₄</td>
</tr>
</tbody>
</table>
Compounds Produced by Ore Processing

On-site processing (such as ore roasting, heap leaching and pressure oxidation) may produce new solid compounds. These compounds include Fe(II)(CN)$_6$$_3$ complexes. Commonly known as Prussian blue. These authigenic cyanide precipitates contained significant amounts of Ni, Cu, and Zn.

Secondary Minerals

Secondary minerals formed from the weathering of primary sulfide minerals comprise a large group of mine waste minerals. Selected examples of oxyhydroxides and sulfates are given in Table 2, but secondary carbonates, sulfides, silicates and oxides may also precipitate (Alpers et al. 1994; Lottermoser 2010). Many of these minerals are fine grained and have a high capacity for adsorption of potentially toxic metals. These precipitates can therefore limit the aqueous concentration of such elements, although not necessarily to concentrations that are low enough to meet water-quality guidelines. Identification of these secondary minerals provides information on the aqueous conditions under which they form (pH, redox, metal and sulfate concentrations). For example, under acid conditions galena may oxidize to anglesite (PbSO$_4$), whereas in a pH-neutral environment the secondary mineral will be cerussite (PbCO$_3$). Spectacular examples of secondary minerals are the Fe sulfate precipitates that occur underground at the Richmond mine at Iron Mountain in northern California (Nordstrom et al. 2000; Nordstrom 2011) and downstream from the Rio Tinto mine workings in Spain (Hudson-Edwards et al. 1999, 2011 this issue). In many other cases, the secondary minerals occur as weathering rims on primary minerals (Fig. 2a) or as poorly crystalline crusts and cements. Even when present in minor amounts, these secondary minerals are very important in mineral–water interaction, and characterizing them requires a combination of careful and novel analytical techniques.

Methods of Mineral Characterization

Identification of the minerals associated with mine wastes is key to understanding mineral–water reactions. Particle size, porosity, surface area, degree of crystallinity, and trace element concentration are all important since these characteristics may control the long-term stability of these minerals and their role in releasing potentially toxic elements to water and organisms. Selected examples of the techniques used to characterize mine waste minerals are given in Table 3. If significant quantities of a monomineralic sample can be collected, as in the case of the Richmond mine Fe sulfate minerals, then “bulk” techniques, including X-ray diffraction (XRD) or the partial or complete dissolution of the mineral samples followed by chemical analysis of the resulting solution, can be used (e.g. Peterson 2003). More often, however, samples are mixtures. Conventional techniques, particularly petrography (reflected and transmitted light), electron microprobe analysis, and scanning electron microscope imaging and analysis, can be very helpful in identifying minerals and characterizing textures (Jambor and Blowes 1998; Hudson-Edwards et al. 1999). Figure 3 shows how element mapping and electron imaging using an electron microprobe can characterize a primary sulfide grain rimmed by a secondary mineral. Researchers have recognized that many mineral–water interactions occur in microenvironments (Fig. 4) and require nanoscale characterization (Hochella et al. 2005; Petrunic et al. 2009).

The availability of powerful X-ray beams generated at synchrotron facilities has produced a new family of techniques that are very useful for characterizing mine waste minerals. Synchrotron-based X-ray absorption spectroscopy (XAS) can be used to identify the minerals hosting potentially toxic elements such as Pb (Cotter-Howells et

1998), exhibits textural evidence of dissolution and a reaction rim of Fe oxyhydroxide and sulfate. The adjacent pyrite grain has less-evident oxidation, suggesting a slower rate of reaction. The element of most concern in drainage from the Geco deposit is Zn released from sphalerite, which also appears to dissolve readily in tailings (Jamieson et al. 1995).

Primary Non-Sulfide Minerals

Carbonate minerals in ore deposits or their host rocks have an important role in neutralizing acid drainage. In mine tailings impoundments, it has been observed that calcite is the most soluble carbonate and dissolves rapidly. Dolomite and ankerite dissolve more slowly (Jambor and Blowes 1998) but can still provide neutralizing capacity. Dolomite and ankerite dissolve more slowly (Jambor and Blowes 1998) but can still provide neutralizing capacity.

Silicate minerals may dissolve slowly in mine drainage and are not usually effective in controlling pH (Jambor et al. 2002). In some cases, however, soluble silicates may significantly influence the composition of drainage. At the Ekati diamond mine, Northwest Territories, Canada, crushing and washing of kimberlite during the diamond-removal process produces alkaline, high-Mg discharge water due to the rapid dissolution of serpentine and olivine (Rollo and Jamieson 2006). This also involves the trapping of atmospheric CO$_2$ and production of secondary carbonates, a process that can balance the greenhouse gas emissions of mining operations (Wilson et al. 2009; Lottermoser 2011).

Elements
al. 1994) and As (Foster et al. 1998; Hudson-Edwards et al. 2005). These techniques are called X-ray absorption near edge spectroscopy (XANES) or extended X-ray absorption fine structure (EXAFS), depending on which part of the absorption spectrum is used. If a microfocused synchrotron beam is used, near-simultaneous analysis using micro-XAS, micro-XRF (which uses the X-ray fluorescence signal to provide information on elemental composition) and micro-XRD (X-ray diffraction) can be accomplished (Walker et al. 2005, 2009).

Figure 5 shows an example of synchrotron-based micro-XRD, which is similar to conventional XRD in that the unknown pattern can be compared with thousands of reference mineral patterns; however, micro-XRD has the special advantage that a microfocused synchrotron beam can collect information from individual grains or alteration rims of minerals that are present in low abundance and would not be apparent in a bulk XRD pattern. Moreover, the powerful synchrotron beam tends to produce diffraction from microcrystalline and nearly amorphous materials, typical of secondary minerals in mine wastes. In fact, micro-XRD tends not to work well for coarser mineral crystals formed by high-temperature geological processes since the large individual crystals are unlikely to diffract using the microfocused monochromatic X-ray beam. Thus the method eliminates patterns from quartz, feldspar, and other abundant minerals that tend to dominate mine waste, enhancing the ability to discern metal-bearing minerals of interest.

Rarely is one method adequate to thoroughly characterize the minerals in mine waste, especially as multiple hosts are to be expected, and most researchers use a combination of techniques to characterize mine waste minerals and coexisting water (e.g. Hudson-Edwards et al. 2005; Fawcett and Jamieson 2011). Identification of contaminant-hosting grains is not possible with conventional tools. This last point is an important consideration for risk assessors in situations where the potential hazard associated with mine waste depends on the mineral host, as explained in the following example.

**GEOCHEMICAL AND MINERALOGICAL CONTROLS ON THE ENVIRONMENTAL AND HEALTH IMPACT OF MINE WASTE: AN EXAMPLE**

Abandoned gold-mine tailings from several sites in Nova Scotia, Canada, contain high concentrations of As, a result of mining and processing arsenopyrite-rich ore from 1860 to 1945. Many of these tailings are now located close to residential areas, and they are publicly accessible and used
these materials may generate acid (neutralization potential slightly less than one, indicating that the nearby wetland have a ratio of acid potential to neutralization potential). The typical tailings exposed at the balance between acid-generating sulfide and neutralizing carbonate minerals. The standard tailings at Dartmouth, Nova Scotia, several geochemical types of mine wastes have been delimited, based on element ratios and practices resulted in the deposition of sulfide concentrates, some of which have weathered to form hardpans consisting of residual arsenopyrite cemented by Fe arsenate minerals (DeSisto et al. 2011). These materials are clearly acid-generating. In terms of their influence on surface water and groundwater compositions, the typical tailings, unoxidized tailings and hardpan would conventionally be considered the riskiest material (Meunier et al. 2010).

for recreational purposes, such as dirt biking and trail walking (Fig. 6a). The total As concentration (in the <150 µm fraction) measured in a suite of 14 near-surface materials from sites throughout Nova Scotia ranges from 0.07 wt% As to over 30 wt% As. Arsenic in the tailings was originally present mainly as arsenopyrite (FeAsS), but decades of exposure to the atmosphere has transformed the sulfide into various arsenate and, more rarely, arsenic minerals (Walker et al. 2009). Typically, a near-surface tailings sample contains at least four types of As-hosting phases.

In the Montague gold district, one of the abandoned and unremediated sites within a few kilometers of the city of Dartmouth, Nova Scotia, several geochemical types of mine wastes have been delimited, based on element ratios and the balance between acid-generating sulfide and neutralizing carbonate minerals. The typical tailings exposed at surface and their unoxidized counterparts submerged in the nearby wetland have a ratio of acid potential to neutralization potential slightly less than one, indicating that these materials may generate acid (Fig. 6b). Past processing practices resulted in the deposition of sulfide concentrates, some of which have weathered to form hardpans consisting of residual arsenopyrite cemented by Fe arsenate minerals (DeSisto et al 2011). These materials are clearly acid-generating (Fig. 6b). In terms of their influence on surface water and groundwater compositions, the typical tailings, unoxidized tailings and hardpan would conventionally be considered the riskiest mine waste and warrant the most attention for remediation. The high-Ca/As tailings found in some areas of the site provide neutral drainage and are not acid-generating (Fig. 6b) and, on these grounds, would be considered less risky.

However, a different interpretation of the risk associated with this site arises when we consider the possible oral ingestion of fine dust. Based on near-surface tailings samples from several abandoned gold mines in Nova Scotia, Meunier et al. (2010) showed that As bioaccessibility (that is, the fraction of arsenic dissolved in simulated gastric and intestinal fluids) depends on As mineralogy. As explained by Plumlee and Morman (2011), bioaccessibility testing provides a measure of how easily potentially toxic elements are released to bodily fluids. In particular, samples rich in scorodite (FeAsO4·2H2O) and arsenopyrite exhibited relatively low As bioaccessibility, whereas samples containing Ca–Fe arsenate minerals, such as yukonite [Ca3Fe2(AsO4)4(OH)20·15H2O], have relatively high bioaccessibility. This is consistent with the known character and geochemical behavior of these minerals. It is not surprising that the coarse-grained primary arsenopyrite does not release much As (0.62% of total As present in the sample which is mostly arsenopyrite) during the 1-hour gastric (pH = 1.5) and 4-hour intestinal (pH = 7) bioaccessibility tests. The scorodite-rich sample released only 0.13% of its total As in the gastric step and 0.32% in the intestinal step, reflecting the pH dependence of scorodite solubility. The significantly higher As bioaccessibility (49%, 29%) associated with samples where Ca–Fe arsenate is the major As host is probably related to the fact that these tailings contain residual carbonate and that the As-hosting Ca-bearing minerals dissolve more readily in the gastric fluid. From the point of view of the oral ingestion of dust, the high Ca/As tailings might therefore be considered the riskiest material (Meunier et al. 2010).

Figure 5 Micro-XRD results from a transect across cemented layers in an As-rich hardpan in gold-mine tailings. The left and center panels of the figure show diffraction data for the three points indicated in the thin section photo (transmitted + reflected light; ASP = arsenopyrite) on the right. These data can be compared with those from reference minerals in order to identify the phases present. The stick patterns shown in the central panel correspond to scorodite (FeAsO4·2H2O, spot 1, top), a mixture of HFA (= amorphous hydrous ferric arsenate) and scorodite (spot 2, middle), and HFA with traces of tooeleite [Fe6(AsO4)4(SO4)4(OH)12·4H2O, spot 3, bottom]. In the middle and bottom stick figures, the HFA component does not have sticks due to its amorphous nature but is identified by the broad hump in these patterns. Scorodite, which is stable at low pH, is found in close proximity to oxidizing arsenopyrite where pore water is acid. Moving away from the arsenopyrite, grain-scale pH changes result in the differing cement composition, which influences the stability and long-term As sequestration of the hardpan. Source: DeSisto et al. (2011)

Figure 6 (A) Children riding dirt bikes on abandoned tailings at Montague Gold Mines, Nova Scotia, Canada, which contain very high concentrations of arsenic. Source: S. DeSisto. (B) Net acid and net neutralization potentials of different types of tailings from Montague. The standard unit for expressing AP (acid potential) and NP (neutralization potential) is the equivalent kg CaCO3 per tonne. Criteria are from Price (2009). See text for further explanation. Courtesy of J. Kavalec, Queen’s University, and M. B. Parsons, Geological Survey of Canada (Atlantic).
OUTLOOK
Reducing the environmental and health impact of mine wastes requires expertise and skills from several disciplines. Central to these are geochemistry and mineralogy. In particular, understanding mineral–water interaction requires characterizing phases at the micrometer scale or less, which is usually accomplished by a combination of conventional and newly developed analytical techniques. Very few of those who make multimillion-dollar decisions to grant permits for mines to operate, approve clean-up plans for mine closure, or cope with disastrous events such as tailings-dam failures or community health impacts related to mining are able to tackle or interpret mine waste mineralogy. Our professional community can make important contributions in this area by providing expertise and access to novel analytical techniques and by training students.

ACKNOWLEDGMENTS
I am very grateful for the contributions from many graduate students, research associates and colleagues.

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Waste Streams of Mined Oil Sands: Characteristics and Remediation

Kim L. Kasperski and Randy J. Mikula

INTRODUCTION

With production in excess of $1.5 \times 10^6$ barrels per day (1 barrel = 158.9 L)—and expectations that this will double in the next ten years—Canada’s oil sands, located near Fort McMurray, Alberta, represent a world-class oil reserve. Canada is the largest exporter of oil to the United States, ahead of Saudi Arabia, and a significant portion of that is from oil sand. The oil sands of Alberta constitute the world’s largest bitumen reserve, containing an initial in-place resource of $1730 \times 10^9$ barrels, of which the estimated remaining established reserve is $170 \times 10^9$ barrels. Oil sand deposits, which are exploitable through a combination of technologies, encompass an area of slightly more than $140,000 \text{km}^2$ (Fig. 1).

The resource is well defined, but the estimate of reserve could double in the next five years as technology is developed to exploit the carbonate deposits in the western regions of the oil sands. Even without that, Canada has the third-largest oil reserve, behind only Saudi Arabia and Venezuela (Fig. 2), and over 97% of these reserves are in oil sands. Ultimately, about 80% of the oil sand reserve will be developed using in situ technologies such as thermal methods, in which steam is injected underground to soften the bitumen to the point where it can be pumped to the surface. However, since the start of commercial production of bitumen from oil sand in 1967, with the opening of the Suncor mine, the bulk of production has been from surface-mined oil sand, and surface mining will continue for at least the next few decades. One of the reasons for this is that bitumen recovery from surface-mined ore is significantly greater than from any in situ method. However, with surface mining comes land disturbance and an increasing number of tailings ponds. Approximately 600 km$^2$ of land have been disturbed by oil sand mining, and of that, tailings ponds cover about 180 km$^2$ (Fig. 1).

Oil sand production increased by about 12% from 2008 to 2009 (Burrowes et al. 2010). This rapid growth in production has produced a proportional increase in the impacts on land, air, and water, with one of the main issues being the accumulation of fluid fine tailings (FFT) and associated water in the tailings ponds. The aim of this article is to provide the reader with an introduction to the properties and remediation of tailings that arise from the production of bitumen from oil sand mining in Canada.

TAILINGS FROM SURFACE-MINED OIL SAND

Oil sands that are within 60 to 80 m of the surface can be recovered using surface-mining methods. The bitumen is subsequently recovered from the oil sand using warm water, mechanical energy, and sometimes process chemicals such as sodium hydroxide. Since the bitumen represents only about 10 wt% of the oil sand ore, about twelve volumes total of wet sand, silt, and clay suspensions are created as waste streams for every volume of bitumen produced (Kasperski 1992).

Three main tailings streams are associated with the extraction of bitumen from mined oil sand ore: (1) coarse tailings, (2) fluid fine tailings, and (3) froth-treatment tailings. All three streams are aqueous slurries containing varying proportions of minerals, water, dissolved inorganic salts, and residual organics. The solids in coarse tailings are largely sand (mineral particles greater than 44 μm) and, in fluid fine tailings, mostly fines (less than 44 μm). Froth-treatment tailings make up a relatively small stream that results from the addition of solvent to the extracted bitumen froth or concentrate. Solvent, such as naphtha, is added to decrease the viscosity of the bitumen, allowing...
for more efficient separation of the bitumen from the residual minerals and water. Froth-treatment tailings are a combination of water, sand, fines, residual bitumen, and solvent.

Tailings from the extraction process are pumped to recycle water ponds, where the sand quickly settles and forms a beach, while the fines run off into the pond as a slurry. A large portion of the sand is used to build containment dikes for the fluid tailings and recycle water. Currently, all water released from the settling sand and fines is recycled back to extraction.

The minerals in fluid fine tailings gradually settle over three to five years until they reach 30 to 40 wt%, at which point the material is known as mature fine tailings (MFT). The consolidation rate of MFT after this point is extremely slow, and over the past forty-four years of commercial operations the fluid fine tailings and MFT have been steadily accumulating. Figure 3 shows the relative volumes of the constituents of the tailings produced compared to the volume of oil sand, plus water added to extract the bitumen. The volumes in this figure assume that 10 wt% of the minerals in the beach are fines, which means that 52% of total fines are captured in the beach rather than forming the fluid fine tailings that are stored in ponds. The capture estimates for fines vary, and a lower fines capture would mean higher MFT volumes for a given amount of ore processed. However, as a rule of thumb, approximately 1.5 m$^3$ of MFT are formed for every cubic metre of bitumen produced.

Approximately twelve barrels of water are used to extract one barrel of oil from oil sand. Although about 75% of this water is recovered and recycled, the rest remains between the grains of the settled minerals of the tailings. The capture estimates for fines vary, and a lower fines capture would mean higher MFT volumes for a given amount of ore processed. However, as a rule of thumb, approximately 1.5 m$^3$ of MFT are formed for every cubic metre of bitumen produced.

The mine planning associated with the handling of the water and tailings can be very complex. Some operations keep the froth-treatment tailings separate from the other streams, whereas others combine all the tailings streams. No matter what the strategy, current estimates of the total MFT or fluid fine tailings inventory stand between 720 and 1000 Mm$^3$ (million cubic metres). The return of the sand tailings to a landscape of equivalent productivity (reclamation) is relatively straightforward, but the consolidation of the fluid fine tailings to a trafficable landscape, strong enough to support reclamation equipment, has been challenging.

**PROPERTIES OF OIL SAND TAILINGS**

The high clay content of the fluid fine tailings results in a very slow settling suspension, requiring storage ponds of large surface area. Settling and consolidation of the minerals in the fluid fine tailings is controlled by the particle size distribution and ultimately by the permeability and compressibility of the system (Yong et al. 1983; Dusseault and Scott 1983; Kasperski 1992). The settling and consolidation parameters are also a function of the mineral type, residual organics, and water chemistry, the latter through its effect on clay properties (Yong et al. 1983; Omotoso and Mikula 2004).

The fines fraction of tailings consists of clay minerals and quartz, with the proportions varying depending on the ore. An average often used for modeling purposes is one-half clay minerals and one-half quartz, but this can vary considerably, with reported values for clay content in the fines ranging from 20% to 80% by weight (Mikula et al. 2009). In addition, the clay mineral composition also varies, but the predominant clays are kaolinite, interlayered kaolinite (meaning the kaolinite layers have layers of another clay mineral interspersed between them), illite, and interlayered illite, with minor amounts of chlorite and...
occasional traces of smectite (Omotoso and Mikula 2004). Minerals such as zircon, rutile, and ilmenite are also present, predominantly in froth-treatment tailings (Kasperski 1992; Kaminsky et al. 2008). They represent potentially valuable sources of titanium and zirconium. Table 1 shows data from several samples, highlighting the –2 μm (clay-size) fraction of the minerals. As most of the mineral matter in oil sand is quartz, focusing on the –2 μm fraction makes X-ray diffraction analysis more sensitive to the clay minerals, which might otherwise be missed in the high-intensity quartz diffraction patterns and which are most important in determining the properties of the fluid fine tailings.

![Figure 2](image)

The inability of the fine tailings fraction to consolidate sufficiently to make the surface trafficable was thought to be due to the presence of amorphous iron oxides (Yong and Sethi 1978). Amorphous iron oxides, at only about 4 wt%, were thought to be responsible for 35% of the water-holding capacity of the fluid fine tailings. Our understanding of the mineral components in the tailings stream has improved significantly since that time, and it is now known that the iron oxides present are not amorphous but crystalline. Figure 4 shows how the increased resolution available at synchrotron sources relative to laboratory-based X-ray diffraction allows one to demonstrate that the iron oxide is crystalline. The higher resolution of the synchrotron is evident from the reduced line widths, and a marked goethite peak is clearly visible in the synchrotron pattern, whereas the peak is not visible in a conventional diffraction pattern. The demonstration that amorphous iron is not important in determining the fluid fine tailings

![Figure 3](image)

**TABLE 1** TYPICAL COMPOSITION (wt%) OF THE –2 μm FRACTION MINERALS DERIVED FROM MINED AREAS IN THREE OIL SANDS LEASES

<table>
<thead>
<tr>
<th>No of samples</th>
<th>Ore</th>
<th>Froth</th>
<th>Tailings</th>
</tr>
</thead>
<tbody>
<tr>
<td>K(90)-smectite</td>
<td>0–23</td>
<td>0–22</td>
<td>0–16</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>5–67</td>
<td>31–58</td>
<td>14–79</td>
</tr>
<tr>
<td>I(85)-smectite</td>
<td>0–70</td>
<td>0–38</td>
<td>0–58</td>
</tr>
<tr>
<td>Illite</td>
<td>3–23</td>
<td>6–21</td>
<td>2–24</td>
</tr>
<tr>
<td>Chlorite</td>
<td>0–9</td>
<td>0–1</td>
<td>0–8</td>
</tr>
<tr>
<td>Quartz</td>
<td>3–13</td>
<td>6–10</td>
<td>5–57</td>
</tr>
<tr>
<td>Rutile + anatase</td>
<td>0–2</td>
<td>1–10</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Siderite</td>
<td>0–1</td>
<td>1–11</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Pyrite + marcasite</td>
<td>0–2</td>
<td>1–2</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

*K(90)-smectite = interlayered structure of kaolinite and smectite that is 90% kaolinite layers. I(85)-smectite = interlayered structure of illite and smectite that is 85% illite layers.*

The inability of the fine tailings fraction to consolidate sufficiently to make the surface trafficable was thought to be due to the presence of amorphous iron oxides (Yong and Sethi 1978). Amorphous iron oxides, at only about 4 wt%, were thought to be responsible for 35% of the water-holding capacity of the fluid fine tailings. Our understanding of the mineral components in the tailings stream has improved significantly since that time, and it is now known that the iron oxides present are not amorphous but crystalline. Figure 4 shows how the increased resolution available at synchrotron sources relative to laboratory-based X-ray diffraction allows one to demonstrate that the iron oxide is crystalline. The higher resolution of the synchrotron is evident from the reduced line widths, and a marked goethite peak is clearly visible in the synchrotron pattern, whereas the peak is not visible in a conventional diffraction pattern. The demonstration that amorphous iron is not important in determining the fluid fine tailings...
properties suggests that the behaviour of the clay minerals may be responsible. As a result, any tailings treatment should emphasize the role of the clay components and should be designed to change their behaviour in the tailings suspension.

