Distilling Ultra-Pure Acid Just Became
Ultra-Quick › Ultra-Easy ›
Ultra-Affordable

Savillex DST-1000
Sub-Boiling Distillation System

The DST-1000 features:
- Wetted parts of molded PFA
- No cooling water required
- Controlled, gentle heating
- Elegant, compact design
- Built-in waste drain

View the DST-1000 in action online at www.savillex.com.

Savillex Corporation has been proudly serving the Geochemistry community for over 30 years. We are committed to providing high-quality PFA labware solutions for all your sample analysis needs.
Tel: 952-935-4100
www.savillex.com
Sustainable Soil Remediation
Guest Editor: Mark E. Hodson

The Need for Sustainable Soil Remediation
Mark E. Hodson

Organic Amendments for Remediation: Putting Waste to Good Use
David L. Jones and John R. Healey

Mineral-Based Amendments for Remediation
Peggy A. O’Day and Dimitri Vlassopoulos

Assisted Phytoextraction: Helping Plants to Help Us
Filip M. G. Tack and Erik Meers

Bioremediation: Working with Bacteria
Blanca Antizar-Ladislao

Nanoparticles for Remediation: Solving Big Problems with Little Particles
Nicole C. Mueller and Bernd Nowack

About the Cover:
Sustainable soil remediation has many faces. At this site in Belgium, willow is grown and harvested to remove metals from the contaminated soil and give a commercial crop. Conventional remediation treatments were uneconomic for the area.

Photo: Stijn Van Slycken, used by permission

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

Elements is published six times a year. Individuals are encouraged to join any one of the participating societies to receive Elements. Institutional subscribers to any of the following journals—American Mineralogist, Clay Minerals, Clays and Clay Minerals, Mineralogical Magazine, and The Canadian Mineralogist—also receive Elements as part of their 2010 subscription. Institutional subscriptions are available for US$160 (US$175 non-US addresses) a year in 2010. Contact the managing editor (tremblpi@ete.inrs.ca) for information.

Copyright 2010 by the Mineralogical Society of America

All rights reserved. Reproduction in any form, including translation to other languages, or by any means—graphic, electronic or mechanical, including photocopying or information storage and retrieval systems—without written permission from the copyright holder is strictly prohibited.

Publications mail agreement no. 40037944
Return undeliverable
Canadian addresses to:
PO Box 503
RPO West Beaver Creek
Richmond Hill, ON L4B 4R6

Printed in Canada
ISSN 1811-5209 (print)
ISSN 1811-5217 (online)

www.elementsmagazine.org
The Mineralogical Society of America is composed of individuals interested in mineralogy, crystallography, petrology, and geochemistry. Founded in 1919, the Society promotes, through education and research, understanding and application of mineralogy by industry, universities, and the general public. Membership benefits include special subscription rates for American Mineralologist as well as other online resources and reviews in Mineralogy & Geochemistry series and Monographs, Reduction registration fees for annual meetings, and discounted and free registration for students. The Society is also involved in the following activities: publishing the quarterly Journal of Geochemical Education, the monthly Geochemical News, and the annual Geochemical Transactions; administering the Geochemical Society of America Awards and the Geochemical Society of America Scholarships; organizing international conferences and workshops; and developing and supporting student development programs.

The Clay Minerals Society (CMS) began as the Clay Mineralogists Section of the National Academy of Sciences – National Research Council in 1925. In 1952, the CMS was incorporated with the purpose of promoting research and disseminating information relating to all aspects of clay science and technology. The CMS organizes annual meeting, workshop, and field trips, and publishes Clay and Clay Minerals and the CMS Workshop Lectures series. Membership benefits include reduced registration fees for annual meetings, discounts on the CMS Workshop Lectures, and subscriptions to Clay and Clay Minerals.

The Clay Minerals Society

The European Association of Geochemistry (EAGE) is the international association of geochemists in Europe. It is now recognized as the premiere study of geochemistry as it relates to exploration geochemistry. Our community reflects the broad range of geochemical research, teaching and research as well as the personal relationships among all geochemists. The European Association of Geochemistry is committed to providing opportunities for geochemists from all parts of the world to meet and to exchange ideas, and to disseminate information through refereed publication and conference proceedings. Membership benefits include refereed publication and conference proceedings.

The European Association of Geochemistry

The Society of Petrology and Economic Geology (SPEG) was founded in 1962 to promote and advance study, research, and teaching in the fields of petrology, geochemistry, and economic geology. The Society promotes links between the science, education and technology through annual conferences, held trips, invited lectures, and publications. Membership benefits include subscriptions to Mineralogical and Economic Geology.

The Society of Petrology and Economic Geology

The Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), founded in 1925, brings together professionals and amateurs interested in mineralogy, crystallography, petrology, and geochemistry. The Society promotes links between the science, education and technology through annual conferences, held trips, invited lectures, and publications. Membership benefits include subscriptions to Mineralogical and Economic Geology.

The Polskie Towarzystwo Mineralogiczne

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

The Swiss Society of Mineralogy and Petrology

The Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), founded in 1925, brings together professionals and amateurs interested in mineralogy, crystallography, petrology, and geochemistry. The Society promotes links between the science, education and technology through annual conferences, held trips, invited lectures, and publications. Membership benefits include subscriptions to Mineralogical and Economic Geology.

The Polskie Towarzystwo Mineralogiczne

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

The Società Italiana di Mineralogia e Petrologia

The International Association of Geoanalysts (IAGA) is a worldwide organization supporting the professional interests of those involved in the analysis of geological and environmental materials. Activities include the management of proficiency testing programmes for bulk rock and micro-analytical methods, the production and circulation of reference materials and the publication of the Association's journal, Geoanalysts' Newsletter, and Geochemical Research.

The International Association of Geoanalysts

The Society of Geoanalysts (SGA) acts as an umbrella for other groups in the fields of mineralogy, geochemistry, and petrology, but that do not themselves have a membership base.

The Society of Geoanalysts

The Clay Minerals Society

The Clay Minerals Society was founded in 1955 in order to promote and advance the knowledge of the science of clay mineralogy and to foster cooperation in the advancement of applied clay mineralogy. The Society organizes annual meeting, workshop, and field trips, and publishes Clays and Clay Minerals and the CMS Workshop Lectures. Membership benefits include reduced registration fees for annual meetings, discounts on the CMS Workshop Lectures, and subscriptions to Clays and Clay Minerals.

The Clay Minerals Society

The Polish Society of Geological Sciences in the Earth and Planetary Environment is an international organiza-
WE’VE COME A LONG WAY

The theme of this issue makes me think back on the relationship between geochemistry and soil science and how it has evolved. When I started working on weathering processes and clay mineral formation back in the 1960s, there was remarkably little communication between geochemists and soil scientists. From a geochemist’s perspective, soil scientists (with a few very notable exceptions) were not interested in the same set of questions as us. They were concerned with nutrients and organic matter, whereas geochemists studied silicate mineralogy and major element chemistry. We had little interest in nutrients and paid almost no attention to biology. Geochemistry, in this context, was an inorganic science. Furthermore, to geochemists, the terminology of soil classification, in the United States at least, seemed an impenetrable barrier. As an extreme example, I was involved in a PhD thesis in France many years ago on the subject of chemical weathering. A boundary was drawn at 60 cm depth below the ground surface. Below 60 cm was the realm of soil science/geology; above 60 cm was the proper domain of the geology department; and that geochemists need to become involved with issues of environmental sustainability. The future habitability of our planet depends on understanding and managing its surfaces. Our understanding of surfaces, adsorption processes, and contaminant migration on the field scale comes largely from the geochemical/environmental chemistry community, and geochemical codes such as MINTEQ and PHREEQC are the workhorses for modeling contaminant migration.

Another important topic is the adhesion of microbes to mineral surfaces: will microbes stay in place or be transported by infiltrating water? What electron acceptors and donors are present and how reactive are they? We need expertise in both mineralogy and microbiology. Geochemists and mineralogists have become deeply involved in environmental questions, and we should become more involved, particularly in projects that bring together the various disciplines involved in understanding Earth surface processes. The future habitability of our planet depends on understanding and managing its surface layers.

* Tim Drever was the principal editor in charge of this issue.
THIS ISSUE

When it comes to soil remediation, sustainability makes a lot of sense. We cannot afford to condemn soils, as in the dig-and-dump approach, mentioned by guest editor Mark Hodson. We need to preserve this precious resource to feed the ever increasing world population. The authors of this issue share with their readers the accomplishments and challenges of sustainable soil-remediation research. Many good ideas turn out to be challenging under the wide range of possible field conditions, and much research is still needed to bring these promising concepts to maturity. It is also abundantly clear that the ideal scenario would be to avoid polluting this resource in the first place, as there is a risk and a cost attached to any remediation scenario.

Six Years Old!

With this issue, Elements closes its sixth year of publication. In 2010, we published 38 thematic articles and 2 perspective articles, contributed by 64 coauthors from 13 countries. We have now covered 35 topics in the Earth sciences, and there seems to be no shortage of ideas for the future. Our lineup is complete till the middle of 2012. We have many proposals on hand, and we always welcome new ones. The next two pages offer a preview of the exciting topics we are going to cover next year. We work hard at selecting topics so that there is something for everyone in this mix of review and leading-edge science.