OIL SAND TAILINGS REMEDIATION

Two of the main objectives for remediating tailings are to reclaim the ponds and to recover the water tied up in the MFT. Water use in surface-mined oil sand production is steadily growing as a result of increasing bitumen production, and, because the regulators prohibit discharge of any process-affected water from a mine site, this has resulted in increasing water inventories at these sites. In 2008, oil sand mining operations withdrew 0.15 × 10^9 m^3 of water from the Athabasca River (CAPP 2010). For comparison, in 2008 the mean annual discharge of the river at Fort McMurray was 20.9 × 10^9 m^3. However, the impact on the river of this withdrawal rate is very dependent upon the time of year. Because the river flow varies tremendously with the seasons, the relative intake is higher in winter than in spring or summer. The intake of water is controlled by licences granted to the operators and by the in-stream flow-needs guidelines established by Alberta Environment and the federal Department of Fisheries and Oceans. The in-stream flow-needs guidelines regulate total intake from the river as a function of actual river flow rates, irrespective of licensed volumes. If more water is recovered from the fluid and sand tailings, less water will be required from the Athabasca River, and the impact on its aquatic environment will be smaller.

Until about 2005, the operating companies were proposing to reclaim the fluid tailings using the consolidated or composite tailings process (CT) coupled with wet-landscape reclamation. Wet-landscape as used here means water-capping of the remaining MFT in end-pit lakes. From 2005 to 2009, however, a variety of tailings remediation alternatives appeared to show some promise, and this culminated in the issuance of Directive 74 by Alberta’s Energy Resources Conservation Board. This directive mandates that by 2013 a minimum of 50% of the fines in the ore must be placed in a dedicated disposal area where the material, after one year, must have a strength of at least 5 kPa, and after five years, a strength of 10 kPa or higher. This would allow for sand capping, return of the overburden and original soil horizon, and reestablishment of the boreal forest. The implementation of Directive 74 will significantly reduce the volume of MFT that would be earmarked for wet-landscape reclamation; it would also improve the image of surface-mined oil sands as reclamation of the fluid fine tailings proceeds to a dry landscape.

There are currently five prominent treatment options. Wet-landscape reclamation with MFT stored in end-pit lakes has already been mentioned. The four dry-landscape options include CT, rim-ditching, thin-lift dewatering, and centrifugation, of which the latter two do not require any initial containment (dry-stackable tailings) (Table 2).

The CT process (also called non-segregating tailings or NST) consists of mixing MFT and sand in the correct ratio, along with a chemical amendment such as CaSO_4, such that, when the slurry is pumped to the tailings pond, the sand and fines settle together as a non-segregating mass. This leads to rapid settling, such that after about one year the material is composed of 70 to 80 wt% solids (Mikula et al. 1998), leaving a dry, reclaimable surface once the released water is pumped away for recycling. However,

**Table 2** FLUID FINE TAILINGS REMEDIATION OPTIONS AND THEIR RESPECTIVE IMPACTS ON THE SURFACE-MINED OIL SANDS PROCESS

<table>
<thead>
<tr>
<th>Tailings remediation option</th>
<th>Fluid containment/dikes needed?</th>
<th>Sand requirement</th>
<th>Water use per barrel^1</th>
<th>Impact on recycle water chemistry</th>
<th>Bitumen recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT/NST</td>
<td>yes</td>
<td>for process as well as for containment</td>
<td>3</td>
<td>medium</td>
<td>no</td>
</tr>
<tr>
<td>Thin-lift dewatering</td>
<td>no, but significant surface area is required</td>
<td>none</td>
<td>3</td>
<td>low</td>
<td>no</td>
</tr>
<tr>
<td>Rim ditching</td>
<td>yes</td>
<td>for containment only</td>
<td>3</td>
<td>medium</td>
<td>no</td>
</tr>
<tr>
<td>Centrifugation</td>
<td>no</td>
<td>none</td>
<td>2-3</td>
<td>medium-high</td>
<td>to some extent from centrate</td>
</tr>
<tr>
<td>Wet-landscape reclamation</td>
<td>yes</td>
<td>none</td>
<td>5+</td>
<td>none</td>
<td>no</td>
</tr>
</tbody>
</table>

^1 Currently, 4 barrels of water per barrel of bitumen is typical.

4 An end-pit lake is defined here as a lake formed by natural seepage of water or deliberate capping with water in part of the mined-out pit, at the end of the mine’s production.
because the process is not completely reliable, and because it requires a lot of sand (which is often needed elsewhere) and also initially requires containment (which may not always be available), other methods are required.

Rim ditching, a technology borrowed from phosphatic tailings treatment, consists of pumping chemically treated MFT into a pit. Once the mixture has developed some strength, a ditch is dug around the rim to increase dewatering. Water is pumped away for recycling, and the ditch is enlarged as dewatering progresses. Pilot tests were quite successful, but again, this method initially requires containment. Thin-lift dewatering is the process whereby a thin layer or lift of chemically treated MFT is spread on a shallow slope so that the water drains away or evaporates. Once the layer is sufficiently dry, another lift of treated MFT is added on top, and so on (Fig. 5). While a significant amount of water is recovered, a portion is lost to evaporation and so is not available for recycling. This method also requires a large land area for the lifts. Centrifugation is exactly as the name implies: chemically treated MFT is spun in massive centrifuges, leaving a solid cake that does not need containment and rapidly becomes a dry surface (Fig. 6). The recovered water (centrate) is returned for recycling. However, this is an expensive technology, in terms both of equipment and operation costs.

All of these dry-landscape options require an initial modification of the clay behaviour in the fluid fine tailings. Consequently, an understanding of clay science and surface chemistry contributes to our ability to modify and control the behaviour of oil sands tailings. Different water chemistries (a result of differences in ore composition and process conditions) will give rise to different clay-floc structures, which will determine the settled volume of otherwise identical tailings samples. These properties in turn define the depositional and accumulation behaviour of the fluid fine tailings in tailings containment. The success of each of these technologies depends entirely upon our ability to control the clay properties.

**Figure 3** shows the relative volumes of the coarse and fine tailings and the proportion of the recycle water recovery (1) without implementation of a tailings treatment, (2) with implementation of CT/NST, and (3) with implementation of centrifuged dry-stackable tailings. As the tailings management approach improves, a greater proportion of the extraction water is recycled, and therefore (shown by the double-headed arrows) a smaller amount of water needs to be taken from the environment. The greater the proportion of MFT in the dry tailings, the smaller is the double-sided arrow that represents make-up water removed from the Athabasca River and elsewhere.

One consequence of recovering more water using technologies such as CT/NST or centrifugation is that the chemistry of the recycle water will be increasingly determined by the water that comes from the ore. This is because less fresh water is brought in from the river (because more is recovered from the tailings), the proportion of fresh water to the much more saline water found in the ore decreases. This invariably leads to an increase in total dissolved solids.
Table 2 summarizes qualitatively the effect of these tailings-treatment technologies on the mine plan and recycle water chemistry.

Both the CT/NST process and the thin-lift dewatering process are being used at a commercial scale, but given the complexity of oil sands mining operations, it is expected that the reclamation goals will be achieved by applying a suite of technologies.

Since the reclamation plan is generally to cap the dry-stackable tailings deposits with sand, and later with the original overburden and soil horizons, the reestablishment of the original boreal forest should be achievable, with the dry-stackable tailings products replacing the original oil sands.

OUTLOOK

In spite of what might be considered a slow start to the reclamation of the fine tailings component of oil sands tailings, the industry is improving technologies and is implementing them at commercial scales at an ever increasing rate. With a scale approximately twenty to thirty times that of some of the largest coal mines and with strict specifications for water quality in the extraction process, the industry has moved slowly on the types of chemical interventions that, while giving dry-stackable tailings, could also negatively affect (in terms of what is needed for extraction) recycle water quality. Commercialization of dry-stackable tailings technologies has the potential to make the accumulation and storage of large volumes of fluid fine tailings a thing of the past.

ACKNOWLEDGMENTS

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**Mine Waters: Acidic to Circumneutral**

D. Kirk Nordstrom*

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Acid mine waters, often containing toxic concentrations of Fe, Al, Cu, Zn, Cd, Pb, Ni, Co, and Cr, can be produced from the mining of coal and metallic deposits. Values of pH for acid mine waters can range from –3.5 to 5, but even circumneutral (pH ~ 7) mine waters can have high concentrations of As, Sb, Mo, U, and F. When mine waters are discharged into streams, lakes, and the oceans, serious degradation of water quality and injury to aquatic life can ensue, especially when tailings impoundments break suddenly. The main acid-producing process is the exposure of pyrite to air and water, which promotes oxidative dissolution, a reaction catalyzed by microbes. Current and future mining should plan for the prevention and remediation of these contaminant discharges by the application of hydrogeochemical principles and available technologies, which might include remining and recycling of waste materials.

**KEYWORDS:** mine water, dissolved metals, water quality, water contaminants, pyrite oxidation

**INTRODUCTION**

There is no doubt that ancient civilizations were aware that acid mine drainage (AMD) is toxic and results from pyrite oxidation. These people even utilized some of the soluble efflorescent salts that form during the evaporation of AMD for dyes, inks, and paper preparation (Theophrastus, 3rd century BCE; Caley and Richards 1956). Many names given by the Greeks and Romans were used for centuries afterward. “Oil of vitriol” was the ancient name for sulfuric acid, which could be made by heating melanterite (FeSO₄·7H₂O, also known as “iron vitriol” or “green vitriol”), an efflorescent salt formed from pyrite oxidation.

Mine drainage is not only acidic (pH 0–5) but can be circumneutral (pH 6–8) or even strongly basic (pH 8–12). It can be radioactive, corrosive, and highly toxic. Because extraction of valuable minerals is from mineralized rock, the surface waters and groundwaters around mines are also mineralized and unfit for most purposes unless treated. Although the hydrogeochemical and microbiological processes that control the chemistry of mine waters are complex, research has greatly increased our understanding of them, thereby benefiting remediation. This paper outlines some of these processes, including the microbiology that catalyzes these reactions, the chemistry of mine waters, the environmental consequences of accidental releases from mine sites, the formation of efflorescent salts, and the fluvial transport of metals and sulfate to the ocean.

**GENERATION OF ACID MINE WATERS**

The chemistry and microbiology behind sulfide mineral oxidation and the formation of AMD are rather complicated and still the subject of research. The most commonly written reaction is the oxidation of pyrite by oxygen from the air in the presence of water:

\[
\text{FeS}_2 + 15/4\text{O}_2 + 7/2\text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3(s) + 2\text{H}_2\text{SO}_4 .
\]

Some form of hydrous ferric oxide (HFO) is precipitated and is represented ideally here as ferric hydroxide. Reaction 1 is a composite of two half-cell reactions, one for pyrite oxidation and the other for oxygen reduction:

\[
\text{FeS}_2 \rightarrow \text{Fe}^{3+} + 2\text{S}^{6+} \text{ (in sulfate)} + 15\text{e}^- ,
\]

\[
15/4\text{O}_2 + 15\text{e}^- \rightarrow 15/2\text{O}^{2-} \text{ (in sulfate)} .
\]

However, reactions 1, 2, and 3 oversimplify the process because we know that (1) iron-oxidizing bacteria and archaea are important catalysts in this reaction (Nordstrom and Southam 1997), (2) chemical reactions do not transfer more than one electron (or possibly two) at a time, (3) aqueous Fe³⁺ is a more powerful oxidant (lower activation energy) than oxygen, (4) pyrite oxidizes to an acid ferrous sulfate solution before Fe²⁺ (aq) oxidizes and precipitates an HFO, and (5) pure Fe(OH)₃(s) can be made in the laboratory but does not occur in the environment. The HFO precipitate that forms in AMD is a mixture of iron-bearing minerals that may include ferrihydrite, schwertmannite, microcrystalline goethite, and lepidocrocite. Hence, reaction 1 is written in the alternative form:

\[
\text{FeS}_2 + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} \rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 16\text{H}^+ .
\]

with Fe³⁺ regenerated from Fe²⁺ by iron-oxidizing bacteria and archaea such as *Acidithiobacillus ferrooxidans*, which oxidizes both Fe²⁺ and reduced sulfur species (thiosulfate and sulfur), and *Leptospirillum ferrooxidans*, which oxidizes only Fe²⁺. Without Fe-oxidizing bacteria, pyrite oxidation would stop because the abiotic oxidation of Fe²⁺ at low pH...
is much too slow. Consequently, the role of microbial communities in acid mine waters has been a subject of much research.

Sulfur transforms from an oxidation state of 1– in pyrite to 6+ in sulfate, but because 7 electrons cannot transfer in a single step, some intermediate sulfoxyanions must form. Experiments have confirmed this hypothesis. In the presence of (1) a strong oxidant such as Fe$^{3+}$, (2) a community of Fe- and S-oxidizing microorganisms, and (3) a conductive pyrite surface, intermediate sulfoxyanions are oxidized to sulfate so rapidly that they can be difficult to determine analytically (Goldhaber 1983; Moses et al. 1987).

**LIFE IN ACID MINE DRAINAGE**

Acid mine waters are often described as devoid of life, for example, “Peru Creek east of the Keystone ski area has been pronounced ‘biologically dead’ ” (The Denver Post, May 30, 2011). However, such creeks are not biologically dead: they are teeming with microbes, including bacteria, archaea, yeasts, fungi, and algae (Edwards et al. 2000). Wherever there is an abundance of oxidizable dissolved iron and/or reduced sulfur compounds, chemolithoautotrophic bacteria will grow. These bacteria can gain their carbon needs from CO$_2$ in the air (hence “autotrophic”) and their energy needs from oxidation of inorganic sources such as reduced Fe and S (hence “chemolithotrophic”). Once colonies of chemoautotrophs develop, their degradation products provide a source of organic carbon for heterotrophic bacteria (those that derive their energy from organic compounds) and eukarya (multicellular organisms that contain a nucleus and other organelles within their cells, in contrast to bacteria and archaea).

**THE BIG ONES THAT GOT AWAY**

Anywhere from 95 to 99.999% of the earth materials mined or moved for extraction of Cu, Pb, Zn, Au, and Ag become waste, some of it containing pyrite and other metallic sulfides and some not (Da Rosa et al. 1997). A few billion tons of solid wastes were produced at the Butte-Anaconda Superfund complex (Montana, USA) alone. Past, present, and future ore production from one of the largest copper mines in the world, Chuquicamata, Chile, is estimated at 11.4 billion metric tons (Ossandón et al. 2001). Much of this waste rock and tailings exposes sulfide minerals to air and water, thus creating AMD (Fig. 2). Of at least 161,000 abandoned hardrock mines in 12 western U.S. states and Alaska, 33,000 have degraded the environment primarily by contaminating surface water and groundwater (Nazarro 2008). The toll on fish populations has been immense. It is not uncommon for tens to hundreds of thousands of fish to die from a single spill or rainstorm event. Billions of dollars have been spent by U.S. federal agencies to clean up these sites, and there is still much more to be done. These numbers provide some measure of the scope of the problem.

In spite of efforts to contain AMD and to treat it, numerous accidents have caused the release of large quantities of AMD to the environment. Between 1975 and 1988, approximately 84 million metric tons of toxic mine tailings were discharged into Calancun Bay from the mining and processing of the Mt. Tapian copper ore deposit on Marinduque Island, Phillipines. Those discharges were terminated because of ecological harm to aquatic life along the coast, and the tailings were diverted to the Tapian pit. However, containment failures occurred in 1996, which led to the discharge of 2–3 million cubic meters of tailings into the Makulapnit-Boac River drainage system in 4–5 days, causing an environmental disaster (UNEP/OCHA 1996). At least three spills from failed tailings impoundments in northwestern Romania (Baia Mare) seriously affected the Sasar, Lapus, Tisza, and Danube rivers between January and mid-March 2000. Approximately 1200 metric tons of fish were killed, thousands of fishermen were unable to work, and water supplies for several town and farm communities were badly contaminated (UNEP/OCHA 2000).
MINE-DRAINAGE CHEMISTRY

The most acidic waters known, other than industrial and laboratory solutions, are AMD (Nordstrom et al. 2000). Acid mine waters can have a range of constituents, but the major cations are usually Fe and Al and the main anion is SO4. The pH can range from −3.5 to 5 (Nordstrom and Alpers 1999)*. Examples of acid and circumneutral water compositions are shown in Table 1. Average world river-water composition is included for reference. Most solutes in mine waters are orders of magnitude higher in concentration than those in average river water. The analyses in Table 1 were chosen to show the broad ranges of pH (from −2.5 to 11.74) and solute concentrations. One site, Straight Creek in New Mexico, USA (analysis 3), is natural acid rock drainage (NARD), and two analyses are from coal-mine drainage (CMD), one in Pennsylvania, USA, and the other in South Africa. The lowest-pH sample is from Iron Mountain, a massive sulfide deposit that was once the largest copper producer in California. The ultra-acidic mine waters from Iron Mountain are produced by the oxidation of large sulfide masses consisting of ~95% pyrite. A considerable amount of heat is also produced during oxidation, which drives evaporation of these waters, further concentrating them.

The NARD sample from New Mexico shows that the process that generates acid drainage also occurs naturally, but usually at slower rates and with lower concentrations of metals than AMD. Acid rock drainage from natural weathering of pyrite-bearing rock has been of considerable interest during the last 20 years because both regulators and the mining industry would like to know how much mining affects water quality relative to “natural background” conditions, so that a water-quality standard might be developed that takes into account the geological context (Runnells et al. 1992). A paleomagnetic study at Iron Mountain demonstrated that mining increased the rate of pyrite oxidation by 2–3 orders of magnitude relative to the

* Remembering that pH = −log(aH+) = −log(γH+H+); for pH values below 0 the activity coefficient, γ, increases substantially above 1 so that the molal concentration, m, is not as high as it would be using the assumption that the activity coefficient is unity.

### Table 1

<table>
<thead>
<tr>
<th>Constituent (in mg/L)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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</thead>
<tbody>
<tr>
<td>SO4</td>
<td>760,000</td>
<td>11,200</td>
<td>1950</td>
<td>510</td>
<td>5.3–16.8</td>
<td>376</td>
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<td>Cl</td>
<td>n.d.</td>
<td>9.2</td>
<td>7.5</td>
<td>5</td>
<td>5.92</td>
<td>196</td>
<td>75</td>
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<td>F</td>
<td>n.d.</td>
<td>5.1</td>
<td>1.06</td>
<td>&lt;0.1</td>
<td>0.3</td>
<td>0.34</td>
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<td>HCO3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>48.8</td>
<td>311</td>
<td>2666</td>
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<td>35</td>
<td>109</td>
<td>76.2</td>
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<td>2.52</td>
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<td>Na</td>
<td>416</td>
<td>24.3</td>
<td>7.93</td>
<td>6.7</td>
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<td>24,038</td>
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<tr>
<td>K</td>
<td>194</td>
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<td>2.7</td>
<td>1.72</td>
<td>26.4</td>
<td>222</td>
</tr>
<tr>
<td>Ca</td>
<td>279</td>
<td>266</td>
<td>337</td>
<td>53</td>
<td>13.4–23.8</td>
<td>71.2</td>
<td>n.d.</td>
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<tr>
<td>Mg</td>
<td>437</td>
<td>97.0</td>
<td>106</td>
<td>61</td>
<td>3.4–5.95</td>
<td>74.6</td>
<td>100</td>
</tr>
<tr>
<td>Fe2+</td>
<td>34,500</td>
<td>2150</td>
<td>0.256</td>
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<td>n.d.</td>
<td>&lt;0.001</td>
<td>n.d.</td>
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<td>2510</td>
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<td>49.0</td>
<td>0.0066</td>
<td>0.437</td>
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<td>Al</td>
<td>1420</td>
<td>623</td>
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<td>0.022</td>
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<td>Mn</td>
<td>23</td>
<td>9.32</td>
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<td>6.1</td>
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<td>0.003</td>
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<tr>
<td>Cu</td>
<td>4760</td>
<td>9.64</td>
<td>1.55</td>
<td>0.0014</td>
<td>0.00148</td>
<td>&lt;0.001</td>
<td>0.283</td>
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<tr>
<td>Pb</td>
<td>11.9</td>
<td>0.037</td>
<td>&lt;0.008</td>
<td>0.0016</td>
<td>0.000079</td>
<td>n.d.</td>
<td>0.032</td>
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<tr>
<td>Zn</td>
<td>23,500</td>
<td>2.62</td>
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<td>0.36</td>
<td>0.0006</td>
<td>0.001</td>
<td>n.d.</td>
</tr>
<tr>
<td>Cd</td>
<td>211</td>
<td>0.338</td>
<td>0.038</td>
<td>0.0017</td>
<td>0.000008</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Ni</td>
<td>3.7</td>
<td>13.0</td>
<td>0.706</td>
<td>0.24</td>
<td>0.000152</td>
<td>&lt;0.001</td>
<td>n.d.</td>
</tr>
<tr>
<td>Co</td>
<td>5.3</td>
<td>5.07</td>
<td>0.301</td>
<td>0.18</td>
<td>0.000148</td>
<td>&lt;0.001</td>
<td>n.d.</td>
</tr>
<tr>
<td>Cr</td>
<td>0.6</td>
<td>3.69</td>
<td>0.038</td>
<td>0.0006</td>
<td>0.7</td>
<td>&lt;0.001</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

Sources of data – a: Nordstrom et al. (2000); b: Ball and Nordstrom (1989); c: Naus et al. (2005); d: Cravotta (2008); e: Meybeck (2003) and Gaillardet et al. (2003), includes a range for Ca, Mg, and SO4 concentrations because of differences in opinion on how to estimate these (Berner and Berner 1996); f: Azzie (2002); and g: Kraynov et al. (1969). AMD = acid mine drainage; NARD = natural acid rock drainage; CMD = coal-mine drainage; n.d. = not determined
natural rate (Alpers et al. 2007). Laboratory studies indicate a maximum pyrite oxidation rate of about 1 mmol/hour whereas field rates from mine portal discharges are always higher, sometimes by several orders of magnitude (Nordstrom 2011). The higher field rates suggest that evaporation and salt dissolution contribute to the weathering rate.