Thanks

We thank the guest editors (names in bold) and the authors of volume 6 who have made a special effort to bring their science to the non-specialist audience of Elements: Blanca Antizar-Ladislao, Håkon Austrheim, Wolfgang Bach, Costanza Bonadonna, Andreas Bott, Peter R. Bouseck, James A. D. Connolly, Reid F. Cooper, Edward Derbyshire, Volker Dietze, Benjamin R. DiTullo, Patricia M. Dove, Adam J. Durant, Niles Eldredge, Johann P. Engelbrecht, Guenter Engling, John M. Ferry, Gretchen L. Früh-Gress, Santiago Gasso, Andras Gelencsér, Reto Gieré, Benjamin C. Gill, Vicki H. Grassian, Bernard Grobety, Robert M. Hazen, John R. Healey, Grant S. Henderson, Mark E. Hodson, Tim Holland, Claire J. Horwell, Bjorn Jamtveit, Timm John, David T. Johnston, David L. Jones, Penelope L. King, Namhey Lee, Timothy W. Lyons, Charles W. Mandeville, Timothy J. McCoy, Scott M. McLennan, Erick Meers, Nicole Métrich, Ron L. Miller, Frank J. Millero, Nicole C. Mueller, Daniel R. Neuvile, Bernd Nowack, Peggy A. O’Day, Clive Oppenheimer, Giulio Ottonello, Dominic Papineau, Roger Powell, Andrew Putnis, Xavier Querol, Pascal Richet, Surenda K. Saxena, Hendrik Schatz, Peter Stille, Henrik Svensen, Dimitrii A. Sverjensky, Filip M. G. Tack, Alan B. Thompson, Dimitri Vlassopoulos, and Pierpaolo Zuddas. We also acknowledge the contribution of reviewers, copy editors, and proofreaders who toil in the background.


Pierrette Tremblay, Managing Editor
David Vaughan, Hap McSween, and Tim Drever, Principal Editors

FROM THE EDITORS

Back issues of Elements for the classroom

Order online at www.elementsmagazine.net
Iron is the fourth most abundant element at the Earth's surface. As an essential nutrient and electron source/sink for the growth of microbial organisms, it is metabolically cycled between reduced and oxidized chemical forms. This flow of electrons is invariably tied to the reaction with other redox-sensitive elements, including oxygen, carbon, nitrogen, and sulfur. The end result of these interactions is that iron is intimately involved in the geochemistry, mineralogy, and petrology of modern aquatic systems and their associated sediments, particulates, and pore waters. In the geological past, vast iron sediments, the so-called banded iron formations, suggest that iron played an even greater role in marine geochemistry, and these deposits are now being used as proxies for understanding the chemical composition of the ancient oceans and atmosphere. This issue will explore not only the modern expression of iron cycling but also its record in Earth's history.

The ageing–rejuvenation cycle
Kevin G. Taylor and Kurt O. Konhauser

A major player in chemical and biological processes
Robert R. Raiswell

Iron transport from the continents to the open ocean
Kurt O. Konhauser, Andreas Kappler (University of Tübingen), and Eric E. Roden (University of Wisconsin–Madison)

Ferruginous oceanic conditions:
Simon W. Poulton (Newcastle University) and Donald E. Canfield (University of Southern Denmark)

Geomicrobiology of iron in extreme environments
Alexis Templeton (University of Colorado)

Iron in marine sediments:
Minerals as records of chemical environments
Kevin G. Taylor and Joe H. S. Macquaker (Memorial University of Newfoundland)

Iron in Earth surface systems:
A major player in chemical and biological processes
Kevin G. Taylor and Kurt O. Konhauser

Iron transport from the continents to the open ocean:
The ageing–rejuvenation cycle
Robert R. Raiswell (University of Leeds)

Iron in microbial metabolisms
Kurt O. Konhauser, Andreas Kappler (University of Tübingen), and Eric E. Roden (University of Wisconsin–Madison)

Ferruginous oceanic conditions:
A dominant feature of the ocean through Earth’s history
Simon W. Poulton (Newcastle University) and Donald E. Canfield (University of Southern Denmark)

Geomicrobiology of iron in extreme environments
Alexis Templeton (University of Colorado)

Iron in marine sediments:
Minerals as records of chemical environments
Kevin G. Taylor and Joe H. S. Macquaker (Memorial University of Newfoundland)

COSMOCHEMISTRY

THEMATIC TOPICS IN 2011

COSMOCHEMISTRY

Guest Editor: Dante S. Lauretta (University of Arizona)

Cosmochemistry is the study of extraterrestrial materials aimed at understanding the nature of Solar System bodies, including the planets, their natural satellites, and small bodies. An important goal is to increase our understanding of the chemical origin of the Solar System and the processes by which its planets and small bodies have evolved to their present states. Research in cosmochemistry covers a wide range of disciplines and techniques, including mineralogy, petrology, major and trace element chemistry, isotope compositions, radiometric ages, magnetism, and radiation-exposure effects. These studies provide a wealth of data about the processes of stellar evolution, planetary system formation, alteration in asteroidal and cometary interiors, and the accretion history of the Earth, including the origin of Earth’s volatile and organic material.

• A cosmochemical view of the Solar System
  Dante S. Lauretta

• Presolar history recorded in extraterrestrial materials
  Ann Nguyen (Johnson Space Center) and Scott Messenger (ESCAG/Jacobs Technology)

• The asteroid–comet continuum: In search of lost primitivity
  Matthieu Gounelle (Museum National d’Histoire Naturelle, Paris)

• Organic chemistry of carbonaceous meteorites
  Zita Martins (Imperial College London)

• Stable isotope cosmochemistry
  Douglas Rumble (Geophysical Laboratory), Ed Young (UCLA), Anat Shahar (Geophysical Laboratory), and Weifu Guo (Geophysical Laboratory)

• Chronometry of meteorites and the formation of Earth and Moon
  Thorsten Kleine (Westfälische Wilhelms-Universität Münster) and John F. Rudge (University of Cambridge)

GLOBAL WATER SUSTAINABILITY

Guest Editors: Janet Hering (Eawag), Chen Zhu (Indiana University), and Eric H. Oelkers (CNRS, Toulouse)

Iron in Earth surface systems:
A major player in chemical and biological processes
Kevin G. Taylor and Kurt O. Konhauser

Iron transport from the continents to the open ocean:
The ageing–rejuvenation cycle
Robert R. Raiswell (University of Leeds)

Iron in microbial metabolisms
Kurt O. Konhauser, Andreas Kappler (University of Tübingen), and Eric E. Roden (University of Wisconsin–Madison)

Ferruginous oceanic conditions:
A dominant feature of the ocean through Earth’s history
Simon W. Poulton (Newcastle University) and Donald E. Canfield (University of Southern Denmark)

Geomicrobiology of iron in extreme environments
Alexis Templeton (University of Colorado)

Iron in marine sediments:
Minerals as records of chemical environments
Kevin G. Taylor and Joe H. S. Macquaker (Memorial University of Newfoundland)

GLOBALS WATER SUSTAINABILITY

Guest Editors: Janet Hering (Eawag), Chen Zhu (Indiana University), and Eric H. Oelkers (CNRS, Toulouse)

The term water resources refers to natural waters (vapor, liquid, or solid) that occur on the Earth and that are of potential use to humans. These resources include oceans, rivers, lakes, groundwater, and glaciers. The Earth has plenty of water, over 1.4 × 10¹³ km³. However, 97% of global water is saline seawater. Of the 3% that is freshwater, nearly 70% is locked in the polar ice caps and glaciers. The majority of nonglacier freshwater is groundwater (98%). Surface freshwater (rivers and lakes), which has historically served most human needs, constitutes only a small fraction of the Earth’s water resources.

Water interacts with minerals, soils, sediments, and rocks, and hence studies of Earth materials have a direct bearing on water resources. Studies of the acquisition, mobility, and fate of elements and isotopes in water provide valuable signatures for tracking water cycles at regional and global scales and are essential for the development of remediation technologies for contaminated water.

• Societal needs for water and our dependence
  and influence on water
  Eric H. Oelkers, Janet Hering, and Chen Zhu

• Millennium Development Goals for water supply
  and sanitation: Geochemical aspects of water quality
  and treatment
  Richard Johnston, Michael Berg, Annette Johnson, Elizabeth Tilley, and Janet Hering (Eawag)

• Groundwater as a critical yet vulnerable resource
  Frank W. Schwartz and Motomu Ibaraki (Ohio State University)

• Hydrogeochemical processes and water resource
  management
  Chen Zhu and Frank W. Schwartz (Ohio State University)

• Management of water produced in oil and gas production
  Kelvin B. Gregory and David Dzombak (Carnegie Mellon University)

• Water conservation, efficiency, and reuse
  Henry Vaux (University of California–Riverside)
Volume 7, Number 5 (October)

TOURMALINE: FROM GEMSTONE TO GEOCHEMICAL INDICATOR

Guest Editors: Darrell J. Henry and Barbara L. Dutrow (Louisiana State University)

From the Vikings’ sunstone to a modern piezometric pressure sensor, tourmaline is an intriguing mineral with a new degree of significance. Tourmaline was considered by 18th century physicists as the key to a grand unification theory relating heat, electricity, and magnetism, but new studies define its role as an indicator of Earth’s processes. With its plethora of chemical constituents and its wide stability range, from near-surface conditions to the pressures and temperatures of the mantle, tourmaline has become a valuable mineral for understanding crustal evolution. Tourmaline encapsulates a single-mineral thermometer, a provenance indicator, a fluid-composition recorder, and a geochronometer. Although also prized as a gemstone, tourmaline is clearly more than meets the eye.