The sample with the highest pH, 11.74, is from a deep mine in the Lovozero massif in the Kola Peninsula of Russia (Kraynov et al. 1969). This same water sample had SiO₂ concentrations of 9000–13,000 mg/L and F concentrations of 11,000 mg/L. The main source of F is interpreted to be from the dissolution of the highly soluble mineral villiaumite (NaF). Many examples of circumneutral mine drainage have been reported. Uranium mill tailings near Riverton, Wyoming, USA, produced a groundwater plume with a pH of 6.8 and containing more than 2 mg/L dissolved U (White et al. 1984). Circumneutral discharge waters from the Endako Mine in British Columbia, Canada, contain up to 30 mg/L dissolved Mo (B.C. provincial Ministry of Energy and Mines, written communication 2010). These are but a few extreme examples; many more exist worldwide and many are not adequately documented because of the proprietary nature of mining activities and the lack of enforcement.

The analyses in Table 1 show several characteristic trends. Although metal concentrations generally decrease substantially with an increase in pH, there are exceptions. Iron solubility depends on its redox state as well as the pH. If dissolved Fe is largely reduced as Fe²⁺ (e.g. as reflected in analysis 2), it will be much more soluble than when oxidized to Fe³⁺ (analysis 6). Analysis 4 has more dissolved iron than analysis 3 because of the presence of Fe²⁺. Metals must hydrolyze to precipitate, and Fe³⁺ hydrolyzes near its pK₁ of 2.2, as shown in the following reaction:

\[
Fe³⁺ + H₂O \rightarrow FeOH²⁺ + H⁺; \ pK₁ = \log K₁ = 2.2
\]

Hence dissolved Fe³⁺ precipitates at pH values of 2–2.5. In addition to pH, four main factors determine metal concentrations: abundance in the source rocks, weatherability (or solubility), redox conditions, and postweathering sorption or precipitation reactions. As an example of source rock differences, high-silica rocks such as rhyolites and granites tend to be higher in Mo, Be, F, Sn, and W concentrations, whereas mafic to ultramafic rocks such as basalts and peridotites tend to be higher in Co, Ni, Cr, Mg, and Fe concentrations.

Acid waters rich in dissolved Al will precipitate Al as a hydroxysulfate mineral once the pH rises to about 5 or higher from dilution and neutralization in surface waters (Fig. 3; Nordstrom and Ball 1986; Bigham and Nordstrom 2000). Aluminous minerals will precipitate at lower pH values, closer to 4, in groundwaters (Blowes et al. 2003). The pK₁ for Al hydrolysis is 5.0, again a good predictor of when to expect Al precipitation.

Most groundwaters contain Ca concentrations greater than or equal to Mg concentrations, but the Iron Mountain AMD (Table 1) has the reverse relation. Mine waters with a very low pH and a high concentration of metals have Mg > Ca because high Ca and high SO₄ concentrations reach equilibrium saturation with respect to gypsum solubility, thereby limiting Ca concentrations but not Mg concentrations (Mg sulfate minerals are much more soluble than gypsum). Gypsum is commonly produced by the weathering of mine waste material and mineralized rock and by evaporation.

### EFFLORESCENT SALT FORMATION

The term efflorescence is from the Latin efflorescere, which means to flower or blossom. For mine sites it refers to the formation of soluble sulfate salts rising like cauliflower out of pyritic wastes, such as tailings or waste rock, on underground mine surfaces, or on muck piles as the acid mine water dries up. Pyrite oxidation is a strongly exothermic reaction. The heat produced increases the evaporation rate of mine waters and promotes the formation of efflorescent salts. Melanterite, rozenite, szomolnokite, copiapite, rhomboclase, halotrichite, and chalcantite are a few common examples of efflorescent salts. The first five are iron sulfate salts, halotrichite is a mixed metal sulfate salt, and chalcantite is a copper sulfate salt. These soluble salts form from waters that have extremely low pH (1.0 to −3.5). For example, at Iron Mountain, drip water from a melanterite stalactite had a pH of −0.7 (Fig. 4), rhomboclase was found precipitating from underground drip water with a pH of −2.5 (analysis 1 in Table 1), and an efflorescence of copiapite was found with an associated fluid having a pH of −0.9 (Jamieson et al. 2005).

These solid soluble salts store acidity and metals until rainstorms flush them out (Jambor et al. 2000). The resulting sudden release of metals and acidity can cause major fish kills during rapid flush-out events, as shown by historical fish kills downstream from Iron Mountain. If not remediated, these flush-outs may increase in intensity and cause greater injury to aquatic life because of climate change resulting from global warming (Nordstrom 2009).
Estimates of metal and sulfate flux from mining activities are severely hindered by lack of sufficient data. The current global estimate of the sulfate flux is about 430 Tg/y (teragrams per year) (Berner and Berner 1996). Roughly half of the global sulfate flux is likely to be from anthropogenic sources, such as fertilizers, industrial and municipal wastes, pyrite weathering from mining, and atmospheric deposition from fossil fuel combustion and forest burning. However, estimates of the annual anthropogenic sulfate flux range from 138 to 178 Tg, of which 72 Tg is considered a maximum from industry (non-fertilizer and non-fuel burning; Berner and Berner 1996). Raymond and Oh (2009) showed that during the 1940s, the annual sulfate flux caused by coal mining from one river basin alone (the Susquehanna River) was about 0.7–0.8 Tg/y. Iron Mountain was releasing about 30 Gg (gigagrams) annually for a 50-year period (Alpers et al. 2003). More recently, Olías et al. (2006) reported that the Tinto and Odiel rivers in Spain, which drain one of the oldest and largest metal-mining districts in the world, have a sulfate flux rate of 0.18 Tg/y. Raymond and Oh (2009) scaled their fluxes for the Susquehanna River to a worldwide flux and estimated that 18 Tg/y sulfate may be released from coal mining; they predicted that this flux may increase to 25 Tg/y by 2030. Add to that a comparable amount from metal mining and at least half of the industrial releases of sulfate could be from mining activities. It should be noted that these are very rough estimates, because there is very little monitoring of solute fluxes from mine sites.

Much more surprising is the result for metal transport in rivers. Olías et al. (2006) estimated the Zn flux in the combined Tinto and Odiel rivers to be 3.5 kt/y (kilotons per year), which represents 60% of the worldwide fluvial transport of zinc based on 1987 data. Most of the metal flux occurs during a short wet season of about one month and is ascribed to flushing of mine tunnels and dissolution of efflorescent salts (Cánovas et al. 2008). A more recent estimate of global riverine Zn flux is 23 kt/y (Gaillardet et al. 2003). Hence the Tinto and Odiel rivers constitute 15% of the global riverine flux. Although the data are insufficient to make a reliable determination of the worldwide Zn flux, we can say that the Zn flux from mining sites is a substantial portion of the global flux. A similar estimate for the Tinto–Odiel Cu flux indicates it is 3% of the global Cu flux, which is even more impressive when one realizes that these rivers constitute only 0.0058% of the global river-water flow. With more data from other mining areas, the Tinto–Odiel flux would be smaller, but the total from mining sites would be a larger proportion of the global metal flux.

**FUTURE MINING AND THE GENERATION OF MINE WATERS: THE CHALLENGE OF RESPONSIBILITY AND SUSTAINABILITY**

As the world’s population continues to increase, with a concomitant rise in metal and coal demand, conflicts between the mining industry and local communities and environmental groups will continue unless issues are resolved in the planning stages. During the last decade, many steps by mining companies and consortiums of companies have been taken to decrease the problems created by acid mine drainage (e.g. INAP, International Network for Acid Prevention; ADTI, Acid Drainage Technology Initiative; MEND, Mine Environment Neutral Drainage). More remedial work is needed, but the most cost-effective and environmentally effective approach is to consider worst-case scenarios and plan for them from the beginning as part of the overall mining operation. Highly acidic mine waters are often rich enough in metals to be included in the extraction process, and some companies are currently leaching tailings and waste rock. Continued recycling of waste materials can keep contaminants contained on site. Solution extraction methods can be very effective if carried out appropriately, and they may be needed for the recycling of metals from waste products as naturally occurring metal resources become depleted or uneconomic. Hydrogeologists, geochemists, and microbiologists can contribute considerably to improved extraction methods and to remediation efforts with their knowledge of water–rock interactions and of the microbiological effects on these processes.

**ACKNOWLEDGMENTS**

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**Mine Wastes and Human Health**

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**INTRODUCTION**

The metals and mineral commodities used by society are mined from ore deposits, which are areas in the Earth’s crust where geological processes have concentrated the commodities sufficiently that they can be mined and processed economically. Mining of ore deposits and processing (beneficiation) of the ores generate by-product mine wastes, which collectively include mine waste piles, tailings, smelter slag, particulate emissions, spent processing solutions, and mine-drainage waters.

In this paper, we will show how the mineralogical and geochemical characteristics of mine wastes can predictably influence (1) human exposure pathways for potentially toxic minerals, metals, and other materials, (2) the routes by which these materials enter the body, (3) the chemical behaviors and toxicological properties of the materials inside the body, and (4) possible resulting health effects. This discussion focuses primarily upon several elements of toxicological concern, including lead, mercury, and arsenic. However, many other potential toxicants can, depending upon the deposit type, occur in mine wastes, including heavy metals such as cadmium, nickel, and thallium, radioactive elements such as uranium, mineral toxicants such as crystalline silica and asbestos, and some processing chemicals (Plumlee 1999; Lottermoser 2010).

**THE COMPLEX MAKEUP OF MINE WASTES**

Ore deposits can contain complex mixtures of minerals, and these mixtures can be modified or transformed substantially by mining and processing. As a result, many different minerals and some amorphous phases can be found in mine wastes and in soils, sediments, and waters contaminated by mine wastes, with potentially complex implications for toxicity and health impacts. The types of minerals present in mine wastes are quite predictable based on the geological characteristics of the deposits being mined and the rocks that host them, the mining and processing methods used, and climate (Plumlee 1999).

The mineralizing process produces “primary” economic ore minerals (e.g. metals and metal sulfides), noneconomic gangue minerals (e.g. iron sulfides, crystalline silica, and carbonates), and host-rock alteration minerals (e.g. clays). As mineral deposits become exposed at the Earth’s surface by erosion and other geological processes, they are subjected to weathering and oxidation. These processes can transform the primary minerals into many different “secondary” metal oxides, carbonates, and sulfates. The economic part of an ore deposit may include primary and/or secondary minerals.

Mine waste piles can contain clay-sized particles to boulder-sized blocks of unmineralized or partially mineralized rocks. Tailings contain ore, host rocks, and alteration minerals that were ground into clay- (<4 µm) to sand-sized (<500 µm) particles, and are often enriched in noneconomic iron sulfides, crystalline silica, and aluminosilicates. Acid mine drainage (AMD) forms when oxygenated rain, snowmelt, or groundwater oxidizes iron sulfides exposed in mine workings, mine wastes, or tailings impoundments. AMD can contain high levels of potentially toxic metals (e.g. lead, cadmium, nickel) and metalloids (e.g. arsenic, antimony) leached from the ores. Postmining, secondary minerals form by the weathering of mine wastes, and these can include soluble salts formed by the evaporation of AMD. These salts commonly incorporate high levels of iron, other metals, and acid, and easily dissolve when they come into contact with water (Plumlee 1999). Calcines and particulates produced by roasting or smelting of sulfide ores commonly include water-soluble chlorides, oxychlorides, oxides, and sulfates of the ore metals; weathering...
can shift the metals into iron or manganese oxides (Bove et al. 2011). Smelter slag contains metal-enriched glass, residual sulfides, and metal chlorides, sulfates, and oxides.

**FACTORS INFLUENCING HEALTH EFFECTS OF MINE WASTES**

Many factors can influence the health effects of mine wastes and other Earth materials on exposed humans and other organisms (Sullivan and Krieger 2001; Plumlee et al. 2006). The initial factor is the exposure pathway, which includes the mine waste source, transport media (soil, dusts, water, foodstuffs, etc.), points of exposure, and exposure route. The exposure route is how humans take up the mine wastes or mine waste–contaminated materials, and can be via inhalation, ingestion, or skin or eye contact. The dose, which is the intensity and duration of the exposure, is a key factor in potential health effects.

The body has a range of physiological defenses against foreign matter such as mine waste particles. Larger inhaled particles can be trapped in mucus lining the respiratory tract, cleared upward into the throat by ciliated cells, and then swallowed or expectorated. Alveolar macrophages are free-roaming cells that engulf foreign particles respired deep into the lungs; they either digest the particles or clear them into the lymph system or throat.

The size of mine waste particles determines how readily they can be ingested incidentally by hand-to-mouth transmission (<250 µm), inhaled into the upper respiratory system (<100 µm), inhaled into the lung bronchia (<10 µm), or respired deep into the alveoli (<4 µm). Fibers less than ~0.5–15 µm wide and less than ~15–20 µm long can be respired deep into the alveoli, but those longer than ~5–10 µm are too long to be engulfed by alveolar macrophages. Large doses of equant particles or smaller doses of fibers can exceed the capacity of the lungs' various physical clearance mechanisms.

Chemical reactions between mine waste particles and the body's fluids and tissues along the different exposure routes are key factors in the disposition and toxicity of such contaminants in the body. The same mineral can have greatly different solubilities and dissolution rates in fluids lining the respiratory tract (near-neutral pH, abundant mucoproteins and surfactants), fluids in alveolar macrophage lysosomes (which are acidic and have abundant enzymes and oxidants), acidic gastric fluids, and near-neutral-pH intestinal fluids. Biosoluble minerals dissolve quickly in the body, whereas biodurable minerals dissolve slowly and can persist in the lungs and tissues for years.

The bioaccessibility of metal and metalloid toxicants measures how readily they are released into the body's fluids from mine waste particles and are available for uptake, whereas bioavailability measures how readily toxicants are solubilized, absorbed by the body, and transported to a site of toxic action. Not all bioaccessible toxicants are bioavailable; for example, some metal toxicants that dissolve in stomach acids reprecipitate or sorb onto solids in the higher-pH intestinal fluids and are excreted. Mine waste particles may be chemically bioreactive in the body. For example, acid-containing soluble salts may cause tissue irritation or damage. Mine waste particles can also be redox-bioreactive in the body. For example, fresh crystalline silica, iron sulfides, and iron released from asbestos particles are all thought to generate reactive oxygen species that cause oxidative stress and potential DNA damage, toxicity, and cancer (Schoonen et al. 2006). The body's immune response to mineral particles can also vary according to mineralogy. For example, biodurable crystalline silica minerals, asbestos, and coal dusts are fibrogenic (i.e. they trigger fibrotic diseases of the lungs), whereas other biodurable minerals (e.g. calcium phosphate) are not.

The integrated toxicological effects (possibly synergistic or antagonistic) of complex toxicant mixtures found in mine waste particles likely play an important role in their health effects. Individual-specific factors, such as age, gender, genetics, and habits (i.e. smoking), and socioeconomic, health, nutritional status, and dietary cofactors may promote or counteract the toxic effects of exposure to mine wastes.

**INTERDISCIPLINARY METHODS USED TO STUDY THE HEALTH EFFECTS OF MINE WASTES**

Many health science methodologies are used to assess the potential health effects of exposures to mine wastes and other Earth materials (Sullivan and Krieger 2001; Plumlee et al. 2006). Medical care and screening of individuals or populations that may have had exposures to mine wastes are an important first step. Biological monitoring determines if mine waste toxicants are present in blood, urine, hair, or tissue samples, and can thus indicate if exposure has occurred. Exposure assessments examine how people come into contact with hazardous mine wastes. Epidemiology studies examine disease rates in worker cohorts or populations exposed to mine wastes, and pathology studies examine tissue samples collected through biopsy or autopsy of individuals. In vivo uptake tests measure the absorption of toxicants from materials fed to live animals. Toxicity testing of materials can involve in vitro tests on cell cultures and in vivo tests on live animals. In vitro, physiologically based extraction tests (also called in vitro bioaccessibility assessments) are bench tests that model release of toxicants from materials into simulated gastric, intestinal, lung, and other body fluids.

The Earth sciences can make substantial contributions to this spectrum of health science investigations, contributions that collectively have been termed “toxicological” or “medical” geology or geochemistry (Selinus et al 2005; Plumlee et al. 2006). Earth scientists can provide health scientists with key predictive information about the minerals and toxicants likely to be present in mine wastes at specific sites, based on the geology of the mineral deposit being mined or processed. Epidemiological studies of diseases potentially related to mine waste exposures can be enhanced by linkages to Earth science databases on mineral production, commodity occurrences, deposit geology, soil geochemistry, and water quality. Many Earth science methods measure toxicologically important characteristics of mine wastes, such as particle mineralogy, shape, and size; the content and oxidation state of potentially toxic elements; the isotopic composition of lead and certain other elemental toxicants (to help determine their sources); and likely biosolubility/bioreactivity behavior in the body. Such characterization is essential to help understand the nature and potential sources of mine wastes to which populations or individuals may have been exposed and the pathways by which these exposures occurred.

**EXPOSURE PATHWAYS AND ROUTES FOR MINE WASTES**

Human populations may be exposed occupationally or environmentally by a variety of pathways to mine wastes, waters draining mine wastes, and mineral-processing solutions (Fig. 1). Modern mining and processing methods, if properly designed and implemented, greatly reduce or eliminate these exposures.
Occupational exposures of miners and mill workers are largely via inhalation of dusts generated during mining and processing and through incidental ingestion of ore and mine waste particles that are transmitted by hand-to-mouth contact or are cleared from the respiratory tract. Smelter workers can be exposed to atmospheric particulates and gases. Populations living close to mining or mineral-processing sites can be exposed to mine wastes by multiple pathways. These include incidental ingestion of mine wastes or waste-contaminated soils by hand-to-mouth transmission, inhalation of dusts blown from tailings or waste piles, inhalation of gases or atmospheric particulates generated by smelting or roasting, and consumption of vegetables that take up metals from waste-contaminated soils or that accumulate mine waste dusts on their leafy parts. Contamination of drinking-water supplies by mine wastes, AMD, and mineral-processing solutions can result in exposures to dissolved and particulate metals, asbestos, and other fibrous silicate minerals and to processing chemicals such as cyanide. Cases of geophagia, the cultural practice of purposeful soil ingestion by pregnant women, have been noted where the soil consumed has been contaminated by mine wastes (WMC 2006).

Subsistence artisanal mining practices currently carried out in many places around the world can result in significant occupational and environmental exposures to mine wastes (Fig. 1c). Such exposures are often problematic because the workers and nearby populations are not aware of the potential health risks and do not practice any health-protection measures.

**HEALTH EFFECTS OF LEAD IN MINE WASTES**

From an exposure, uptake, and toxicological perspective, lead is the best understood of the potential metal toxicants in mine wastes. Many health science studies have demonstrated that mining or smelting of lead-bearing ores is linked to elevated blood lead levels and resulting health effects on exposed populations of workers, their families, and others living near mining sources, smelting sources, or ore transportation routes (e.g. Hu et al. 2007; Branan 2008; Gulson et al. 2009). The toxic effects of lead are well known and are particularly suffered by children. They range from high-dose acute effects, such as blindness, convulsions, encephalopathy, renal failure, severe gastrointestinal distress, and death, to lower-dose chronic effects, such as adverse impacts on neurodevelopment, intelligence quotient, behavior, memory, and motor development, as well as kidney disease and anemia (Sullivan and Krieger 2001).

**Mineralogical Controls on Lead Uptake**

Lead can occur as a major or trace component in many different mine waste minerals. Casteel et al. (2006) documented significant mineralogical controls on the relative bioavailability of ingested lead. They measured lead uptake in juvenile swine (whose gastrointestinal systems most closely approximate those of human children) that were fed soils from various mining/smelting sites and soils artificially spiked with specific lead minerals. Lead carbonates and lead associated with manganese oxides were the most bioavailable via ingestion. Lead phosphates, lead oxides, and lead associated with iron oxides show intermediate
bioavailability. Lead sulfides, silicates, and vanadates, as well as lead associated with arsenic oxides, are the least bioavailable. However, these results may be matrix-specific and could vary according to soil composition and mineralogy.

The bioaccessibility of lead from mine wastes has also been studied extensively with physiologically based extraction tests. Drexler and Brattin (2007) validated a gastric test for lead against the Casteel et al. (2006) uptake study. As a result, the US EPA lists this test as a standard operational procedure for lead bioaccessibility. Sequential simulated gastric fluid to intestinal fluid extractions are also commonly used for bioaccessibility studies of lead and arsenic (e.g. Basta et al. 2007).

We have carried out gastric and sequential gastric-intestinal extraction tests on a number of waste or soil samples from various mining or processing sites. We used gastric protocols based upon those of Drexler and Brattin (2007) and intestinal protocols based on Basta et al. (2007). The results for lead released into simulated gastric fluid with a pH of 1.5 (Figs. 2 and 3) are consistent with those of Casteel et al. (2006): the highest levels of bioaccessible lead are found in materials that contain abundant lead carbonate or lead oxide. Lead arsenate (mimetite) is also very soluble in gastric fluid (Bove et al. 2011). In contrast, lead bioaccessibility from evaporative soluble iron- and sulfate-rich salts in simulated gastric fluid is predicted to be very low, likely because the high levels of sulfate released from the salts cause precipitation of insoluble lead sulfates. A significant portion of lead dissolved in the acid gastric fluid either reprecipitates (perhaps as lead carbonates) or sorbs onto other particles (such as ferric iron phases) in the higher-pH (5.5) simulated intestinal fluid (Fig. 3).