• Tourmaline: Nature’s DVD
  Darrell J. Henry and Barbara L. Dutrow

• From polarity to piezometry:
  Tourmaline crystallography and applications
  Frank C. Hawthorne (University of Manitoba) and Dona Dirlam (Gemological Institute of America)

• No element left behind: Tourmaline isotopes
  Horst Marschall (University of Bristol) and Shao-Yong Jiang (University of Nanjing)

• Tourmaline as a guide to ore deposits
  John Slack (U.S. Geological Survey) and Bob Trumbull (GFZ, Potsdam)

• Tourmaline in sedimentary, igneous, and metamorphic systems
  Darrell J. Henry, Vincent van Hinsberg (Oxford University), and Barbara L. Dutrow

• Tourmaline as a gemstone
  Federico Pezzotta (University of Milan) and Brendan Laurs (Gemological Institute of America)

Volume 7, Number 6 (December)

MINE WASTES

Guest Editors: Karen Hudson-Edwards (Birbeck College, University of London), Heather E. Jamieson (Queen’s University), and Bernd Lottermoser (University of Tasmania)

Since the dawn of civilization, humankind has been extracting metals and minerals for the production of goods, energy, and building materials. These mining activities have created great wealth, but they have also produced colossal quantities of solid and liquid wastes, known collectively as “mine wastes.” Mine wastes represent the greatest proportion of waste produced by industrial activity. In fact, the quantity of solid mine wastes and the quantity of Earth materials moved by fundamental global geological processes are of the same order of magnitude—approximately several thousand million tons per year. Therefore, the large-scale production, secure disposal, and sustainable remediation of mine wastes represent problems of global significance. Over the past 10–15 years, novel geochemical, mineralogical, microbiological and toxicological techniques have led to a much better understanding of the character, weathering mechanisms, long-term stability, ecotoxicology, and remediation of mine wastes. This issue of Elements will bring readers up to date with these current findings and will highlight new frontiers for mine waste research.

• History and significance of mine wastes
  Karen Hudson-Edwards

• Chemistry and mineralogy of metallic mine wastes
  Heather Jamieson

• Chemistry and mineralogy of coal and oil sands mine wastes
  Kim Kasperski and Randy Mikula (Natural Resources Canada)

• Acid mine drainage and other mine water wastes
  Kirk Nordstrom (USGS)

• Ecotoxicology of mine wastes
  Geoff Plumlee (USGS)

• Recycling, reuse, and rehabilitation of mine wastes
  Bernd Lottermoser and Graeme Spiers (Laurentian University)
Vladimir Vernadsky was one of the giants of geochemistry. Considered the founder of the field of biogeochemistry and a true pioneer in “whole Earth” studies, he realized by 1945 that “Man under our very eyes is becoming a mighty and ever-growing geological force.” In the intervening 65 years, his “ever-growing force” has become a tidal wave. The global population has been increasing exponentially since the beginning of the industrial revolution, and as a result has increased by nearly a factor of three between 1945, when his observation was published, and today (see figure). Current projections anticipate a population exceeding 9 billion by 2050. This explosive human population growth has been fueled by ancient hydrocarbons and has come with high costs. Most Earth scientists are concerned with the implications of the rapid accumulation of greenhouse gases in the atmosphere. The consequences include a climate state without polar ice, acidifying oceans, and increasingly variable water fluxes. The rate and extent of these and many other negative climate-related impacts, and how to mitigate them, have caused a vigorous discussion on climate change that is in the news on a nearly daily basis.

However, as a society we are much less aware of another major impact of this rapid increase in human population. Without seeking to minimize the significance of climate change, I point out that land-use impacts associated with the dramatic post-industrial revolution population increase currently exceed climate impacts at most scales. Prominent among these land-use issues is soil degradation, which is highly consequential for the obvious reason that we rely on soil to grow our food.

History teaches us that inattention to soil conservation can have disastrous consequences. One emblematic example of many that could be cited took place in the United States. Until the early 19th century, prairie grasses with deep root systems covered the central plains of the United States. These deeply rooted grasses held the soil in place and served as a water storage system that afforded drought resistance. In 1838, John Deere, a blacksmith, developed a plow that would cut through the dense prairie-grass roots, opening up the plains to extensive wheat farming. Wheat farming flourished, particularly during the late 1920s, aided by increased mechanization and a series of wetter than average years. But when an intense drought affected the region in the 1930s, the soil, which now lacked deeply rooted native grasses, dried up. Billions of tons of topsoil blew away, creating the “dust bowl.” The exodus of population from the region was the largest migration in American history. By 1940, 2.5 million people had emigrated from the plains states. This dust bowl episode led to a focus on soil conservation practices and eventually to approaches such as no-till agriculture. Despite improvements brought about by conservative agricultural practices, soil erosion by water and wind on cropland in the United States was still over 1.7 billion tons per year in 2007.