We have also run physiologically based extraction tests on mine wastes using simulated lung fluid and a serum-based fluid as the extracting fluids (see Gray et al. 2010 for the method). For most mine waste samples, lead is much less bioaccessible in these fluids than in simulated gastric fluids (Fig. 3). This is due in part to the less-aggressive pH (7.4), coupled with the reaction of any soluble lead with the phosphate-rich fluids to precipitate lead phosphate phases. Schaider et al. (2007) found that lead bioaccessibility in simulated alveolar macrophage lysosomal fluids (pH 4.5) was substantially lower than that in simulated gastric fluids. These results collectively indicate that inhalation may not be an important uptake pathway for lead from most lead minerals in mine wastes.

**Case Studies**

In northern Nigeria, artisanal processing of lead-rich gold ores has resulted in confirmed deaths of at least 400 children, most less than 5 years old (UNEP/OCHA 2010). Surviving children have extremely high blood lead levels, with some well over 100 µg/dL (values greater than 10 µg/dL are considered indicative of lead poisoning). Grinding of the ores in flour mills creates a high proportion of ingestible particles less than 250 µm in size, which contaminate soils and residences where the ore is processed (Figs. 1c and 4). High concentrations of secondary lead carbonate and lead oxide in the ores and contaminated residential areas provide a clear source for the lead poisoning (Figs. 2, 3, and 4), with incidental ingestion of the lead particles by inadvertent hand-to-mouth transmission an important exposure pathway.

Mining, processing, and smelting of low-sulfide lead–zinc ores at Kabwe, Zambia, from the early 1900s through the early 1990s heavily contaminated the city’s soils and sediments with lead carbonates and other bioaccessible lead minerals (WMC 2006; Branan 2008). Although the mine is now closed, artisanal remining of the mine wastes still occurs. Local residents build houses with mud bricks made from mine wastes (Fig. 1d), and vegetables are grown in lead-contaminated soils. One of several commercial soils sold in local markets for consumption by pregnant women is contaminated by mine wastes. Due to these many exposure pathways, up to 30,000 Kabwe children have lead poisoning (Branan 2008).

On Marinduque Island, Philippines, exposures to mine tailings from a large copper mine were blamed by public health officials for elevated blood lead (up to 20 µg/dL) in some local children (Plumlee et al. 2000). In contrast to Nigeria and Kabwe, there are very low levels of total lead present in the bulk Marinduque copper tailings (Fig. 2). The concentration and bioaccessibility of lead increase with decreasing size fraction, but the total mass of these fractions and the total lead dose resulting from them are small. Other sources of lead, such as leaded gasoline combustion by-products and lead-bearing paints could also be evaluated as part of a broader exposure assessment.

The Drexler and Brattin (2007) gastric extraction test was validated only for lead, but it also indicates potential bioaccessibility behavior of other elements in the wastes (Fig. 2). For example, mine wastes and contaminated soils from Kabwe also have extremely high levels of gastric-bioaccessible cadmium, zinc, manganese, copper, vanadium, and arsenic. Cadmium in the Kabwe samples is relatively bioaccessible in both gastric and intestinal leaches (Fig. 3), and it is relatively soluble in serum-based and simulated lung fluids. While lead poisoning is the most apparent health problem at Kabwe, these results suggest that potential toxicological effects from exposures to cadmium via ingestion and inhalation, as well as exposure to other elements, should also be evaluated.

**HEALTH EFFECTS OF MERCURY IN MINE WASTES**

Epidemiological studies of miners and smelter workers exposed to inorganic mercury forms in historic mercury-mining areas such as Almadén, Spain, have found elevated rates of hypertension, and cardiovascular, cerebrovascular, and genito-urinary diseases (García Gómez et al. 2007). Significant health impacts of mercury are associated with both modern artisanal gold mining and historical gold mining using amalgamation extraction. Many studies of artisanal miners and nearby residents have measured elevated mercury levels in blood and urine, and have found adverse health effects such as mercury intoxication and altered immune system effects (e.g. Bose-O’Reilly et al. 2010). Elemental mercury vapor released during amalgam smelting can readily be inhaled and absorbed. Other likely, but possibly less important, exposure pathways are inhalation or incidental ingestion of mercury-contaminated dusts or soil particles and uptake through the skin when amalgamation is done by hand. Substantial concerns have also been noted regarding the health effects of environmental exposures to mercury that has been released from artisanal gold operations, transformed into more bioaccumulative methylmercury, biomagnified in the food chain, and consumed by humans (Bose-O’Reilly et al. 2010).

**Mineralogical Controls on Mercury Uptake**

Roaster calcines containing mercury oxides, chlorides, oxychlorides, and sulfates can have extremely high levels of mercury that is highly bioaccessible in water, simulated gastric and lung fluids, and serum-based fluids (Gray et al. 2010). Mercury(II), the form most likely released from these minerals, is well absorbed in the gastrointestinal tract. In contrast, recent bioaccessibility studies of cinnabar (mercury sulfide) suggest that it does not readily dissolve in gastric fluids (Zagury et al. 2009).
**HEALTH EFFECTS OF ARSENIC IN MINE WASTES**

Some studies note adverse health impacts of occupational exposures to arsenic-rich mine wastes, but arsenic is typically not the only toxicant to which the cohort populations were exposed. Examples include lung cancers in miners exposed to arsenic and radon daughter products in mine dusts (Kusiak et al. 1991) and lung cancers in workers at a smelter that processed arsenic-rich ores (Pershagen et al. 1987). Other studies have found adverse health outcomes from environmental exposures to arsenic-bearing mine wastes, such as DNA damage in blood cells of children exposed to arsenic and lead in a mining area (Yañez et al. 2003). Some studies have found elevated arsenic concentrations in urine that exceeded health guidelines, but no clear adverse health outcomes.

**Mineralogical Controls on Arsenic Uptake**

Recent studies have examined speciation of arsenic in various mine wastes, modeled arsenic bioaccessibility using physiologically based extraction tests, and validated these tests against animal uptake tests (e.g. Bruce et al. 2007; Walker et al. 2009; Meunier et al. 2010). Many primary and secondary minerals can contain arsenic as a dominant or trace component. Gastric to intestinal extraction tests indicate the following general order of decreasing arsenic bioaccessibility via ingestion: calcium iron arsenate, lead arsenate, arsenic trioxide > amorphous iron arsenates, arsenic-bearing iron-(oxy)hydroxides > arsenic-rich pyrite and simple arsenic sulfides (e.g. realgar) > arsenopyrite (iron–arsenic sulfide), scorodite (crystalline iron arsenate) (Basta et al. 2007; Meunier et al. 2010; Bove et al. 2011; our unpublished data).

Arsenic residing in soluble sulfate salts may be bioaccessible in simulated lung fluids or serum-based fluids (Plumlee et al. 2006). Arsenic bioaccessibility may, for some minerals, be greater in near-neutral-pH intestinal fluids than in acid stomach fluids. However, arsenic bioaccessibility can depend upon its oxidation state and the matrix of other materials that accompany the arsenic phases. For example, if iron is abundant, arsenic dissolved in the stomach can precipitate as scorodite or can sorb onto abundant iron (oxy)hydroxides and hydroxysulfates in the intestines (Basta et al. 2007). Organic soil carbon may reduce As(V), which is more readily sorbed onto particulates in the intestines, to As(III), which is less readily sorbed. An in vitro gastrointestinal microbial ecosystem simulator found that colon microbes may enhance the gastrointestinal bioaccessibility of arsenic (Laird et al. 2007).

**SUMMARY**

There are clear links between the mineralogical and geochemical characteristics of mine wastes and their potential to cause adverse health effects via occupational and environmental exposures. Much is known about these linkages for lead, and knowledge is growing rapidly for some other toxicants, such as mercury and arsenic. However, fewer studies have examined the toxicity (and mineralogical/geochemical controls on toxicity) of other metals in mine wastes (e.g. cadmium, nickel, cobalt, and manganese). Studies indicate that iron sulfides can cause oxidative stress and toxicity (Schoonen et al. 2006), but a possible similar role for soluble iron sulfate salts is yet to be examined. Epidemiological studies of miner cohorts suggest statistical associations of disease with multiple factors (e.g. crystalline silica, radionuclides, and arsenic), but the integrated effects of multiple metal, mineral, and (or) radionuclide toxicants in complex mine wastes are poorly understood. These uncertainties illustrate the need for increased interdisciplinary collaborations between health and Earth scientists to understand better the nature of exposure to mine wastes, the behavior of mine waste particles in the body, and the mine waste characteristics of toxicological concern.
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ACKNOWLEDGMENTS
Many analysts at the USGS contributed to the analytical results summarized in this paper. Dr. Gary Krieger (Newfields, Inc.) provided samples and information on Kabwe, Zambia. James Durant, Dr. Antonio Neri, and Carrie Dooyema (U.S. Centers for Disease Control and Prevention) collected an excellent environmental sample suite from Nigeria and provided many critical medical insights into the lead poisoning there. USGS and Elements reviewers made many beneficial editorial suggestions.
Recycling, Reuse and Rehabilitation of Mine Wastes

Bernd G. Lottermoser*

INTRODUCTION

Humanity faces many environmental challenges in the 21st century. The issues of land degradation, resource depletion and waste recycling are regarded as some of the critical global challenges for present and future generations. At the first United Nations Earth Summit in 1992, environmentally sound management of wastes was identified as one of the major concerns in maintaining the quality of the Earth’s environment. At the World Summit on Sustainable Development in 2002, governments reaffirmed the importance of solid-waste management. They called for priority attention to be given to prevention, minimization, reuse and recycling of waste.

A sustainable future for the human race must include the effective reuse and recycling of waste streams. The concept of waste as a resource is not new to the modern world. Since the dawn of civilization, the recycling or reuse of originally discarded materials, including mine wastes, has been practised. For example, during Roman times, iron ore slags were used in construction, road surfacing and as a flux in the production of iron. To this day, the recycling and reuse of mine wastes are largely driven by their practical applications and financial returns. The increasing demand for mineral and energy resources by a growing world population will make the recovery of waste – through reuse, recycling and energy recovery – even more attractive.

Modern mining operations produce vast waste streams that compel planning and informed decision-making in matters of waste reduction, resource recovery, waste disposal and environmental protection. The waste hierarchy is a well-established guide for prioritizing waste-management practices, with waste prevention being the preferred option and disposal and treatment being the least desirable (Fig. 1).

Regardless of our increasing reuse and recycling efforts, the great majority of waste produced at mine sites is still placed into storage facilities. The reclamation of such repositories has become an integral part of modern mine development and mine closure. Consequently, mine sites and their wastes have been the subject of considerable rehabilitation efforts and countless scientific studies.

Recent developments in mine waste rehabilitation have led to more sophisticated reclamation approaches and solutions. However, the impacts of poorly rehabilitated or non-rehabilitated wastes are well known, and there is growing concern whether our best practice rehabilitation efforts will be successful and protect the environment in the long term.

Keywords: recycling, reuse, rehabilitation, sustainability, mine waste, zero waste

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Figure 1
The mine waste hierarchy, from prevention, through reuse, recycling, and energy recovery, to treatment and disposal. The reuse option considers mine waste for alternative uses that are environmentally sound, and the recycling and energy recovery options view mine waste as a resource.
In the following sections, the recycling, reuse and rehabilitation of mine wastes are documented, focussing on mining wastes that accumulate at mine sites. Consideration of mineral processing and metallurgical wastes is limited to those waste types accumulating at or near mine sites. Readers interested in the resource recovery and recycling of mineral processing and metallurgical wastes are advised to consult the relevant literature (e.g. Rao 2006).

**DEFINING THE “R WORD”**

The “R word” has proliferated in the scientific literature covering aspects of mine waste management, resource recovery and mine closure. Authors freely use the terms remining, reprocessing, recycling, resource recovery and reuse, as well as rehabilitation, reclamation, restoration, recuperation, reconstruction and remediation. Moreover, these terms are sometimes used inconsistently. In this paper, remining refers to the extraction of an energy or mineral resource from previously mined areas. Reuse of mine wastes is defined as the process that involves the new use or application of the total mine waste in its original form for a defined purpose directly without any reprocessing. By contrast, recycling of mine wastes is the practice that extracts new valuable resource ingredients, or uses the waste as feedstock and converts the entire mine waste into a new valuable product or application with some reprocessing. Recycling activities subject the waste to physical, thermal, biological or chemical methods designed to extract valuable elements, compounds, minerals or energy, rendering the remaining waste material suitable for a new benign use or disposal on the mine site. Reprocessing is different from treatment because reprocessing is designed to use the waste material as a feedstock for producing a valuable product, such as recovered minerals and metals. By contrast, treatment of mine waste is intended to reduce the waste’s toxicity or volume. Numerous terms refer to post-mining measures that return waste repositories and mined land to a standard allowing future land use. In this work, the terms rehabilitation and reclamation of mine wastes are used interchangeably to refer to measures that alleviate environmental impacts during post-mining waste storage.

### REUSE AND RECYCLING OF MINE WASTES

Ideally, the reuse and recycling of mine wastes, like all other recycling efforts, create financial assets, slow consumption of natural resources, limit waste production, encourage innovation and local industries, create jobs and teach responsibility for the environment shared by all. In addition, the reuse and recycling of solid mining wastes and mine waters may also decrease the exposure of humans and ecological receptors to contaminated materials. Various reuse and recycling options have been proposed for mine wastes by numerous researchers (Table 1). Today only some of these options, such as reprocessing and using tailings as backfill, are commonly applied at operating mine sites.

<table>
<thead>
<tr>
<th>Waste type</th>
<th>Reuse and recycling option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste rocks</td>
<td>• Resource of minerals and metals</td>
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<tr>
<td></td>
<td>• Backfill for open voids</td>
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<tr>
<td></td>
<td>• Landscaping material</td>
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<td></td>
<td>• Capping material for waste repositories</td>
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<td></td>
<td>• Substrate for revegetation at mine sites</td>
</tr>
<tr>
<td></td>
<td>• Aggregate in embankment, road, pavement, foundation and building construction</td>
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<td></td>
<td>• Asphalt component</td>
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<tr>
<td></td>
<td>• Feedstock for cement and concrete</td>
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<tr>
<td></td>
<td>• Sulfidic waste rock as soil additive to neutralize infertile alkaline agricultural soils</td>
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<tr>
<td>Mining wastes</td>
<td></td>
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<tr>
<td>Mine waters</td>
<td>• Dust suppression and mineral processing applications</td>
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<td></td>
<td>• Recovery of metals from AMD waters</td>
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<td></td>
<td>• Drinking water</td>
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<td></td>
<td>• Industrial and agricultural use</td>
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<td></td>
<td>• Coolant or heating agent</td>
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<tr>
<td></td>
<td>• Generation of electricity using fuel cell technology</td>
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<tr>
<td></td>
<td>• Engineered solar ponds to capture heat for electricity generation, heating, or desalination and distillation of water</td>
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<tr>
<td>Mine drainage sludges</td>
<td>• Extraction of hydrous ferric oxides for paint pigments</td>
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<tr>
<td></td>
<td>• Extraction of Mn for pottery glaze</td>
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<tr>
<td></td>
<td>• Flocculant/adsorbant to remove phosphate from sewage and agricultural effluents</td>
</tr>
<tr>
<td>Tailings</td>
<td>• Reprocessing to extract minerals and metals</td>
</tr>
<tr>
<td></td>
<td>• Waste reduction through targeted extraction of valuable minerals during processing</td>
</tr>
<tr>
<td></td>
<td>• Sand-rich tailings mixed with cement used as backfill in underground mines</td>
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<td></td>
<td>• Clay-rich tailings as an amendment to sandy soils and for the manufacturing of bricks, cement, floor tiles, sanitary ware and porcelains</td>
</tr>
<tr>
<td></td>
<td>• Mn-rich tailings used in agro-forestry, building and construction materials, coatings, cast resin products, glass, ceramics and glazes</td>
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<tr>
<td></td>
<td>• Bauxite tailings as sources of alum</td>
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<td></td>
<td>• Cu-rich tailings as extenders for paints</td>
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<td></td>
<td>• Fe-rich tailings mixed with fly ash and sewage sludge as lightweight ceramics</td>
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<td></td>
<td>• Energy recovery from compost–coal tailings mixtures</td>
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<td></td>
<td>• Phlogopite-rich tailings for sewage treatment</td>
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<td></td>
<td>• Phosphate-rich tailings for the extraction of phosphoric acid</td>
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<td></td>
<td>• Ultramafic tailings for the production of glass and rock wool</td>
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<td></td>
<td>• Carbon dioxide sequestration in ultramafic tailings and waste rocks</td>
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<tr>
<td>Processing wastes</td>
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<tr>
<td>Bauxite red mud</td>
<td>• Treatment of agricultural and industrial effluents</td>
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<td></td>
<td>• Raw material for glass, tiles, cements, ceramics, aggregate and bricks</td>
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<tr>
<td></td>
<td>• Treatment of AMD waters</td>
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<tr>
<td></td>
<td>• Carbon dioxide sequestration</td>
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<tr>
<td>Metallurgical wastes</td>
<td></td>
</tr>
<tr>
<td>Historical base metal smelting slags</td>
<td>• Production of concrete and cement</td>
</tr>
<tr>
<td></td>
<td>• Use as fill, ballast, abrasive and aggregate</td>
</tr>
<tr>
<td></td>
<td>• Extraction of metals (e.g. Cu, Pb, Zn, Ag, Au)</td>
</tr>
<tr>
<td>Phosphogypsum</td>
<td>• Soil amendment</td>
</tr>
<tr>
<td></td>
<td>• Building and construction material</td>
</tr>
<tr>
<td></td>
<td>• Extraction of elements and compounds (e.g. U, Y, REE and calcium sulfate)</td>
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</tbody>
</table>
Reprocessing

Mine wastes are generally considered worthless at the time of production, yet they can still contain mineral and energy resources that may become valuable. Changing circumstances may turn a particular waste into a valuable commodity, either because the economic extraction of metals, energy and minerals may now be possible using superior technology, or a market has been identified for the previously discarded waste. Most importantly, improved commodity prices fuel the interest in waste reprocessing and the extraction of metals and minerals from a waste stream. What may be waste to some can be a very useful resource to others, either now or in the future.

Reprocessing of mine wastes subsequent to the original mining or site abandonment has been carried out for hundreds or possibly thousands of years. In the 16\textsuperscript{th} century classic *De Re Metallica*, Agricola (1556) described this practice in central Europe:

“There are some people who wash over the dumps from exhausted and abandoned mines, and those dumps which are derived from the drains of tunnels; and others who smelt the old slags; from all of which they make an ample return.”

Yesterday’s waste can be today’s resource (Lottermoser 2010). This approach is widely used in the modern mining and metallurgical industries. Today, reprocessing of mine wastes is gaining importance because of vastly improved mineral processing technologies, which in turn lead to economic benefits and address environmental concerns. In some cases, the mining industry supports major research efforts that will identify novel and economically viable methods and allow increased resource recovery (e.g. Barrick’s Unlock the Value program; Barrick 2011).

Reuse and Recycling of Waste Rocks

Rehabilitation of mine sites and waste repositories commonly makes use of benign waste rocks for landscaping as well as capping and revegetation of waste repositories (Table 1). Waste rocks are also exploited as backfill in open voids, reducing waste piles and leaving fewer mine workings. The most promising reuses for coarse-grained mining wastes and especially barren waste rocks from coal and metal mining are as building and construction materials. These wastes are used as fill for subsided land or as aggregates in embankment, dam, road, pavement, foundation and building construction. They also find applications as feedstock for the production of cement and concrete. Whether these alternative uses can be pursued depends on the waste’s geotechnical, mineralogical and geochemical characteristics. For example, pyritic waste has been evaluated as a soil amendment to neutralize infertile, alkaline agricultural soils (e.g. Castelo-Branco et al. 1999). Yet, the presence of potentially mobile and bioavailable trace metals and metalloids in pyritic waste limits its possible use as a soil additive. While sulfide oxidation and the development of acid mine drainage (AMD) represent a major environmental menace, the exothermic sulfide oxidation reactions in large oxidizing sulfidic waste rock dumps may provide future opportunities to obtain geothermal energy and thus use these waste heaps as unconventional energy sources (e.g. Raymond et al. 2008).

Recycling Mine Waters and Sludges

Water scarcity, local regulation and environmental impacts are forcing the mining industry to reuse much of the waste water it produces. As a result, the reuse and recycling of process water for dust suppression and mineral processing applications are commonly pursued at operating mines (Table 1). The recovery of metals and salts from mine waters is also achievable. For example, the selective and sequential extraction of metals is possible from AMD waters by employing metal-accumulating algae or establishing sulfate-reducing bacteria in a bioreactor (e.g. Tabak et al. 2003). The hydrogen sulfide produced in the bioreactor is used to precipitate metals as insoluble sulfides. Advanced treatment technologies, such as filtration, reverse osmosis and ion exchange, allow mine waters to be processed into drinking water. Furthermore, benign or treated mine waters may find applications as water for aquaculture enterprises and the irrigation of agricultural crops. Whether such alternative applications are possible is largely controlled by the chemical characteristics of the treated water. Regardless, underground mine water may be exploited for heating or cooling purposes using geothermal heat pump systems (Banks et al. 2004). Acid mine drainage waters may even be treated using fuel cell technologies, generating beneficial products such as electricity and recovered metals (Cheng et al. 2007).

Acid mine drainage is associated with the formation of solid phases and treatment sludges that mainly consist of amorphous and poorly crystalline hydrous ferric oxides. These sludges have high adsorption capacities and therefore may be used as adsorptive material to remove phosphorus from sewage effluent and agricultural wastewaters (Sibrell et al. 2009; Dobbie et al. 2009). Iron-rich mine drainage sediments and sludges can also be a resource for iron minerals and industrial pigments (Zinck 2005).

Reuse and Recycling of Tailings

At mine sites, sandy tailings may be mixed with cement and disposed of in underground workings as backfill to provide ground or wall support (Table 1). Such a practice also reduces the amount of tailings that needs to be stored in waste repositories. Moreover, benign tailings can be placed as a surface cover over metalliferous or acid-generating tailings. This establishes a hydrogeological barrier and protects the underlying wastes from oxygen and water ingress.

The targeted extraction of gangue minerals from previously discarded tailings or a current waste stream may also be pursued. For example, the extraction of lithium-bearing minerals may be possible from micaceous tailings. Also, gangue pyrite may be removed for the production of sulfuric acid, ferric or ferrous sulfate, and pigments – a practice that may also reduce the likelihood of sulfide oxidation and AMD generation. Such careful extraction of targeted minerals from a waste stream or existing tailings pile requires a detailed knowledge of the waste’s mineralogical, geochemical and bulk physical properties (Geise et al. 2011). This is to ensure that the extracted minerals are suitable for their intended application and that the remaining material is safely disposed of.

A detailed mineralogical characterization of waste clay present in coal spoils and metalliferous tailings can reveal suitable resources for the building and ceramics industries. Clay-rich tailings can be alternative raw materials for the manufacturing of bricks, cements, floor tiles, sanitary ware and porcelain. Also, the addition of clay-rich mine spoils and tailings to agricultural land can improve the structure of sandy soils.

Tailings of certain mineral commodities may have particular reuse and recycling potentials. For example, manganese-rich tailings may be used in agro-forestry, building and construction materials, coatings, cast resin products, glass, ceramics, and glazes. Bauxite tailings could be sources of alum; copper-rich tailings have been tested as extenders for the development of paints; and iron ore tailings mixed with coal fly ash and sewage sludge can be
sintered into lightweight ceramics. Finney et al. (2009) proposed the recovery of energy from coal tailings by combusting them with compost. Phlogopite-rich tailings may have potential applications in the treatment of sewage effluent. Ultramafic tailings can have the appropriate composition for the production of glass and rock wool insulation materials. However, any reuse or recycling of tailings, for example into waste-derived fertilizers, requires a solid evaluation of the potential release of contaminants from these materials (cf. Williams et al. 2006).

**Recycling Wastes of Aluminium Ores**

Bauxite red mud is a solid alkaline residue produced during the digestion of bauxite with sodium hydroxide at alumina refineries. Red mud has a very high alkalinity and consists of a mixture of amorphous phases and finely crystalline minerals, including gypsum, quartz, hematite, calcite, böhmite, gibbsite, sodalite and whewellite. Neutralizing red mud with seawater lowers the pH value to approximately 8.5, allowing secure disposal and revegetation. Several alternatives to the disposal of bauxite residues have been proposed, such as using the metallurgical waste as a raw material for extracting elements or making glass, tiles, cements, ceramics, aggregate or bricks (Table 1). In addition, red mud can be used to treat dairy wastewaters, to remove dyes from wastewater and to remove metals from solution (Genç-Fuhrman et al. 2004). Seawater-neutralized red mud has been applied successfully to neutralize AMD waters, to strip AMD waters of their dissolved metals and metalloids, and to promote revegetation of sulfidic wastes.

**Recycling Slags**

Slags are a partially vitreous by-product of smelting ore to separate the desirable metals from unwanted elements. Slags have unique physical and mechanical characteristics that make them suitable in a wide range of applications (e.g. for the production of concrete and cement, and as fill, ballast, abrasive and road aggregate) (Table 1). The reuse of ferrous slag has been a widely accepted practice since Roman times.

Slag piles commonly occur at historical base metal mine sites of the 19th and 20th centuries (Fig. 2). Such slags are known to be mineralogically and chemically diverse and heterogeneous (Parsons et al. 2001). They are commonly characterized by elevated metal and metalloid contents as a result of inefficient metal recovery technologies (weight percent levels of Cu, Pb and Zn; Ettler et al. 2001; Lottermoser 2002). In some cases, the metal contents of historical base metal smelting slags are similar to or even higher than those of geological ore deposits currently mined for metals. Consequently, the extraction of metals from ferrous and non-ferrous slags has been considered. Much of the metals are hosted by glass and microcrystalline silicates and may be extracted using electro- or hydrometallurgical treatment processes.

**Reuse and Recycling of Wastes from Phosphate Ores**

The necessity to provide adequate food supplies to a growing world population has resulted in the significant growth of phosphate mining and fertilizer consumption over the last 100 years. This growth has also led to the ever-increasing volume of phosphate mine wastes, including waste rocks, tailings and phosphogypsum. Phosphatic waste rocks can be put to good use in landscaping and in the capping and revegetation of waste repositories (Table 1). Similarly, the extraction of phosphoric acid from phospha tic tailings is achievable. However, phosphogypsum is the major waste product of phosphate fertilizer production, with over 1000 million tonnes of phosphogypsum stored in Florida alone. Phosphogypsum consists dominantly of calcium sulfate crystals, but it also contains minor reaction products, unreacted phosphate rock and gangue mineral particles, as well as liquid inclusions and process waters trapped in the interstices of mineral particles (e.g. Silva et al. 2010). The term *phosphogypsum* is, therefore, a collective expression for an acid waste mixture.

The ever-increasing volume of phosphogypsum has stimulated research into extracting resource ingredients from it or finding alternative uses for the material. Recycling of phosphogypsum aims to extract pure elements (e.g. sulfur for sulfuric acid production) or pure calcium sulfate solids (e.g. for building materials such as gypsum plaster boards, tiles, cement, hydraulic binder, mineralizer, artificial marble, fibre boards, glass, glass-ceramics). The reuse of phosphogypsum involves minimal or no reprocessing for large-scale applications in agriculture, mine and landfill reclamation, earthworks and construction (Pérez-López et al. 2010). However, phosphogypsum has to compete with synthetic gypsum produced as a coal combustion by-product and with mined natural gypsum, which has considerably higher purity. The reuse of phosphogypsum is limited due to its residual phosphate, acid, metal, radionuclide, fluorine and water contents, fine particle size and variable composition. To be used for building and agricultural applications, phosphogypsum may need to be puri-
REHABILITATION OF MINE WASTES

Mine Site Rehabilitation

Rehabilitation of mine wastes returns wastes and their repositories to a state allowing future land use. Similar to the mine waste hierarchy (Fig. 1), the mine site rehabilitation hierarchy is a guide for prioritizing rehabilitation strategies of mined land, including its waste repositories (Fig. 3). The future land use of a waste repository is site specific. In sparsely populated areas, mine waste repositories may be rehabilitated to a standard which requires fencing off or allows only limited grazing, and tailings may be placed under water cover or capped with benign rocks. Yet in densely populated areas, rehabilitated mine waste dumps have become centres of social amenity, such as parklands, football fields, golf courses, open air theatres, and even artificial ski slopes (Pearman 2009).

Vegetation is one key to the efficient functioning and sustainability of dry covers, partly because plants protect covers against erosion and transpire infiltrated water. Therefore, a solid understanding of vegetation performance on dry covers is crucial to the successful long-term establishment of vegetation over waste repositories. Nevertheless, the cover design of waste repositories still focusses on the physical and engineering properties of the cover materials, and gives minimal consideration to vegetation growth needs and the effect of vegetation on cover performance in the long term. In particular, the uptake of metals and metalloids into plants colonizing dry covers is still poorly understood. This is despite the knowledge that salt-rich solutes rise in engineered waste covers in response to capillary and evaporative suction forces, potentially threatening the integrity of cover systems. For example, at the Rum Jungle uranium mine in Australia, the soil covers have been acidified and contaminated with copper by the capillary rise of water from pyritic wastes underlying the soil capping (Menzies and Mulligan 2000). At this particular site, plants take up metals from the capped tailings, introducing the contaminants into the surrounding environment and leading to vegetation dieback on the capped waste repository. In general, colonizing plants that have a significant root penetration depth and a tendency to accumulate metals into their above-ground biomass may penetrate dry covers and transfer metals from capped waste repositories into their above-ground tissue, potentially causing harmful effects on animals feeding on them (Lottermoser et al. 2009). As a result, the effectiveness offered by dry barrier–type covers can be compromised, even though the waste remains physically isolated.

Genetically metal-tolerant plants (i.e. metallophytes) are known to occur over metal-rich soils. In particular, metallophytes that accumulate metals in their biomass have received much attention because hyperaccumulating plants can potentially be used to extract metals (i.e. phytomining) from soils and wastes (e.g. Tack and Meers 2010). By contrast, only a few studies have investigated species that colonize metalliferous ground without acquiring significant element concentrations (e.g. Lottermoser et al. 2008). Yet, metal-excluding plants are of significant interest in mine site rehabilitation. Such plant species do not acquire high metal concentrations in their biomass despite elevated metal concentrations in the root substrate (Fig. 4). The exclusion of metals from the above-ground plant biomass reduces the exposure of wildlife and grazing animals to metals and limits the transfer of metals up the food chain.

Figure 3. The mine site rehabilitation hierarchy, in descending order of favourability, from avoiding disturbance to leaving the site unusable or environmentally harmful. After EPA (2008)

Revegetation of Waste Repositories

The presence of environmentally significant elements and compounds in some mine wastes invariably requires their isolation in suitably constructed waste repositories. Capping mine wastes with a thick layer of solid, inert material is an effective strategy for isolating tailings and waste rocks. Materials used for dry covers include benign waste rock and tailings, clays, soils, organic wastes and neutralizing materials (e.g. limestone). Such engineered dry covers have been developed to prevent migration of solid and dissolved contaminants from tailings storage facilities and waste rock dumps into the surrounding environment. The long-term performance of dry covers is strongly affected by climate, material selection and availability, cost and construction practices, physical stability, volume change, soil evolution, ecological stability and vegetation growth. Mine operators and government authorities install these technologies with the expectation that such covers will provide a long-term solution to waste isolation and will reduce the likelihood of interaction with the biosphere, acid generation, contaminant drainage and treatment costs. Yet, there is little evidence of the proven long-term performance of engineered dry covers, despite the fact that the design life of cover systems has been predicted to extend up to hundreds of years.
CONCLUDING REMARKS

Since the first attempts to salvage metals during the Bronze Age and the recycling practice of reusing slags during Roman times, humanity has pursued the recycling and reuse of mine wastes. Yet today, many concepts of reuse and recycling of mine wastes remain ideas that have not been taken up by industry, because poor economics have prevented their application in the real world. More than ever, geochemists and mineralogists have important contributions to make by providing the knowledge necessary for the identification of cost-effective reuse and recycling options that will be adopted by industry and for rational decision-making in critical areas such as waste recycling and reuse.

The most urgent problem facing scientists working on the recycling and reuse of mine wastes is the quantification and distribution of elements in wastes. We must precisely describe the chemistry and mineralogy of wastes and understand their long-term behaviour. Developing predictive tools and reliable, field-tested modelling of long-term waste behaviour are among the greatest challenges. We need to drastically improve our scientific effort to explain the occurrence and distribution of elements and minerals in wastes on all scales, from the nano-scale to the macro-scale as well as in space and time. Such data are needed to establish the recycling and reuse potential of wastes.

While the rehabilitation of many mine sites and waste repositories is pursued by using best practices, we must continue to search for innovative, cost-effective reclamation technologies and sustainable rehabilitation methods. Hydro- and biogeochemical evaluations of recently rehabilitated mine sites and waste repositories would produce data on the successes and failures of modern rehabilitation efforts. Such studies should sharpen our ideas on the development of new rehabilitation technologies. Successful rehabilitation of mine wastes requires a new precision in the total description of wastes and their repositories and an understanding of whether our current rehabilitation practices are sustainable in the long term.

We are increasingly recognizing the need to put all components of mined resources to good use and to protect the environment from waste disposal. If innovative alternatives to current waste-disposal practices are pursued and if all waste is recycled or reused, then waste-disposal problems will be eliminated. Total resource utilization, where all of the material mined is put to good use, is a challenging concept for researchers and miners. Achieving zero waste would be the ultimate solution to waste production, disposal and rehabilitation.

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Elements 410  December 2011
The AAG’s biennial symposium was held this past August in Rovaniemi, Finland. From the comments of the more than 350 registrants (drawn from almost 50 countries), the meeting was a great success in all regards. The technical sessions covered a wide variety of topics, ranging from minesite rehabilitation to continent-scale geochemical mapping. The latter was particularly relevant for this meeting. Indeed, 2011 is the 125th anniversary of the Geological Survey of Finland, which has a long history in the use of geochemistry for mineral exploration, including a series of national geochemical atlases. The oral and poster program held at the University of Lapland was complemented by five pre- and post-conference field trips, two mid-conference trips, six workshops, and a diverse social programme highlighting the culture of northern Finland. A major attraction of AAG symposia is that they are not only held in different countries, but in most cases, they are located in regional centres. Hotels are close together, and it’s not uncommon to encounter other delegates around town, leading to impromptu drinks and meals. Rovaniemi is such a place, with the added advantage of Lappish culture, and only a few kilometres from the Arctic Circle and Santa Claus’s home.

The success of AAG symposia relies on the commitment of volunteer members to organise these meetings, which is also the case for the overall running of the Association. At the end of 2011, my two-year term as president of AAG will end, and Bob Epping of the USGS will take over. Rather than summarise the events of the last two years, I suggest that interested readers look at AAG’s website (www.appliedgeochemists.org) and read through back copies of the Association’s EXPLORE magazine, which can be downloaded from the site free of charge; information about events held by the organisation plus a range of applied geochemistry articles are contained in this quarterly publication.

There are, however, a few items I would like to mention. Particularly satisfying in the last two years has been the recruitment to AAG Council of a number of younger members, who I hope will continue their association with AAG in other roles. Towards the end of 2011, an initiative to broker in-kind support to students in applied geochemistry should be finalised and ready for implementation in 2012. We now have a program of subsidised membership for potential members from developing countries, and I am hopeful that both this and the student-support initiative will ensure that applied geochemistry and the Association grow in the coming years.

Like many non-profit organisations, AAG is aware that its capital is vulnerable to fluctuations in world markets, and we have been fortunate over the past years to have one of our members looking after our investment portfolio. As shown in regular financial updates provided over the years, Eion Cameron’s efforts have seen AAG prosper financially, even during the recent financial crisis, when purportedly wiser financial portfolios. As shown in regular financial updates provided over the past years to have one of our members looking after our investment portfolio. As shown in regular financial updates provided over the years, Eion Cameron’s efforts have seen AAG prosper financially, even during the recent financial crisis, when purportedly wiser financial heads failed to deliver. Eion has been a member of AAG since its inception (as AEG) 41 years ago, but he is probably better known for his contribution to applied geochemistry, for which he was awarded the Association’s Gold Medal at the Rovaniemi meeting.  

Paul Morris
Geological Survey of Western Australia, AAG President

The Association of Applied Geochemists honours with its Gold Medal Eion M. Cameron in recognition of his exceptional contributions to exploration geochemistry and to the promotion of interdisciplinary collaboration to understand complex geochemical phenomena. His diverse research activities led to the establishment of lake sediment geochemistry as an effective exploration tool, major advances in the technique of “deep penetrating geochemistry” to locate buried deposits, new concepts in the formation of various deposit types, and improved understanding of the sulfur cycle and its impact on the evolution of the oceans and atmosphere, amongst others.

Eion’s leadership and encouragement of the Applied Geochemistry Group at the Geological Survey of Canada spawned further research into such areas as environmental geochemistry, analytical method development and multivariate statistics. Numerous postgraduate students at the University of Ottawa have benefited from his tutelage.

Eion was a founding member of the Association. In 1972, he established the Journal of Geochemical Exploration and served as editor-in-chief for 25 years. More recently he has protected and grown the coffers of the Association by acting as its wise and strategic investment manager.

Gwendy Hall (ghall@nrcan.gc.ca), Geological Survey of Canada

News from AAG Regional Councillors

Exploration Challenges in Chile

Chile, a traditional mining country, with the world’s largest copper resource and production, faces mature stages of exploration. As such, evident outcrop-ing ore deposits are no longer available. World-class copper porphyry deposits exist, mostly in clusters, in northern and central Chile. Questions remain as to the potential for additional ore deposit clusters hidden beneath large expanses of transported overburden and/or volcanic rocks. Northern Chile, in particular, is largely covered by Miocene (Atacama) to recent gravels. Seeking ore deposits beneath cover has been tackled through research programs such as FONDEF 1083, AMIRA P778, and one-on-one research projects with Codelco, Newcrest, Xstrata, Vale, and others. These projects, carried out at the University of Chile in collaboration with other national or international institutions (such as CSIRO), have advanced our knowledge of processes occurring beneath cover and within ore deposits, and of mechanisms of geochemical dispersion through transported overburden to the surface. Despite better knowledge, additional exploration tools are necessary. The combination and integration of tools – regional and local geophysics (e.g. seismic tomography, aeromagnetics), detailed geological and structural mapping, conceptual ore deposit models, regolith and landscape evolution studies, together with geochemistry – will provide the best exploration targets. Our present challenge requires smarter, integrated and transversal techniques and highly competent professionals to provide robust interpretations that can be used with confidence.

Brian Townley (btownley@ing.uchile.cl) Universidad de Chile
An international school entitled Minerals and Biosphere, promoted by the informal groups Gruppo Nazionale di Mineralogia (GNM) and Georisors, Ambiente e Beni culturali (GABeC), under the aegis of SIMP, was held in Campiglia Marittima from 27 to 30 September 2011. The school was endorsed by the EMU and by the French and Spanish mineralogical societies (SFMC and SEM). It was attended by about twenty Italian and foreign students, many of whom were financially supported by EMU, SFMC, the company FEI, and the European project Umbrella. The school included 2½ days of lectures on both fundamental and applied topics delivered by a distinguished staff of lecturers, including three non-Italians (Karim Benzerara, Paris; Robert M. Hazen, Washington; and Richard A. D. Pattrick, Manchester). The students were also offered the opportunity to display posters about their projects.

The school, blessed by extraordinarily favorable weather, ended with a one-day tour of the archeological and mining parks of San Silvestro and Baratti-Populonia. More details, including the abstracts of the lectures, can be found at www.socminpet.it/minbio2011/index.html.

**SIMP Prizes for PhD Students**

**Bianchi Prize (in Petrology) – Two Winners Ex Aequo**

**Marco Viccaro** graduated cum laude at the University of Genoa in 2003. He completed his PhD in petrography and petrology at the University of Catania in 2007, with a thesis titled “Genesis, Differentiation and Eruptive Dynamics of Mt. Etna Magmas.” Since 2008, he has been a researcher and assistant professor of geochemistry and regional volcanology at the same university. His main research activity is focused on magma genesis and the dynamics of magma differentiation and ascent at various active volcanic systems on Earth (e.g., Etna, Aeolian Islands, Kamchatka). He investigates these topics by combining whole rock trace element and isotope systematics (Sr-Nd-Pb-Hf-O) with textural and in situ microanalysis of crystals and their inclusions. Marco is also involved in scientific collaborations with researchers in applied mineralogy/petrography and the geophysics of volcanic systems. He is a member of groups and societies active in scientific research and outreach in the fields of volcanology, geochemistry, and petrology. Marco is an author or coauthor of 77 publications, including 22 articles in international journals and 55 abstracts and proceedings for national and international conferences.

**Christian Biagioni**

“Calcium Silicate Hydrates: Crystal Structure and Thermal Behavior”

**Marcella Davì**

“Mineralogical Transformations in Serpentinites from the Mt. Capanne Thermo-Metamorphic Aureole (Elba Island, Italy)”

**Marco Ferrari**

“Mineralogical Transformations in Serpentinites from the Mt. Capanne Thermo-Metamorphic Aureole”

**Society News**

**The 2011 Nobel Prize in Chemistry Has a Mineralogical Flavor**

The 2011 Nobel Prize in chemistry has been awarded to Dan Shechtman for his studies on quasicrystals. In a “Scientific Background” document, available at www.nobelprize.org/nobel_prizes/chemistry/laureates/2011/sciback_2011.pdf, two papers are cited [Bindi et al.: Science 324: 1306 (2009); Am. Mineral. 96: 928 (2011)] that refer to the discovery of the first natural quasicrystal, icosahedrite, found at Khatyrka River, Chukotka (Russia); icosahedrite has been approved as a new mineral species. The senior author, Luca Bindi, is curator of the mineralogy section of the Natural History Museum, University of Firenze, where the holotype of icosahedrite is preserved.
The Clay Minerals Society

www.clays.org

THE PRESIDENT’S CORNER

The Clay Minerals Society Annual Meeting was held September 25–30, 2011, in beautiful Lake Tahoe, Nevada. The meeting, organized by program general chair Sam Traina with the assistance of CMS president Paul Schroeder and business manager Mary Gray, brought together academic, industry, and government scientists and engineers for discussions on the latest advances in clay science. Clay science integrates geoscience, soil science, chemistry, materials science, environmental science, civil engineering, geotechnical engineering, and anthropology with diverse clay applications, such as paper coating, adsorbents, cosmetics, environmental remediation, and petroleum exploration and development (to name a few). The cross-disciplinary nature of clay science is fertile ground for innovation, and the congenial nature of the CMS annual meetings provides an incubator for new ideas and an opportunity for students, professors, and professionals to network in an open and relaxed atmosphere. The Clay Minerals Society expresses sincere thanks to the organizers of the 2011 meetings and to our meeting sponsors, University of California Merced, Chevron, Oil-Dry Corporation of America, Theile Kaolin Company, KS Analytical Systems, Wyo-Ben, Inc., and H. H. Murray and Associates.

The Clay Minerals Society congratulates Mark Raven and Peter Self, winners of the 5th Reynolds Cup competition, the premier round-robin quantitative mineralogy competition. Mark Raven is a senior research projects officer with the CSIRO Land and Water Centre for Environmental Contaminants Research. At the Lake Tahoe meeting, he described their winning procedure, which integrated X-ray diffraction analysis of “as-received” samples with XRD analysis; these procedures followed grain-size fraction and various cation saturation and glycolation pretreatments. The award-winning CSIRO Land and Water lab in Urrbrae, South Australia, will host the 6th Reynolds Cup competition in 2012. Mark promised to challenge those entering the next competition. Meanwhile his lab will proudly display the Reynolds Cup.