Soil degradation can also occur via chemical processes, including salinization, which is the accumulation of salts in soil. Salinization occurs in irrigated arid and semi-arid regions where rainfall is insufficient to leach salts from the root zone. Many agricultural crops have limited tolerance for elevated soil salinity, rendering impacted soils unsuitable for farming. Salinization is currently a major concern in several regions of the world, including parts of western and southern Australia and the San Joaquin Valley in the western United States. Taken to its extreme, salinization has played a role in the fall of civilizations. Mesopotamia has been called the cradle of civilization. One of the earliest city states in this region, with a dense population, full-time bureaucracy, military, and economically stratified society, was Uruk. Founded around 5000 BCE, it flourished until around the third millennium BCE. At about 2900 BCE, it may have been the largest city in the world. Uruk’s complex society was possible because of sedentary agriculture that produced an excess of food. Today the site of this former center of early civilization is a desolate desert landscape, the result in large part of irrigation practices and climatic conditions that led to salinization of the soils.

These historical examples illustrate how reduced soil fertility as a result of land-use practices has had deleterious impacts on regional-scale societies. However, the population explosion of the 20th century and beyond has made soil degradation a global problem with foreboding consequences. Humans are causing widespread physical degradation of soil by sealing, compaction, and erosion. One analysis describes the sealing of soil by buildings and roads in western Europe and compaction of soil in eastern Europe by Soviet-era intensive tillage as major concerns. However, it is the loss of soil fertility by soil erosion due in large part to conventional agricultural practices that is a problem of global consequence. Mainly as a result of agriculturally induced erosion, humans may now be an order of magnitude more important at moving sediment than the sum of all natural processes. An extensive compilation of soil formation and erosion rates documents that soil production by natural weathering processes and geologic erosion are approximately in equilibrium. In stark contrast, soil erosion by conventional agriculture is up to several orders of magnitude more rapid than these natural processes. By one estimate, between one-third and one-half of the ice-free Earth surface has already been transformed by human action. The United Nations–sponsored GLASOD (Global Assessment of Human Induced Soil Degradation) study estimated that about 15% of the Earth’s ice-free surface is afflicted by some form of land degradation. A more recent assessment using a different methodology likewise documents extensive land degradation. All this matters because we will require more land to feed our expanding population. The estimated areal increase in cropland required to feed the increased population on the planet between now and 2050 is roughly the size of Brazil.

There is no doubt that the combined impacts of humanity on the planet justify Vernadsky’s prophetic characterization of our species as a mighty geologic force. In fact, I am sure that if he were alive today, he would endorse the suggestion that we have entered a new geologic era, the Anthropocene. But it is not enough just to understand the scope of civilization’s transformation of the planet. We should also heed the warning of one of America’s great conservationists, Aldo Leopold, who wrote in 1933, “The reaction of land to occupancy determines the nature and duration of civilization.”

Martin B. Goldhaber, USGS mgold@usgs.gov

INTERNATIONAL WATER ASSOCIATION
GLOBAL HONOUR AWARD

Rajeshwar Dayal Tyagi, research professor at the INRS – Eau Terre Environnement Research Center, Québec City, Canada, is the recipient of a 2010 Global Honour Award for Applied Research from the International Water Association. The award recognizes his work on the bioconversion of wastewater and sewage sludge into high-value-added products. These prestigious awards are given every two years in recognition of projects from around the world that promote effective, sustainable approaches to water management. The Global Honour Award recognizes the importance of Prof. Tyagi’s research in developing environmentally friendly and cost-effective processes for treating wastewater, wastewater sludge, and residual biomass to produce enzymes, bioinsecticides, bioherbicides, biofungicides, bioinoculants, and bioplastics. Along with his research team, Prof. Tyagi has made significant advances in environmental biotechnology by creating valuable products from such waste materials, which are normally difficult and expensive to dispose of. Further, using this biomass as raw material can reduce the cost of producing increasingly sought-after biomaterials by 40–60%. Tyagi’s work was also recently honored by the American Academy of Environmental Engineers, who awarded him the University Research Grand Prize in May 2010.

ROYAL SOCIETY OF CANADA
RECOGNIZES EARTH SCIENTISTS

The Royal Society of Canada (RSC) is the senior national body grouping distinguished Canadian scholars, artists and scientists. It consists of nearly 2000 Fellows—men and women who are selected by their peers for outstanding contributions in the natural and social sciences, arts, and humanities. Its primary objective is to promote learning and research in the arts and sciences.