David Laird (dalaird@iastate.edu)
President, The Clay Minerals Society

NEWS FROM THE 48TH ANNUAL MEETING

The Clay Minerals Society 48th Annual Meeting took place on September 25–30, 2011, in South Lake Tahoe, on the California–Nevada state line. There were approximately 95 attendees who delivered 55 oral and 17 poster presentations. In addition to the general session, technical sessions included the atomistic modeling of clays, clay mineralogy in unconventional reservoirs, the crystal chemistry of clays, and soil clays.

Three CMS awardees gave plenary lectures. Douglas McCarty (Chevron Corporation) gave the Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist Lecture entitled “Illite-Smectite: Three and One Dimensional Characteristics.” Dr. McCarty provided strong evidence for structural control in illite fundamental particles during the formation of smectites and their diagenetic conversion to illite-smectite. Glenn Waychunas (Lawrence Berkeley National Laboratory) gave the Pioneer in Clay Science Lecture entitled “Structural Studies of Mineral–Water Interfaces over 25 Years: The Development of Molecular Geochemistry.” In a tour de force, Dr. Waychunas reviewed 25 years of advances in the technology and the understanding derived from that technology of structure and interactions at the mineral–water interface. Sridhar Komarneni (Penn State University) gave the Marilyn L. and Chrystie M. Jackson Mid-Career Clay Scientist Lecture entitled “Synthetic and Modified Clay and Clay Nanocomposites: Multifunctional Materials.” During his lecture, Dr. Komarneni described the unique properties of various synthetic and modified clays. Some of these materials are highly effective for selectively removing problematic ions from radioactive wastes.

Eleven students received CMS travel awards to attend the meeting. The award for best student oral presentation went to Sarah Saslow (Northwestern University) for her talk entitled “Uranyl Adsorption and Speciation at the Mineral/Water Interface Studied by Resonantly Enhanced Second Harmonic Generation and the Chi(3) Technique.” Sarah’s advisor is Franz Geiger. The award for best student poster went to Ana Barrientos-Velazquez (Texas A & M University) for “Effects of Charge Origin and Octahedral Cations of Smectites on Their Selectivity and Adsorption Capacity for Aflatoxin.” Ana’s advisors are Youjun Deng and Joe Dixon.

Two field trips were offered. The premeeting trip included visits to Mono Lake and Mammoth Mountain. The postmeeting trip visited three clay deposits in northern Nevada: a sodium bentonite deposit near Fallon, a calcium bentonite deposit near Lovelock, and a dickite/kaolinite deposit on the western flank of the Stillwater Range.

The 2012 Annual Meeting will be held in late July in Golden, Colorado. Check the CMS website soon for more details.

Student travel awardees (left to right): Pushparaj Charan, Jean-Baptiste Fernandez, Hongji Yuan, Michael Bishop, Artur Kuligiewicz, Jing Zhang, Michael Cheshire, Sarah Saslow, Sungho Kim, Ana Barrientos-Velazquez, and Andrew Russell

Reiner Dohrmann inspects the dickite/kaolinite deposit on the western flank of the Stillwater Range.
Two short years ago, when I assumed the responsibilities of president of the Geochemical Society, I set an ambitious agenda—counting on help from fellow members—designed to tackle a few old, persistent problems and also establish new initiatives. In my first message to Society members in the pages of this magazine, I set the following goals:

- Negotiate a favorable contract with Elsevier to continue publication of our journal, Geochemica et Cosmochimica Acta
- Continue the internationalization of the Geochemical Society in its governance, conference participation, conference organization, and venue choices
- Increase the participation of women at all levels in the Society, and ensure gender equity in award nominations, particularly fellowships
- Start a concerted effort in the area of outreach to developing countries, where participation at present is virtually nonexistent
- Start fund-raising efforts with private foundations to underwrite outreach activities, especially streaming conference presentations to developing countries and sponsoring presenters from those countries to attend our conferences
- Nurture our associations with the American Geophysical Union (AGU), European Association of Geochemistry (EAG), and Geological Society of America (GSA) for the purpose of promoting geochemistry worldwide
- Establish a volunteer corps of mentors for PhD students and postdocs, focused especially on young, underrepresented minorities in our Society.

In efforts to further internationalize and gender balance our Society governance and committee service, our soon-to-be president continued the efforts of other recent vice presidents to be inclusive and search far and wide for colleagues to appoint to award committees and committees responsible for nominations, conference programs, and so on. Today, the various committees of the Society are more diverse than they have ever been.

To grow geochemistry and highlight its importance in the developing world, I started an outreach committee with members from four continents (Africa, Asia, North America, and South America). The committee was charged with developing a lecture series and other programs, to be deployed by distinguished members of our Society during visits of several days to weeks at regional hubs that ideally have a large catchment area of national and private universities. In this effort, we subsequently joined forces with the European Association of Geochemistry (EAG) to create an expanded program with a joint financial support of twenty thousand euros per year. We have plans to seek additional funding from the U.S. National Science Foundation and private foundations, and have also started discussions with the American Geophysical Union (AGU) about collaborative initiatives in the area of outreach. To help lead our fund-raising activities in a sustainable manner, I asked the Board of Directors to approve the formation of a Development Committee, now comprised of members from three continents and chaired by Sam Savin, current Geochemical Society treasurer. Our working relationships with sister organizations, such as AGU, EAG, and GSA, have been much improved to our mutual benefit.

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The goal to establish a volunteer corps of mentors for PhD students and postdocs, focused especially on young, underrepresented minorities, did not gain much momentum because of the continued meager number of Society members falling in that category. Attracting more underrepresented minorities to our Society and increasing the number of women nominated for awards because of their contributions to geochemistry are worthy goals that we need to keep alive, and I pledge to help the next group of leaders, united in the common recognition that this is the right thing to do.

I take great pride in what we have accomplished together, and owe a debt of gratitude to the large cadre of colleagues who have sacrificed time and effort to serve the Society and to ensure success for most of the objectives outlined above. I hope that my involvement has helped to move the Society forward and that some of my initiatives will be long lasting and have a significant impact. In closing, it has been a privilege and an honor to serve the Geochemical Society as president and to work with an outstanding Board of Directors, profoundly dedicated and selfless committee volunteers, the general membership, and our incomparable business office manager, Seth Davis, at Washington University in St. Louis. For that I thank you all very much.

Samuel Mukasa

University of New Hampshire

Michael J. Drake (1946–2011)

The Geochemical Society lost a great scientist and leader in Michael J. Drake, who passed away in Tucson on September 21, 2011. Michael engaged in research of great breadth, extending across disciplines that included meteoritics, geochemistry, and planetary sciences, and reaching across the inner Solar System (Earth, Moon, Mars, Venus, asteroid 4 Vesta, and other asteroid parent bodies). He considered himself first and foremost a geochemist. He was president of the Geochemical Society (1998–1999) and the Meteoritical Society (1999–2000), and his service to these societies and the greater geochemical community was enormous. Read the full obituary at www.geochemsoc.org.

Kevin Righter and colleagues

Ian S. E. Carmichael (1930–2011)

The indomitable Ian S. E. Carmichael, who made such a deep and lasting impression on so many of us with his highly imaginative research career and his legendary mentoring of graduate students, died in Berkeley on August 26, 2011. Ian applied thermodynamic theory, experiment, and the ground truth of fieldwork to the study of magmatic rocks. Throughout the arc of his career at the University of California at Berkeley, he played a critical role in transforming igneous petrology from a discipline that was largely descriptive to one that is now rigorously quantitative, and in the process, he inspired multiple generations of students. Read the full obituary at www.geochemsoc.org.

Rebecca Lange
I would like to invite geoscientists from around the world to the 22nd V. M. Goldschmidt Conference to be convened in Montréal, Canada, on June 24–29, 2012. Montréal is a beautiful and vibrant city. With numerous direct flights from American and overseas cities arriving daily at the newly renovated Trudeau International Airport, travel to Montréal has never been easier. Montréal is truly the gateway to Canada, with French and English influences joining in a melting pot of international culture, the hallmark of a great cosmopolitan city. Great shopping, delectable international cuisine, and a breathtaking variety of entertainment abound. The theme of the 22nd V. M. Goldschmidt Conference is “The Earth in Evolution.” Thus, the exciting science to be presented in the symposia and technical sessions will be complemented by thought-provoking plenary sessions related to the theme.

The Local Organizing Committee for the 22nd V. M. Goldschmidt Conference is making a special effort to provide an environmentally sustainable conference. In addition to using more recycled materials, we are also trying to produce less waste by planning new formats for conference programs and presentations. For example, for the first time, the conference program will be made available in a mobile (cell phone) application format, and a limited number of electronic poster formats will also be made available. See the 22nd V. M. Goldschmidt Conference website for details and deadlines (www.goldschmidt2012.org).

So bring your science, bring your family, bring your appetite, and bring your joie de vivre to Montréal in 2012!

Ross Stevenson, President, Local Organizing Committee
22nd V. M. Goldschmidt Conference
2011 ANNUAL MEETING REPORT

The 74th annual meeting of the Meteoritical Society was held in London, United Kingdom, on 8–12 August, 2011. The meeting took place on the campus of the University of Greenwich, on the grounds of the Old Royal Naval College. Over 520 abstracts were submitted by about 460 different authors, breaking the previous record set in New York for abstract submissions. In an effort to accommodate as many oral presentations as possible, a third parallel session was added for the entire meeting. There were 284 oral and 237 poster presentations assigned. The Tuesday poster session was cancelled due to social unrest in the surrounding areas, but the Thursday session was expanded to accommodate 90% of the posters from Tuesday.

There were 477 participants (members and nonmembers), of which 121 were students, and a further 71 registered guests for a total attendance of 548, making the London meeting the second-largest annual meeting in Society history. Thirty-eight students and seven professionals from low-income countries were awarded travel funds totaling about $51,000.

The scientific program was rich and stimulating. It covered a wide range of topics, including the formation of the Solar System, space missions, asteroids (Itokawa and Vesta), impacts and shock processes, refractory inclusions, chondrules, ordinary and enstatite chondrites, carbonaceous chondrites, ordinary and enstatite chondrites, differentiated objects, isotopes, 3-D structures of meteorites, IDPs and micrometeorites, and organic matter. A session dedicated to the memory of Frank Stadermann covered all aspects of micro- to nanoanalysis techniques and results. There was also a session in memory of Betty Pierazzo on modeling and experiments related to impact processes.

The Barringer Invitational Lecture was held in the main hall of the Natural History Museum in South Kensington and was presented by Professor Martin Rees, Astronomer Royal and former president of the Royal Society. He spoke to a full crowd on the topic “From Big Bang to Biosphere.”

The Wednesday afternoon excursion was a guided boat tour of London. The three-hour tour ran from the Thames Barrier to the east to St. Mary’s church in Battersea to the west.

The abstract volume and program are available online at www.lpi.usra.edu/meetings/metsoc2011/pdf/program.pdf.

Field Trip to the Scottish Highlands

Fifteen meteoriticists enjoyed a premeeting field trip to see the geology and scenery of the Scottish Highlands. The trip was led by Martin Lee (University of Glasgow) and John Cosgrove (Imperial College London), and included a spectacular visit to Fingal’s Cave and the columnar basalts on the island of Staffa and stops on the islands of Iona, Mull, and Skye.

2011 SOCIETY AWARD WINNERS

The Society gives five major awards each year. For more information on individual awards see the the Society webpage. Nominations for the Leonard, Nier, and Barringer awards are due by January 15. The deadline for the Service Award and the Pellas-Ryder Award is January 31.

The Leonard Medal, which is the Society’s highest and oldest award, is given to individuals who have made outstanding original contributions to the science of meteoritics or closely allied fields. It is named for Frederick C. Leonard, who was a founder and first president of the Society. The 2010 winner is François Robert, of the Museum d’Histoire Naturelle, for his outstanding contributions to the study of meteorites, especially to our understanding of the D/H ratios of interstellar organic molecules, lunar nitrogen isotope variations, and a host of other isotopic processes. The citation was given by Mark Thiemens.

The Barringer Medal and Award, sponsored by the Barringer Crater Company and created in memory of D. Moreau Barringer Sr. and his son, D. Moreau Barringer Jr., is given for outstanding work in the field of impact cratering. This year, the Barringer Award is given to Bruce Bohor (now retired from the U.S. Geological Survey) for his fundamental contributions to impact crater studies, including his major role in the confirmation that the K-T boundary layer had an impact origin. Through careful mineralogical and petrological work, Bruce and his colleagues were able to document that the K-T boundary layer is a global feature. The citation was given by Billy Glass.
This year’s winner of the Nier Prize for young scientists in the field of meteoritics is Fred Ciesla of the University of Chicago. Fred receives this award for his excellent work on the origin and evolution of solid material during the early stages of planetary-system development and star formation. His work uses constraints from cosmochemical investigations and considerations from the latest astrophysical observations. The citation was given by Dante Lauretta.

Richard Pugh is the winner of this year’s Meteoritical Society Service Award. Dick receives this award for his excellent service toward increasing the education and public awareness of meteorites and the fireballs that produce them. Dick was also instrumental in establishing the Cascadia Meteorite Laboratory at Portland State University and functions as its outreach coordinator. The citation was given by Alex Ruzicka.

The Gordon McKay Award, given for the best oral presentation by a student at the annual meeting of the Meteoritical Society, is awarded to Dennis Harries of the Universität Bayreuth, Germany, for his talk entitled “Nanocrystalline P-Bearing Pentlandite and Chromium Nitrides from CM2 Chondrites Y-791198 and Y-793321.” The award comes with a prize of US$1000 and a certificate.

The Meteoritical Society now has a page on Facebook! Please visit to find job announcements, meeting information, and up-to-date Society news. We can be found at www.facebook.com/#!/pages/Meteoritical-Society/132324490172621. Our Facebook page is maintained by Cari Corrigan (corriganc@si.edu). Suggestions and contributions are welcome!

ANNUAL MEETING SCHEDULE

2012 – Cairns, Australia, August 12–17
2013 – Edmonton, Alberta, Canada, July 29–August 2
2014 – Casablanca, Morocco, September 7–14
2015 – Berkeley, California, USA, July 27–31

RENEW YOUR MEMBERSHIP NOW!

Please renew by March 31, 2012; after that date, a $15 late fee will be assessed. You can renew online at http://metsoc.meteoriticalsociety.net.

SOCIETY NEWS

Société Française de Minéralogie et de Cristallographie

www.sfmc-fr.org

SFMC Student Sponsorship

Julie Cosmidis and Estelle Couradeau, PhD students at the Institut de Minéralogie et de Physique des Milieux Condensés, Paris, received a grant from the Society to help them attend the international school Minerals and Biosphere. The school was held in Campiglia Marittima (Italy), on 27–30 September 2011 in a former mining site now covered by pines and olive trees. It gathered about 20 European PhD students and postdocs in microbiology, mineralogy and geochemistry. The aim was to highlight the diversity of scientific questions concerning both minerals and living organisms/organic matter and how these questions can be addressed. The school featured lectures on techniques for investigating microbe–mineral interfaces and that allow the preservation of living structures and provide micrometre-scale resolution or better. Fundamental topics, such as the selection by organics of the orientation of mineral growth, as well as applied topics, like the remediation of polluted soils by plants and fungi and the impact of mineral dust on human were presented.

MEETING ANNOUNCEMENTS


The Atalante 2012 conference will take place in Montpellier (Le Corum), France, on 3–7 September 2012. Previous Atalante conferences were held in Avignon (2000), Nîmes (2004) and Montpellier (2008). Organized by the French Alternative Energy and Atomic Energy Commission (CEA), these conferences provide an international forum for discussing advances in fuel cycles and waste management.

Increasingly, nuclear energy has to demonstrate that it can contribute safely and sustainably to growing energy needs. Today, the acceptance of nuclear energy is still closely associated with increased reactor safety, with our capability to reduce the lifetime of nuclear wastes and to manage them safely, and with better use of the natural resources. These goals cannot be achieved only by optimizing industrial processes through engineering studies; we must also increase our basic knowledge in actinide science. In this way, we will be able to build the future of nuclear energy using reliable and scientifically based results.

For its fourth edition, the organizers will focus the Atalante conference on the nuclear chemistry of fuel cycles and waste management. More than 150 oral contributions will be presented by the international nuclear chemistry community. A poster session will also be provided. Information can be obtained at www.atalante2012.org. Abstracts must be submitted before the end of February 2012. Registration is open and early booking rates will be available until the end of June 2012.

Serpentine Days – September 2012

After the success of Serpentine Days in Grenoble in 2007, a new edition, sponsored by the SFMC, will be held in September 2012. The conference will take place in Porquerolles, in the south of France. More details will be given in the next issue of Elements. You can also consult the SFMC website, www.sfmc-fr.org/.

Organizing Committee: M. Andreani, A. L. Auzende, A. Delacour
The IAG presented its sixth Early Career Researcher Award at the Goldschmidt Conference in Prague (August 2011). Now a well-established annual event, this award is based on the abstracts submitted for presentation at either poster or oral sessions; this year the IAG’s jury had a record 1150 contributions to consider. We report with great pleasure that the winner of the 2011 award is Dr. Leah Morgan from the Vrije Universiteit Amsterdam for her abstract entitled “Improving the Accuracy of the $^{40}$Ar/$^{39}$Ar Geochronometer.” Leah’s work was judged a significant advancement in improving data quality in the K/Ar radioactive decay system. Her work focuses on using metrologically rigorous methods for refining the decay parameters within the branched K/Ar and K/Ca decay chains. The panel of IAG judges and the IAG Governing Council recognize her work to be of key relevance to our Society’s core goal of improved geochemical metrology.

During this year’s committee meeting, two specific issues came to light that will require future action. First, the data being reported by the IAG “qualified” laboratories have become overly dominated by two analytical techniques: X-ray fluorescence and inductively coupled plasma mass spectrometry. The loss in diversity in the available techniques is making it difficult to assess method-specific biases that might impact results. The Certification Committee recognizes the need to recruit additional laboratories that still have expertise in other analytical methods. Second, the IAG certification protocol, which is the basis of all IAG certificates of analysis, requires updating in light of recent changes in metrology guidelines. Modifications to the protocol that are seen as necessary include the justification of outlier rejection based on geochemical criteria and the modification of terminology to bring it into compliance with VIM-3 guidelines.

The IAG’s Materials Certification Committee held its annual meeting in Prague immediately before the Goldschmidt Conference. The current work of the committee focuses on four bulk rock materials: a serpentinite, a harzburgite, a rhyolite, and a trachyandesite. Data for major and minor element concentrations have now been collected on each of these materials, and data evaluation is at an advanced stage. In the cases of the serpentinite and the harzburgite, a further round of data collection, employing expert laboratories identified by the IAG, will focus on the characterization of their platinum group element concentrations.

In conjunction with the IAG, Wiley-Blackwell identified a small number of sessions of particular relevance to the journal, with the assessments based on the excellence of the scientific content and on the quality of the presentation. The winners of the Wiley-Blackwell prizes for 2011 and the titles of their work are:

Aude Coutaud (CNRS/UPS, Toulouse, France): “Copper and zinc isotope fractionation during their interaction with phototrophic biofilm”

Janne Koornneef (Institut für Geochemie und Petrologie, ETH-Zürich, Switzerland): “In situ analysis of U-Th disequilibria in titanite by fs-LA-MC-ICP-MS”

Christoph J. Sahle (Fakultät Physik, Universität Dortmund, Germany): “Studying soft X-ray absorption edges under extreme conditions”

The IAG wishes to congratulate all four of these winners and wishes them all a successful future in analytical geochemistry.

**Certification Committee**

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Dear colleagues,

It is a great pleasure for the Organizing Committee of M&M 7 to invite you to the upcoming 7th International Conference on Mineralogy and Museums, which will be held in Dresden on August 27–29, 2012. During the conference, Freiberg and its new mineral exhibit at Schloss Freudenstein will be visited. Pre- and postconference trips are planned, with visits to several German museums and some stops in the field. Germany offers high-quality mineralogical museums with long and interesting historical backgrounds, as well as world-class mineral localities (for example Harz, Erzgebirge, Siergeland, and Schwarzwald).

We kindly request you to submit the preregistration form. This and the first circular can be found at www.mm7-dresden-2012.de. Details on the conference will be continually updated on this website.

We are looking forward to seeing you in Dresden!

On behalf of the Organizing Committee, and with kind regards,

Renate Schumacher
Mineral Museum of Bonn, German representative, IMA Commission on Museums

CALL FOR NOMINATIONS FOR THE 2012 DMG AWARDS

The Abraham-Gottlob-Werner Medal is the highest honor given by the German Mineralogical Society (DMG). It is awarded in recognition of outstanding mineralogical research (in Silver) or merit with regard to the promotion of the mineralogical sciences (in Gold).

The Georg-Agricola Medal in Bronze recognizes outstanding achievements in the field of technical and applied mineralogy.

The Victor-Moritz-Goldschmidt Award is given to honor outstanding young researchers. The candidates should normally be members of the DMG and younger than 39 years of age.

Nominations for the DMG awards should include the curriculum vitae and publication list of the candidate, as well as a cover letter outlining the candidate’s qualifications. Further information on the nomination requirements are on the DMG home page: www.dmg-home.de. Please submit your nominations by February 17, 2012 to Rainer Altherr, Institute of Geosciences, University of Heidelberg, Im Neuenheimer Feld 234-236, D-69120 Heidelberg, Germany; e-mail: Rainer.Altherr@geow.uni-heidelberg.de.

Applications for the 2012 DMG Awards are open to all members of the German Mineralogical Society (DMG) and younger than 39 years of age.

DMG POSTGRADUATE SHORT COURSES IN 2012

Applications of Solid-State NMR Spectroscopy in Mineral and Geological Sciences
Date: 29 May–1 June 2012
Where: Institute of Geology, Mineralogy and Geophysics, Ruhr-Universität Bochum, Bochum, Germany
Information: Michael Fechtelkord (Michael.Fechtelkord@ruhr-uni-bochum.de)

Application of Diffusion Studies to the Determination of Timescales in Geochemistry and Petrology
Date: October 2012
Where: Institute of Geology, Mineralogy and Geophysics, Ruhr-Universität Bochum, Bochum, Germany
Information: Sumit Chakraborty (Sumit.Chakraborty@rub.de), Ralf. Dohmen, Thomas Müller

Calorimetry in the Geosciences – Theory, Experiment and Applications
Date: to be announced
Where: Universität Jena or Salzburg
Information: Klaus-Dieter Grevel (klaus-dieter.grevel@rub.de)

Diffusion in Geological Materials
Date: 3–7 September 2012
Where: Department of Lithospheric Research, University of Vienna, Austria
Information: Rainer Abart (rainer.abart@univie.ac.at)

High-Pressure Experimental Techniques and Applications to the Earth’s Interior
Date: 13–17 February 2012
Where: Bayerisches Geoinstitut, Universität Bayreuth, Germany
Information: Stefan Keysnser (stefan.keysnser@uni-bayreuth.de)

Neutron Diffraction for Mineralogists
Date: Autumn/winter 2012
Where: Helmholtz-Zentrum Berlin für Materialien und Energie, Abteilung Kristallographie, Germany
Information: Susan Schorr (susan.schorr@helmholtz-berlin.de)

Texture Analysis with MTEX Emphasizing EBSD Data Analysis
Date: to be announced
Where: Geoscience Mathematics and Informatics, TU Bergakademie Freiberg, Germany
Information: Helmut Schaeben (schaeben@tu-freiberg.de)
M S A at a Crossroads

Leading this historic and influential scientific society is a great honor, and a daunting task. As the 93rd president, following names like Kraus (1920), Winchell (1932), Bowen (1937), Buerger (1947), Hess (1955), Thompson (1968), and too many extraordinarily eminent scientists in the latter decades to list here, one is completely humbled. Then you realize, as does every president of every society, that there is much work to be done. Now well into the 21st century, with science and technology seemingly advancing at the speed of light and with much of what this world has to offer at our fingertips, you can be sure of at least two things: if you make measured and incremental progress, you will eventually be passed, and if you stop to catch your breath, you will be passed quickly.

I have been a member of MSA for three and a half decades, and I’m still in my fifties. That means that I spent my formative years as a scientist—my graduate school years, plus about 10 more—growing up in MSA and in the fields that it represents. However, even in those days, and continuing until today, I have spent just as much time in the physics, chemistry, and biology literature as I have in the Earth science literature, which perhaps explains why I have been placed, for better or worse, on advisory committees that help oversee federally funded science in all these fields. From this vantage point, I have noticed a disturbing thing. Despite its triumphs, and there are several, MSA has not kept up a pace necessary to truly flourish in today’s lightning-fast scientific environment. A sign: many of the world’s most influential mineralogists publish only sparingly in MSA’s flagship journal, American Mineralogist, if at all. A symptom of this is that the journal’s impact factor is lower than it should be. Another sign: whereas many scientific societies have grown in membership, some dramatically, MSA has not expanded its influence in the fields it represents. However, even in those latter decades to list here, one is completely humbled. Then you realize, as does every president of every society, that there is much work to be done. Now well into the 21st century, with science and technology seemingly advancing at the speed of light and with much of what this world has to offer at our fingertips, you can be sure of at least two things: if you make measured and incremental progress, you will eventually be passed, and if you stop to catch your breath, you will be passed quickly.

How can MSA better reflect the fact that the study of minerals is literally more important than ever before, even by today’s accountability standards? There are many ways, including changes that can be made to American Mineralogist, adding key new relationships with other societies, and lengthening terms for officers so that they can be around long enough to shepherd substantial programs through the system. These I will discuss in this column as my presidential year goes along.

In the meantime, we will all be hard at work. Stay tuned.

Michael F. Hochella Jr. (Hochella@vt.edu) MSA President

M E M O R I A M

Robert J. Gunthorpe – Member, 1973
Harrison Corbin Van Cott – Member, 1946
James B. Thompson – Fellow, 1950
The Minerological Society of America Award is given for outstanding contributions by a scientist beginning his or her career. Dr. Motohiko Murakami of Tohoku University received the 2011 MSA Award for his discovery that MgSiO3-perovskite, the most abundant component of the lower mantle, transforms to a "post-perovskite" phase under P-T conditions corresponding to the D" region, just above the core–mantle boundary. The stability relations of this phase give the potential to determine temperatures in D" , the only anchor point for the geotherm in the lowermost mantle. Dr. Murakami's accomplishments also include providing evidence that lower mantle perovskite phases and (Mg,Fe)O can contain significant amounts of water and discovering a new ultrahigh-pressure amorphous phase of SiO2, which suggests that melts in the lowermost mantle are probably denser than previously thought, causing them to sink.

NOMINATIONS SOUGHT FOR 2013 AWARDS

Nominations must be received by June 1, 2012

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

The Dana Medal recognizes continued outstanding scientific contributions through original research in the mineralogical sciences by an individual in the midst of his or her career.

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

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

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

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

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, http://www.minsocam.org. Completed applications must be submitted by June 1, 2012.

2012 CALENDAR

Arizona Minerals

Arizona was granted statehood on February 14, 1912. This calendar is part of a community-wide Centennial tribute to Arizona's minerals and mines and to their champions. Published by Lithographie, LLC, in cooperation with MSA and Martin Zinn Expositions, it is available from MSA, http://www.minsocam.org/.

AWARDEES AT THE 2011 ANNUAL MEETING

At this year's meeting in Minneapolis, Minnesota, Dr. John G. Liou, Stanford University, Stanford, California, received the 2011 Roebling Medal, given for a lifetime of outstanding original research in mineralogy. Dr. Liou pioneered work on the formation conditions of several important hydrous silicates that dominate low-grade metamorphic and hydrothermally altered rocks. More recently, in studying orogenic belts in China and the former USSR, Dr. Liou discovered microinclusions of dense, ultrahigh-pressure (UHP) polymorphs of SiO2 (coesite) and C (diamond) enclosed in tough, refractory container minerals, thus adding significantly to our understanding of how the Earth works.

AMERICAN MINERALOGIST SPECIAL COLLECTIONS

The journal publishes special thematic sections. These can comprise all-new articles, collected articles from past issues, or both.

Recent themes

See the View Special Issues links for the American Mineralogist on the GeoScienceWorld and MSA websites.
RICHARD PATTRICK SIGNS OFF AS PRESIDENT

Two years fly past and one realises that presidents are, while of course important, dispensable. It is the professionalism and loyalty of the office staff and the energy of the academic volunteers that drive a society forward. The Mineralogical Society of Great Britain and Ireland (like many others) is blessed with riches on both accounts, and it has a bright and developing future, punching above its weight. The ability to award the internationally accepted Chartered Science (CSci) status has been hard won and will help the Society profile. However, we know full well we can only succeed if we continue to work with all other mineralogical societies and cognate disciplines, ensuring that mineralogy has the profile it deserves in a world where ‘spin’ of the non-electronic kind is all too important.

Richard Pattrick, MSGBI President

FROM LONDON

Journals

Like many journals, Mineralogical Magazine and Clay Minerals are still in the transition between paper and e-only subscriptions. The savings in costs are not as much as you might think, and there are still many out there who have not yet availed of their online access. Coupled with the global recession, these are challenging times for publishers of all sizes, and especially those who rely on their journals’ income to support other activities. The Mineralogical Society receives a growing proportion of its journal income from e-journal aggregates, e.g. GeoScienceWorld. We are also examining other possibilities for broadening our income base, for example, selling journal and book content in ‘course pack’ form, in conjunction with colleagues at ASA, and possibly downloading in other formats, such as on mobile devices.

Our journals performed well this year: they both rose in the ISI rankings, both were well oversubscribed in terms of the numbers of papers submitted and both provided healthy sums to the Society’s overall financial position.

Mineralogical Magazine

The June 2011 issue of Mineralogical Magazine consists of the abstracts from the 2011 Goldschmidt Conference – these are available for all to see online. Go to www.ingentaconnect.com/content/minsoc/mag or http://gsminmag.highwire.org/ to see the content. The August 2011 issue included a thematic set of papers arising out of last year’s “Nuclear Waste Management” meeting (see list in Elements 7: 345). These papers will be widely read and cited and have broadened the journal’s readership.

Mark Welch stood down as Principal Editor this year after five years in the journal hot seat. Mark did a great job and worked tremendously hard during his term of office. He is having a well-deserved break for a couple of years but will no doubt be back in another Society role in the future.

Clay Minerals

Clay Minerals had another solid year. The editorial team had a very fruitful meeting in Antalya, Turkey (during the Euroclay meeting), and ideas discussed there will help to position the journal for the future.

Books

Another EMU book – Layered Mineral Structures and their Application in Advanced Technologies (M. F. Brigatti and A. Mottani, editors) – was published this year, which now brings the series up to date. The books are available for sale in our bookshop, accessible at www.minersoc.org.

Meetings

A report of the Society’s annual meeting was published in the October issue of Elements. It was a small but perfectly formed meeting with loads of interesting science.

Facebook

Did you know that Elements has a new Facebook page? Be sure to ‘friend’ it and to post a comment. This is a great place to express views about content in the magazine that others can read immediately. The editors plan to monitor the content and publish extracts in the magazine. How else can Elements use social media to good advantage? Please tell us.

People

At this time of the year we acknowledge those who have served the Society throughout the year, in particular those who leave after a period of service. Richard Pattrick comes to the end of his two-year stint as President. He has worked exceptionally hard at moving the Society forward. Thanks Richard. Back to supporting Macclesfield Town for you! David Morgan has just completed 10 years as a Custodian Trustee of the Society. The Custodian Trustees are a subset of the Finance Committee, responsible for the Society’s investment portfolio and overseeing all aspects of financial management of the Society. As well as serving in this capacity, David has been an ordinary member of Council, Chairman of the Clay Minerals Group, Vice President, President, and Principal Editor of Clay Minerals. He will continue his active involvement in the Society through his participation in the Chartered Scientist scheme and as Chair of the Awards Committee for two more years. Many thanks, David, for all the hard work over the years. Thanks also to Ben Harte who stood down this year. Ben has had an equally illustrious history in terms of involvement, having served as Society President and Chair of the Metamorphic Studies Group, and having organized several important conferences.

Finally, to all members of Council, members of the Special Interest Groups, those who helped to organize meetings or reviewed papers or helped in any other way – a big thank you. Please continue to promote our Society amongst your colleagues and students. Remember, one positive word from you is worth more than anything we can do centrally from the office. We strive to continue to increase our membership numbers, to have more papers in our journals and books and to have more delegates at our meetings. You can help us achieve these goals.

Membership Dues for 2012

Your 2012 dues are due now. The sooner you pay, the less time and money we spend on administration! We look forward to hearing from you! Best wishes for 2012

Kevin Murphy (kevin@minersoc.org)
Executive Director
Jon Davidson becomes the Society President on January 1, 2012. Be sure to welcome him to his new role.

**Medals**

As usual, we will be looking for nominations for our medals and awards. Go to www.minersoc.org/pages/awards/awards.html to read about how to make nominations for the Schlumberger, Max Hey and Collins medals. It is now possible to use a nomination form, which should help to cut down on the paperwork required.

**Geochemistry Group Meeting**

Building a Habitable Planet: The Geochemistry of Earth, Oceans and Atmospheres, 15–16 March 2012, The Open University. Topics will include all aspects of geo- and cosmochemistry relevant to the formation and evolution of the Earth as a habitat for life. Registration fee: £30 (2 days); £20 (1 day). For further information, please go to the Geochemistry Group's web page: www.geolsoc.org.uk/gsl/groups/specialist/geochemistry/page10650.html.

**Joint Meeting in Frankfurt**

Go to http://emc2012.uni-frankfurt.de/ to read more about our joint European Mineralological Conference being held in September 2012. Early indications suggest that this meeting will be brimming with good science. Plan to attend now.

**Field trip of the Volcanic and Magmatic Studies Group**

**MAGMATIC PROCESSES IN THE SHALLOW CRUST, ADAMELLO MASSIF, ITALY**

26 August–1 September 2012

A chance to explore the magmatic processes and products of the sub-volcanic feeder system and shallow level intrusions of Northern Italy. Cost: £350 – Students; £450 – Non-students, flights not included. Deposits of £100 payable by 31 April 2012. Leader: Jon Blundy. More information at www.vmsg.org.uk

**Bursary Report**

The Mineralogical Society kindly awarded me a bursary to travel to Canmore (Alberta, Canada), for the 26th Himalaya-Karakoram-Tibet Workshop in July 2011. At this international conference I presented a talk on the significant new structural findings I have made in Bhutan, my field area in the Eastern Himalaya. Along with the experience of presenting my work to an international audience in my field, I learned a huge amount from invaluable discussions with experts in this area. These included Prof. Djordje Grujic of Dalhousie University, Prof. Lincoln Hollister of Princeton University and Prof. Aaron Martin of the University of Maryland, who are world authorities on Himalayan tectonics. I was able to forge links that may be helpful when applying for positions after I have submitted my thesis.

The two-day conference was followed by a three-day field trip across the Rocky Mountains to the Coast Mountains, finishing in Vancouver. Experiencing this impressive region under the guidance of those who have worked in the area for decades was a great opportunity and allowed me to compare it to the Himalaya and broaden my understanding of large mountain chains.

I would like to thank the Mineralogical Society for their financial support. It allowed me to gain valuable knowledge and experience which I can take forward into the final year of my PhD and beyond.

Lucy Greenwood

**WHAT TO LOOK FORWARD TO IN 2012**

**Sociedad Española de Mineralogía**

The 31st annual meeting of the Spanish Mineralogical Society (SEM) took place from September 7 to 10 in Barcelona. It was organized by the SEM in collaboration with the University of Barcelona, the Autonomous University of Barcelona, the Polytechnic University of Catalonia, and the Spanish Research Council.

As in previous editions, the scientific sessions were multidisciplinary, covering hydrochemistry, fluid–rock interactions, atmospheric geochemistry, crystal growth, and mineral deposits. The increasing importance of the environmental and geochemical disciplines, already noted in previous meetings, was confirmed. There was a significant increase in contributions on fluid–mineral interactions, from atomic to field scale. New topics, such as geological CO₂ sequestration and the mineralogy and geochemistry of atmospheric particulates, were offered for the first time. A total of 96 contributions were presented, including 4 keynotes, 42 talks, and 54 posters. The keynotes were: “Geochemical Processes in a Subsoil of the Siberian Pyrite Belt,” by Ricardo Amils (Centre of Astrobiology, CSIC-INTA); “Global Tectonics and Chromite–Platinum Mineralization Monitoring Genesis and Evolution of Ural–Alaskan Type Complexes,” by Giorgio Garuti (University of Leoben); “Road Dust – Sources, Properties and Abatement Strategies,” by Mats Gustafsson (Swedish National Road and Transport Research Institute); and “Morphology of Gypsum Crystals,” by Juan-Manuel Garcia Ruiz (Laboratory of Crystallographic Studies, CSIC–University of Granada). Extended abstracts of all contributions can be found in the 15th volume of MACLA, the journal of the SEM (www.ehu.es/sem/revista/REVISTA.HTM).

Prior to the scientific sessions, a seminar entitled “Nanoparticles in the Environment” was held. Six lectures were given: “Nanoparticles in the Environment: Where Are They?,” by Laurent Charlet (University of Grenoble); “Characterization of Inorganic Nanoparticles: Traditional Methods and New Tendencies,” by Victor Puntes (Catalonia Institute of Nanotechnology, Barcelona); “Large Facilities and the Structure of Nano-Sized Minerals,” by Gabriel Cuello (Laboratory of Crystallographic Studies, CSIC–University of Granada); “Nanotoxicity: The Impact of Nanoparticles on Health,” by Antonietta Gatti (University of Modena and Reggio Emilia); “Nanoparticles in the Atmosphere,” by Xavier Querol (IDAEA-CSIC, Barcelona); and “Fate and Effects of Engineered Nanoparticles in Aquatic Systems,” by Renata Behra (Swiss Federal Institute of Aquatic Science and Technology Dübendorf).

During the banquet, prizes for young researchers were awarded to Marta Navarro Rojas for her work “Zeolite Synthesis by the Laser Ablation Method” and Montgarrí Castillo Oliver for her study “Use of Indicator Minerals in Diamond Exploration: A Comparison between Barren and Fertile Kimberlites in Angola.” Their studies were selected from among 32 proposals, indicating a high participation by young researchers, confirming the trend of recent SEM meetings.

A field trip to the Catalonia salt-mining district took place on September 10. Drs. Albert Soler, Neus Otero, and Fidel Ribera led the visit to a salt mine and the astonishing Cardona diapir outcrop. They gave details on the impacts of salt mining on the watersheds and buildings and provided information on remediation work.

Next year, the annual meeting of the Society will be held in Bilbao, in conjunction with the Spanish Society of Clays meeting.
SHORT COURSE “QUANTITATIVE MINERALOGY AND MICROANALYSIS OF SEDIMENTS AND SEDIMENTARY ROCKS”

The Mineralogical Association of Canada will offer a two-day short course on quantitative mineralogy and microanalysis prior to the GAC-MAC joint annual meeting to be held in St. John’s, Newfoundland. The purpose of this short course is to introduce geologists to modern technologies and techniques for the study of the petrography and mineralogy of sediments and sedimentary rocks. The approaches can provide new insights into the reconstruction of sedimentary paleoenvironments and basin architecture and the distribution of paleodrainage systems, with applications to mineral processing and oil and gas exploration. Many modern methods in mineralogy are focused on automation, visualization and microanalysis to produce quantitative data in a systematic and automated fashion, and the course will emphasize these developments. Quantitative data can include the identity, abundance, size, shape, ground-boundary association, and chemical and isotopic composition of detrital and authigenic minerals; the textural characteristics of sedimentary rocks, including porosity and permeability; and the distribution of chemical constituents between finely laminated layers of sediments. A particular goal will be to illustrate how mineral liberation analysis (MLA, and similar scanning electron microscope-based approaches, such as QEMSCAN and CCSEM) has evolved from a method developed for process ore mineralogy into a technique for quantitative studies of the petrography and mineralogy of sedimentary rocks in polished thin sections and sediments in polished grain mounts. Information on mineralogy from the MLA and spectroscopic and X-ray techniques links naturally to the in situ microanalysis of minerals, which is one of the most vibrant areas of geochemistry today.

Dates: Friday and Saturday, May 25–26, 2012
Prior to the GAC®-MAC joint annual meeting
Venue: Delta St. John’s Hotel and Conference Centre
St. John’s, Newfoundland, Canada
Organizer: Paul Sylvestre, Memorial University of Newfoundland, Canada
E-mail: psylvestre@mun.ca
Audience: Academics and students; government and industry researchers
Registration: http://stjohns2012.ca

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AIG-9 IN TARRAGONA, SPAIN

The IAGC cosponsored the 9th International Symposium on Applied Isotope Geochemistry (AIG-9) in Tarragona, Spain, held on September 18–23, 2011. The organizing committee, chaired by Albert Soler and Neus Otero, and the local organizing committee from the University of Barcelona (Carme Audi, Raul Carrey, Albert Folch, Massimo Marchesi, Jordi Palau, Roger Puig, Monica Rossell, and Clara Torrento) invited isotopists from around the world working on the applied aspects of isotope science to convene at the Ciutat de Tarragona Hotel in historic downtown Tarragona. This small city in the heart of Catalunya, with its historic splendors and World Heritage status, served as the perfect backdrop for the week’s scientific and social activities.

A total of 138 scientists from 24 countries participated in a plenary session lasting four days. The excellent scientific program centered on seven themes selected by the scientific committee composed of Ramon Aravena (University of Waterloo, Canada), Tom Bullen (USGS, USA), Isabel Cacho (University of Barcelona, Spain), Angels Canals (University of Barcelona, Spain), Ian Cartwright (Monash University, Australia), Matthew Fanta (Pennsylvania State University, USA), Neus Otero (University of Barcelona, Spain), Thomas Prohaska (Universität fur Bodenkultur, Austria), Martine Savard (Geological Survey of Canada, Canada), and David Widory (BRGM, France). The seven themes were:

1. Advances in Isotope Techniques and Instrumentation (keynote: “Instrumental approaches to improve accuracy and precision of isotope ratio measurements with laser ablation-multicollector ICP-MS,” by Bodo Hattendorf)
2. Isotope Signals of Climate Change (keynote: “Ventilation of the deep ocean since the last glacial period: Carbon cycle impacts,” by Luke Skinner)
4. Using Isotopes to Unravel Biogeochemical Cycles (keynote: “Our current understanding of silicon isotope biogeochemistry and its relevance to reconstructions of the silica cycle,” by Christina De La Rocha)
5. Isotope Hydrology (keynote: “The role of stable isotopes in tracing movement and reactions of CO2 at geological CO2 storage sites,” by Bernhard Mayer)
6. Isotope Geology (keynote: “An overview of the energy–water quality nexus: using isotopic tools to elucidate the impact of energy production on water resources in the U.S.,” by Avner Vengosh)

The wide range of oral and poster presentations illustrated the increasingly broad scope of applied isotope geochemistry and showed how isotopes are providing important new and unique information for unraveling scientific problems.

The IAGC Faure Award Committee for AIG-9 presented the award for the best oral presentation by a student to Geneviève Bordeleau, INRS-ETE, Canada (“Chlorine and carbon isotope measurements can help assess the effectiveness of a zero-valent iron barrier”). The awards include a $250 cash prize and a one-year complimentary IAGC membership.

The conference icebreaker was held in the Roman amphitheatre, which boasts an exceptional view of the Mediterranean Sea, and the conference dinner was located in the Roman Circus, with its mysterious atmosphere from 2000 years ago. A mid-conference field trip took participants to the central part of Catalunya and included a visit to a medieval castle and the innards of an old potash mine. A large group of accompanying members had an exceptional time visiting a variety of cultural sites throughout the week.

AIG-9 was fortunate to have several government and corporate sponsors in addition to IAGC, including the Gobierno de Espana-Ministerio de Educacion, Generalitat de Catalunya-Departament de Territori i Sostenibilitat, Agencia de Residus de Catalunya, Agencia de Gestio d’Ajuts Universitaris i de Recerca, Repsol, Thermo Scientific, Spectromat GMBH, Nu Instruments, Picarro Instruments, Elemental, and Vertex Technics. These sponsors were essential for increasing the involvement in the conference of students and participants from disadvantaged countries.

IAGC Vice-President Richard Wanty congratulates Best Student Oral Presentation winner Geneviève Bordeleau and Best Student Poster Presentation winner Stefan Cretnik.}

Don’t forget to renew your IAGC membership for 2012!
Visit www.IAGC-Society.org and click on “Society, Membership” for payment options.