Four Earth scientists were recognized at the Society’s Induction and Awards Ceremony on November 27, 2010.

RSC Bancroft Medal to Frank Hawthorne

Frank C. Hawthorne (Department of Geological Sciences, University of Manitoba) is the recipient of the Bancroft Medal, awarded every two years for publications, instruction and research in the Earth sciences that have conspicuously contributed to public understanding and appreciation of the subject. Frank Hawthorne has investigated some of the most fundamental problems in mineralogy and has made major contributions to our understanding of the factors affecting atomic arrangements in minerals. He is well known for his ability to synthesize knowledge and present the essentials in a clear and succinct fashion to the broader community.

RSC New Fellows

Rodney C. Ewing (Department of Geological Sciences, University of Michigan) was inducted as a foreign Fellow of the Royal Society of Canada, while Donald Bruce Dingwell (Experimental Geosciences, University of Munich), and Guy Narbonne (Queen’s University, Kingston) were inducted as Fellows. We reproduce the citations below.

Rodney C. Ewing is recognized as the world’s leading scientist on the geochemistry of uranium and the role of uranium in all aspects of nuclear power, from nuclear reactor processes to safe storage of radiogenic waste. With his intellectual capabilities and scientific expertise, he has made major and fundamental scientific advances in Earth and environmental sciences. He has tirelessly pursued geological solutions to the problem of nuclear waste disposal, almost single-handedly impressing on the materials science community and government agencies the importance of this approach. His work represents the most creative and sustained scientific initiative in this field since its inception.

Donald B. Dingwell is renowned for establishing the experimental investigation of melts and magma as a vital component of Earth sciences, with implications for Earth evolution, element enrichment, volcanic mitigation, and the physical chemistry of the liquid state.

Guy Narbonne is a paleontologist who is internationally recognized for his research on the origin and early evolution of animals. His descriptions of the biology, life strategies, ecology and history of Ediacaran biota have profoundly influenced our understanding of evolution during this critical period in Earth history.
Blanca Antizar-Ladislao is a lecturer in environmental engineering at the University of Edinburgh. She received her PhD from the Technion Institute of Technology (Israel), MSc and BSc from Coventry University (UK) and BEng from Universidad de Cantabria (Spain). She was a research associate at Imperial College London (UK), Marie Curie research fellow at the Universidad Catolica Portuguesa (Portugal), Senior Ramon y Cajal researcher at the Universidad de Cantabria (Spain) and lecturer at University College London (UK). Much of her research has involved the integration and optimization of sustainable, environmental (bio-)remediation technologies in groundwater, soil, sediments and wastes. She is also interested in the assessment of the carbon and water footprints of current environmental technologies.

John R. Healey is a senior lecturer in forest ecology at Bangor University (UK) and co-director of the Centre for Integrated Research in the Rural Environment, jointly with Aberystwyth University. A major focus of his research is ecosystem restoration of forests, heathlands and grasslands. A major objective of his work is to improve environmental sustainability through increasing the efficiency of carbon sequestration, nutrient cycling and waste utilization, while enhancing other ecosystem services and biodiversity conservation.

Mark E. Hodson is a professor of environmental geochemistry and mineralogy at the University of Reading. He is also director of the University’s newly formed Soil Research Center. His current research interests cover three interrelated strands: mineral weathering, remediation of contaminated land, and earthworm ecology (particularly the secretion of calcite by earthworms and their evolution and tolerance mechanisms at metal-contaminated sites). He is a recipient of the Mineralogical Society’s Max Hey Medal and the European Association of Geochemistry’s Houtermans Medal. He is on the editorial boards of Environmental Pollution and Applied Geochemistry.

David L. Jones holds a Professorial Chair in Soil and Environmental Science at Bangor University (UK). He focuses his research on understanding below-ground processes, with a specific interest in nutrients and human pathogen behavior in soil-plant-microbial systems. Current applications of his work include the use of wastes for land restoration, implementation of strategies for controlling E. coli O157 in agricultural systems, carbon sequestration in grasslands and ways to improve nutrient-use efficiency in cropping systems. He has published more than 180 scientific journal articles and has advised government on their waste and climate change policies.

Erik Meers graduated with an MSc in biotechnology, followed by an MSc in environmental technology, both at Ghent University (Belgium). In 2005 he completed his PhD research in the field of phytoremediation. He has been active as a coordinator in both academic and industrial research. Since 2009 he has been a visiting professor at Ghent University, while also being the technology development manager for the Belgian branch of a multinational renewable energy producer (Eneco). He has founded two technology-driven spin-offs (Innova Manure and Innova Energy) and has published over 50 peer-reviewed papers, 50 conference proceedings and 30 symposia contributions.