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RECENT ACTIVITIES

AIPEA is an umbrella organization for the world’s national clay societies. It organizes the International Clay Conference, which occurs every four years, and strives to encourage and support young researchers. In order to maintain a continued presence in the careers of young researchers, AIPEA actively participates in the Euroclay Conference, which is held between the International Clay Conferences. The most recent Euroclay meeting was jointly organized by the Turkish National Committee on Clay Science and the European Clay Groups Association (ECGA), and took place in Antalya, Turkey, from 26 June to 1 July, 2011. The conference theme, “Clay Science at the Crossroads of Civilisation,” was very popular and attracted over 350 oral presentations and posters addressing the topics of clay geology, clay mineralogy, the methods of clay research, the properties of clays and clay minerals, the modification/interaction of clay minerals, applications, nanoclays and nanoscience, and non-clay fine-grained materials.

During the previous Euroclay meeting, held in Aveiro in 2007, AIPEA inaugurated a programme of student awards. These cash awards were distributed at the Aveiro meeting and at the last International Clay Conference, in Castellana Marina in Italy, in 2009. The standard of competition at the Euroclay Conference in Antalya was extremely high, and this made the judging especially difficult but very rewarding at the same time. After much deliberation, the worthy winners were chosen: Yohei Ishida (Tokyo Metropolitan University, Japan) took first place for his talk “Visible light-harvesting ability of cationic dyes assembly on an anionic clay surface: The effect of adsorption conditions.” Laure Delavennhe (Institut des Matériaux Jean Rouex, France) was runner-up with her paper “Relationship between macroscopic water affinity of kaolinites and their surface properties.” Natalia Matskova (Lomonosov Moscow State University, Russia) took first place for her poster entitled “Characteristics of palygorskite clays from the Dahkovskoe industrial deposit (Moscow region, Russia).” Mazen Ziadeh (University of Bayreuth, Germany) received the runner-up award for his poster entitled “A facile approach for producing high aspect ratio fluorhectorite nanoplatelets by utilizing a stirred media mill.”

AIPEA will hold its next meeting in Rio de Janeiro, Brazil, in June 2013. The meeting is being organized jointly with the Brazilian Clay Group, a member of the Sociedade Brasileira de Geoquimica, with the very welcome involvement of Petróleo Brasileiro S.A., Petrobras. Rio will provide an excellent backdrop for another great opportunity for mineralogists, soil scientists, physicists, geochemists, engineers, chemists, materials scientists and other specialists to debate their findings, share ideas and transfer knowledge.

With the 15th ICC now on the horizon, it is a good time to visit the AIPEA website (www.aipea.org) and refresh your knowledge regarding the different awards. Council is particularly keen that the student travel awards, which AIPEA provides every four years to ensure that the best young scientists are able to attend the International Clay Conference, are well publicized within the student community.

Chris Breen, President

UPCOMING POLISH CONFERENCES

The Geochemical Group of the Mineralogical Society of Poland and the Institute of Chemistry, Jan Kochanowski University in Kielce, will convene the second “Contemporary Problems of Geochemistry” conference in Kielce on September 24–26, 2012. The theme of this conference will be the application of geochemical, mineralogical, and petrological studies in environmental sciences and will include the following topics:

- geochemical interactions in/between various environmental systems
- identification of natural and anthropogenic pollution sources
- establishment of background concentrations
- analytical methods used for solving various environmental issues
- other environment-oriented aspects

Details on registration, the program, and events are available on the website www.ujk.edu.pl/geochronology2012.

The Mass Spectrometry Laboratory, Maria Curie-Skłodowska University in Lublin, the Institute of Chemistry, Jan Kochanowski University in Kielce, and the Geochemical Group of the Mineralogical Society of Poland will hold the 11th geochronological conference “Dating of Minerals and Rocks XI” in Kielce, September 26–27, 2012. The conference will be the latest in a series of all-Polish symposia on the theme of geochronology. The main topics for this conference will include:

- U–Pb, U–Th, Rb–Sr, K–Ar, 40Ar–39Ar, 210Pb, and other isotope dating methods
- non-isotope dating, including fission track, chemical Th(U)–Pb dating, TL and OSL methods
- stable isotopes (strontium, sulfur, etc.) related to dating of geologic materials

The conference program will include a tour of a Neolithic flint mine at Krzemionki and the Romanesque Cistercian abbey at Wachock. Details on registration, the programs, and events are available on the website www.ujk.edu.pl/geochronology2012.
Industrial minerals are geological materials mined for their commercial value. The term does not include gemstones or materials used as fuels or as sources of metals. Industrial minerals are generally used after beneficiation and/or comminution as raw materials or as additives in a multitude of applications in the ceramic, construction, paint, polymer, adhesive, paper and packaging industries, among others. Industrial minerals are used in large quantities – for example, over 25 Mt of kaolin, 37 Mt of gypsum and 75 Mt of calcium carbonate are consumed annually – and most applications depend critically on specific physical and/or chemical properties. Hence, characterization of these materials is of fundamental importance for determining the overall economic potential of a deposit/business or the applicability and value of a sample for a specific use.

In July 2009, the EMU-Erasmus IP School “Advances in the Characterization of Industrial Minerals” was held in the Technical University of Crete, Greece. The chapters in the volume reviewed here were the main topics addressed in the School. The book, edited by George Christidis, is organised into three parts. After an introductory section, the bulk of the text deals with a range of experimental techniques used to characterise physical and chemical properties, while the final section deals with some selected industrial minerals and synthetic materials.

The Introduction, by George Christidis, is rather short (10 pages). It sets the scene, covering definitions, value, competition/substitution, specifications and standards, environmental constraints and economic aspects.

Each of the seven chapters of the Experimental Techniques section is highly readable and authoritative, though not always comprehensive. I did also wonder whether the first of these chapters (“The Geological Setting for Industrial Mineral Resources”) might have been better placed in the Introduction. Peter Scott’s way of classifying minerals by market characteristics (value, scale, etc.) would be a real eye-opener for many, I expect. The XRD chapter (Bish and Plötze) is extremely realistic about what can be achieved. For example, quantification using the Rietveld method is described well, but the authors note that “the ability to consider 2D diffraction effects would considerably enhance the ability of this powerful method to analyse complex mixtures containing clay minerals.” The particle size and shape chapter (Hart, Zhu and Pirard) is comprehensive, covering theoretical and practical matters well. However, we might have benefited from even more information on particle shape, as it controls performance in many applications. The chapter on vibrational spectroscopy (Madejová, Balan and Petit) is excellent, particularly when describing IR applications to clay minerals. A minor criticism is that other minerals are not covered in the same depth. The electron microbeam chapter is also exceptional in what it covers, although, as the authors (Pownceby and Macrae) acknowledge, TEM methods are not covered in detail. Almost all large-volume and high-value applications of industrial minerals involve composites with particles dispersed in other continuous phases. Imaging and imaging analysis have become absolutely key for generating useful information in realistic time frames so that understanding the performance of the composite can be achieved. The chapter by Pirard and Sardini covers both aspects really well. Every reader will learn something new.

Overall, the text is remarkably free of typographical errors. The figures are almost all of good quality and the reference lists at the end of each chapter are wide ranging and useful. The original aim was to produce a reference textbook for university-level courses. The book will meet this target and will also be extremely valuable for postgraduates and scholars interested in these materials and their uses. Not only will the text be valuable to those starting industrial careers, it will also stimulate thought and action by those with years of industrial experience. I recommend the book highly for its authority, clarity, and practicality, and as a stimulus for future work.

John Adams, School of Engineering and Computer Science, University of Exeter, UK
This very attractive new atlas is based on a Catalan precursor volume, *Atlas d'associacions minerals en làmina prima*, and its Spanish counterpart, both of which are out of print. The original editions were published in 1997 with generous support from the Folch Foundation, which was established in honor of Dr. Joaquin Folch i Girona (1891–1984) for his significant contributions to the systematic mineralogical exploration of Catalonia.

Special Publication 7 of *The Canadian Mineralogist* captures the beauty and magic of non-silicate minerals in thin section. With its wealth of mineralogical data and its stunning photographs, it goes well beyond being a mere reference book for researchers and students. It also invites the casual reader to explore the secret universe of minerals through optical microscopy, a key subdiscipline of geology, which, however, is now unfortunately disappearing from the core Earth science curriculum of many universities. It is encouraging to see that a mining company (Osisko Mining Corporation) supported the publication of this book, thus demonstrating that careful microscopic investigations are of interest to the industry as well.

The book describes more than 400 non-silicate minerals, which were selected for their overall petrographic, economic or environmental importance. A special treat is that nearly eighty of the described and depicted minerals are from the respective type localities. The organization of the contents of this volume follows the new Dana classification of minerals (Gaines et al. 1997). It presents Dana’s classes 1 through 50 in 16 chapters, which correspond to the various mineral groups. The book was assembled by Joan Carles Melgarejo and Robert F. Martin, but most of the chapters contain significant contributions from ten fellow mineralogists (acknowledged on pages 17–19).

Before presenting the selected minerals, each chapter starts with a concise introduction into the mineral group and provides a summary on general aspects, such as physical properties, occurrence, petrogenetic and metallogenetic implications, and industrial applications. It notably also addresses environmental aspects of each mineral group, which adds a modern touch, as it sets the stage for an increasingly important part of mineral sciences, namely, environmental mineralogy. The introductory pages also provide a valuable table of contents, which lists all selected minerals, ordered according to their Dana number, with their name and formula as approved by the International Mineralogical Association and their Strunz classification. Each chapter introduction also presents important references for the mineral group as a whole. Fortunately, the book includes an alphabetical index, which helps those readers who are less virtuoso in dealing with the Dana numbers.

The presentations for each mineral are well organized and arranged in an appealing layout, typically on one page. Following the name and formula, basic crystallographic information is provided, including unit-cell constants and some of the most intense peaks observed in powder X-ray diffraction patterns. The authors also suggest elements that should in general be analyzed. These entries are followed by information on optical characteristics and habit, and by features that allow for distinction from similar or related minerals.

Especially valuable are the entries on known occurrences and parageneses of the minerals. This information has been very carefully researched and is supported by an excellent selection of references, which have been chosen to reflect the different geological environments in which the minerals occur. For this reason, the number of references varies widely for different mineral species. Additional references containing structural details of each mineral are given at the end of the description. The invaluable references make this book an ideal starting point for researchers who are beginning to investigate a mineral they have never seen before.

The stunning microscope images were chosen to demonstrate the most valuable distinguishing features of a given mineral. The photomicrographs show the mineral of interest in both singly and doubly polarized light and in various assemblages. In many cases, a second image in plane-polarized light, but with the polarizer rotated by 90º relative to the first image, is provided in order to show pleochroism. More than one page is allocated to some of the most common species (e.g. calcite, gypsum), because the authors wanted to document additional types of occurrences, textures, or assemblages. Unfortunately, scale bars are missing in many pictures. Even though the information on size is available in the figure captions, it would have been much nicer and easier for the reader if all pictures were presented in a consistent manner, i.e. with scale bars appearing on the actual images. Moreover, labels that identify the different minerals visible in the photographs are almost entirely absent. Many of the images would have benefited from such labels.

Particularly noteworthy is that this volume showcases minerals that are neglected in many other publications, namely, diverse species in the borate, phosphate, arsenate, and vanadate groups, a range of minerals occurring primarily in mine waste environments, and a selection of more common organic minerals, presented in chapter 17. This chapter also discusses a shortcoming of the Dana classification, in which all organic minerals are grouped into one class, even though various ionic and molecular groups can be distinguished.

The enclosed CD contains all the photomicrographs presented in the book. It represents a precious resource for the classroom and scientific presentations. The pictures do not appear in the same order as in the book; rather, they are alphabetically ordered within each group. Moreover, in those cases where scale bars are either missing or not labeled, one has to find the size information in the book. These two points make the use of the otherwise valuable CD a bit cumbersome.

This superbly illustrated book is of great interest to all geoscientists. Rather than keeping it on your shelf, however, it would be much better to place it on your coffee table, so that you can browse through it again and again. Immerse yourself in the fascinating and colorful world of non-silicate minerals under the polarizing microscope!

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Institut für Geowissenschaften, Albert-Ludwigs-Universität
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**REFERENCE**

A four-day short course entitled Advanced Tools in Environmental Biogeochemistry was held one week before the Goldschmidt 2011 Conference in Prague. It was generously funded by the European Association of Geochemistry (EAG), the Functionality of Iron Minerals in Environmental Processes Network (FIMIN) and the National Science Foundation (NSF). The short course was given by international experts in the field of biogeochemistry and was complemented by a one-day tour of the nearby synchrotron facility “Anka.” “All participants will be able to learn most from an interactive workshop. This is why we have reserved plenty of time for coffee breaks and social activities, and we will provide the participants with the opportunity to analyze their own samples at the synchrotron,” said Andreas Kappler, professor of geomicrobiology at the University of Tübingen and one of the co-organizers, prior to the start of the course. “But I also expect to learn something about the techniques I am less familiar with myself,” he added. Ruben Kretzschmar, professor of soil chemistry at ETH Zürich, and Thomas Borch, associate professor of environmental soil chemistry added. The 20 participants, all graduate students in chemistry, geology, environmental microbiology or related fields, came from five different countries. During the course, scientists from the University of Tübingen, the CNRS in Paris, Colorado State University and ETH Zürich described their techniques of expertise and also provided some practical demonstrations with the instruments. The topics covered a broad range, including the function and application of microelectrodes in biogeochemical studies, Mössbauer spectroscopy, secondary-ion mass spectrometry, and various microscopy techniques, such as confocal Raman, transmission electron (TEM), focused ion beam/scanning electron transmission (FIB/SEM) and scanning transmission X-ray (STXM) microscopy. After two days of presentations and discussions of possible applications of the individual techniques, the visit to the synchrotron beamlines at Anka in Karlsruhe was a highlight of the course.

The success of the course would not have been possible without the generous funding by EAG, FIMIN and the NSF, which enabled not only the invitation of speakers and participants from all over the world but also hiring student helpers who were involved in copying the course material, preparing coffee breaks, and ensuring that everything worked smoothly. The organizers and participants would like to thank all funding parties.

Further details and additional pictures can be found on the EAG website at www.eag.eu.com/education/shortcourse/.

Maren Emmerich
University of Tübingen, Germany

EAG SHORT COURSE SERIES – ADVANCED TOOLS IN ENVIRONMENTAL BIOGEOCHEMISTRY
‘Spoil’ can be used as a verb or a noun and has many meanings. You can spoil a child by excessive indulgence, spoil a ballot paper by marking it improperly, plunder a nation and head home with your spoils, or dig a mine and surround it with spoil. Among the general public and in the press, new mining developments are almost always seen in a negative way, as operations that spoil landscapes irretrievably. In contrast, while we recognize that agriculture can change landscapes, the changes are usually seen as acceptable or even positive.

The truth is rather different. In densely populated countries, agriculture and urbanization have spoiled landscapes on scales compared to which the effects of mining are trivial. This was brought home to me on a trip to southern New Mexico when we passed the colossal El Chino porphyry copper mine, one of the largest in the world. The pit is over 400 m deep and covers 5 by 3.5 km at surface. Trucks carrying 360-tonne loads shift 439,000 tons of rock each day, of which about half is waste. It seems to represent despoliation on a gigantic scale. But, as my host, Matt Heizler, pointed out at the time, in the context of New Mexico, it is a tiny blemish. New Mexico has half the land area of France and a population of just over 2 million. Overwhelmingly, most of its immense, sunburned landscape remains truly unspoiled.

Not so the landscape that you see when, after crossing the Atlantic, you emerge from the clouds over southern England. That landscape, intensely green, with its ancient and irregular patchwork of fields (inhabited, as we know, by Hobbits!), is totally spoiled. Not one turf is untouched by Man. The locals, however, do not see it in this way. Propose a new motorway or a housing development, and they rise up and protest that their unspoiled countryside is under threat. It is indeed very pretty, and if I lived there I might join such an uprising myself, but unspoiled it is not. The scenery of almost all of England (and much of mainland Europe) has been modified irreversibly by Man over thousands of years.

Even the least populated parts of the United Kingdom, regions that most people would consider to be ‘wild’, have been changed much by agriculture but little by mining. I am sitting in the Lochaber district of Scotland, 4648 km² in area, where the population density is 4.04 people per km², less than that of New Mexico (6.54). The starting gun for records of human activity in Lochaber was fired only 10,500 years ago when the last ice sheet melted. The oldest signs of human occupation are 9500-year-old bloodstone (chalcedony) implements and carbonized hazelnuts from the island of Rum, best known for its spectacular layered gabbro intrusion. Bloodstone implements from Rum are widely distributed in Mesolithic Scotland, so mining reaches right back to the end of the last glacial episode, and predates organized agriculture.

Today most of the Scottish Highlands is treeless mountains and blanket bogs, but 5000 years ago it was covered by a great mixed forest. Hardy Scots pine grew on all but the highest and steepest mountainsides, and dense oak woods lined the fjord coastlines. About 4000 years ago early farmers with grazing animals arrived. They burned and cleared forests to encourage growth of heather for their stock, and grazing in turn inhibited regeneration of the forest. By the time the Romans arrived, 50% of the great forests were gone. They reached an all-time low in the 18th century, and overgrazing by sheep and deer has ensured that the hills remain barren. Today only about 1% of the original native pine woods remains. The main industry is tourism, and while the combination of coastline and bare mountains facing out to the Western Isles is wild, dramatic and beautiful, only the hard rocks are truly natural.

So, what has been the contribution of mining to the spoiling of Lochaber? In the Iron Age, bog iron ore – iron hydroxides precipitated by bacterial action – was smelted on rough hearths using wood or charcoal. Hearths in surviving forests can be identified by expert eyes, and many have been assigned to the 13th to 16th centuries. In the early 18th century, a lead–zinc mine was opened near the village of Strontian, leading to the discovery of the element strontium (see Elements 4: 216) and leaving sporadic workings and isolated spoil heaps (mostly of baryte) over an area of perhaps 15 km². Today, apart from two small quarries for road metal and limestone, there are two active mining operations, one small and one very large.

A white Cretaceous sandstone is mined near the pretty coastal village of Lochaline. It is 99.8% pure quartz, one of the purest silica-sands in the world. The 12 m thick sandstone, which has undergone virtually no diagenesis, is soft, and the middle 5 m are extracted by blasting and
simple shovelling. The mine was opened in 1940, during the Second
World War, to provide quartz for optical glass for gunsights and peri-
sopes. Today, 12 men extract the sand for high-quality speciality-glass
products. It is loaded directly onto small ships, there is no surface spoil,
and the product is chemically as inert as any rock can be.

The other operation is much larger. The Glensanda superquarry is cut
into granite near the west shore of Loch Linnhe, the deep fjord that
follows the line of the Great Glen transcurrent fault, a terrane boundary
that runs SW–NE across the Highlands. It is the largest granite quarry in
Europe and began operation in 1986 when the first load of granite was
shipped to Houston, Texas. Since then, 120,000,000 tonnes of crushed
granite have been shipped to many destinations. It was used during
building of the Channel Tunnel, and recently a record single load of
93,665 tonnes was sent in one of the quarry’s dedicated self-unloading
ships to Rotterdam, where it is being used in a major port extension.

Remarkably, this massive quarry and its loading facility are almost
invisible from any road or inhabited place. You can spot them from
certain viewpoints, and there are complaints about distant light pol-
lution during our 18-hour winter nights, but the uninformed holiday
visitor will be unaware of their presence. Glensanda cannot be reached
by road, and a walk-in is a 30 km round trip. The 160-strong workforce
comes and goes by sea. The trick used to minimise visual impact was to
site the quarry 2 km inland and 500 m above sea level. Blasting brings
down about 70,000 tonnes of granite per bang, and this is transported
by truck to a crusher in which it is reduced to 20 cm pieces. It is then
carried by conveyor to the Glory Hole, a 300 m vertical shaft 3 m in
diameter, which is permanently full of crushed fragments. Deep inside
the mountain, these are transferred to a horizontal conveyor, moved
through a 1.6 km tunnel to a second crusher and loaded onto ocean-
going ships at the rate of 6000 tonnes per hour.

So, who has spoiled Lochaber the most? Late Neolithic Man, the first
agriculturalists, or Modern Man with his insatiable demand for raw
materials? By a large margin it is our forebears of 4000 years ago.

Ian Parsons  (ian.parsons@ed.ac.uk)
University of Edinburgh

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PARTING QUOTE

In science the credit goes to the man who convinces the world,
not to the man to whom the idea first occurs.

Francis Darwin 1848–1925

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<table>
<thead>
<tr>
<th>Company</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activation Laboratories (Actlabs)</td>
<td>371</td>
</tr>
<tr>
<td>Australian Science Instruments (ASI)</td>
<td>372</td>
</tr>
<tr>
<td>Bruker</td>
<td>392</td>
</tr>
<tr>
<td>Energy Frontier Research Center</td>
<td>373</td>
</tr>
<tr>
<td>Excalibur Mineral Corporation</td>
<td>371</td>
</tr>
<tr>
<td>FEI</td>
<td></td>
</tr>
<tr>
<td>Geological Society</td>
<td>371</td>
</tr>
<tr>
<td>Rocks &amp; Minerals</td>
<td>392</td>
</tr>
<tr>
<td>RockWare</td>
<td>374</td>
</tr>
<tr>
<td>Savillex</td>
<td></td>
</tr>
<tr>
<td>SPECTRO</td>
<td>369</td>
</tr>
<tr>
<td>Springer</td>
<td>427</td>
</tr>
<tr>
<td>The Geochemist’s Workbench</td>
<td></td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Position</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Science Foundation</td>
<td>432</td>
</tr>
</tbody>
</table>

See www.elementsmagazine.org/jobpostings
Mapping the world ... one micron at a time

Estuarine mud from the Hayle Estuary, Cornwall, UK, collected by coring, showing distinct layering attributed to the impact of historical mining. Pre-mining sediments in purple (mostly marine-derived carbonate sands) are over lain by laminated muds (brown/red-purple) containing heavy minerals such as cassiterite, pyrite, chalcocystite, sphalerite and galena.
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