Nicole C. Mueller holds an MSc in environmental sciences from ETH Zürich and is currently working as a researcher in the Environmental Risk Assessment and Management Group at Empa (Switzerland). She is involved in the FP7 projects NanolImpactNet and ObservatoryNano and in 2008 published (with B. Nowack) the first exposure modeling of engineered nanoparticles in the environment.

Bernd Nowack is the leader of the Environmental Risk Assessment and Management group at Empa, the Swiss Federal Laboratories for Materials Testing and Research. He obtained an MSc and a PhD in environmental sciences from ETH Zürich. His general interest is the study of anthropogenic pollutants in the environment and their interactions with biota. His research combines the development of analytical techniques, laboratory investigations, field studies, and modeling. Current projects deal with engineered nanomaterials: qualitative risk assessment, quantitative exposure modeling, the release of nanomaterials from products, and the behavior and effects of such materials in the environment.

Peggy A. O’Day is a professor and founding faculty member at the University of California, Merced. She received her BS from the University of California, Davis, her MS from Cornell University, and her PhD from Stanford University. She was a faculty member of Arizona State University for nine years before joining UC Merced in 2003. Her research currently deals with field and laboratory studies of environmental contaminants and remediation, in particular arsenic and mercury, and the application of spectroscopic and microscopic methods to determine speciation, distribution, availability, and reactivity of metal and metalloid contaminants in natural systems.

Filip M. G. Tack is a professor in the biogeochemistry of trace elements at Ghent University, Belgium. He is director of the Laboratory of Analytical Chemistry and Applied Geochemistry, and is currently chairman of the Centre of Environmental Sanitation, which coordinates studies related to the environment at Ghent University. His current research involves the study of the occurrence, chemical speciation and behavior of trace metals in riparian zones and dredged sediment disposal sites, treatment of waste water using plant-based systems, and management/remediation of widespread, moderate metal contamination using phytoremediation and phytostabilisation.

Dimitri Vlassopoulos is a senior associate with Anchor QEA, LLC, in Portland, Oregon, where he practices environmental and water resources consulting, specializing in the development of in situ remediation strategies for contaminated waters, soils, and sediment. His areas of interest include biogeochemical reactive transport modeling, applied isotope hydrology and geochemistry, and environmental forensics. He received a BS in geology from Concordia University, MS degrees from McGill University (geological sciences) and the California Institute of Technology (geochemistry), and a PhD in environmental sciences from the University of Virginia.
FROM our inventory of over 200,000 specimens, we can supply your research specimen needs with reliably identified samples from worldwide localities, drawing on old, historic pieces as well as recently discovered exotic species. We and our predecessor companies have been serving the research and museum communities since 1950. Inquiries by email recommended.

Elbaite crystal, 4.6 cm tall from Nuristan, Afghanistan. Excalibur Mineral Corp. specimen and image.

www.excaliburmineral.com | email: info@excaliburmineral.com
The Need for Sustainable Soil Remediation

Mark E. Hodson*

1811-5209/10/0006-0363$2.50 DOI: 10.2113/gselements.6.6.363

INTRODUCTION

Perhaps uniquely in the animal kingdom, humans have the tendency to damage or destroy the environment upon which they are reliant for survival. One of the many good examples of this is our past attitude to soil. Early, pre-industrial approaches to managing waste materials were mixed. Useful “waste materials” were carefully recycled; for example, animal wastes were added to soil as fertiliser. Other wastes were simply discarded and left to rot or be preserved for the delectation and delight of future archaeologists. As society developed and became industrialised, so our capacity to damage our natural resources increased, and we generated more and more wastes which were not recycled as useful materials. Careless discarding of “rubbish” allied to accidental release of industrial products has left a legacy of contaminated land.

Back in the 1970s a series of high-profile cases across the globe led to an increasing awareness of the issues related to soil contamination. The Love Canal neighbourhood in New York State, USA, was used as a chemical dumping ground and subsequently built on (Engelhaupt 2008). After discovery of the contamination problem the local community was evacuated. Contaminated material was removed from the site and incinerated. A specialised drainage system was installed to deal with contaminated water draining through the site. The site was lined along its base to stop this drainage from spreading further, the top of the site was covered by a protective layer or cap to isolate the site and the whole area (about 40 acres or 16 hectares of land) was fenced off. Parts of the site remain fenced off today (Fig. 1). At Times Beach in Missouri, USA, dioxin-contaminated oil was sprayed on roads to control dust (Yanders 1986; US EPA 2010a). After identification of the problem the community was evacuated and about 19,600 m$^3$ of soil were incinerated. Parts of the town of Lekkerkerk in the Netherlands were built over ditches containing, amongst other contaminants, aromatic hydrocarbons (US EPA 1992). Almost 94,000 m$^3$ of soil were removed and incinerated. In all these cases the costs of remediation were in the order of tens to hundreds of millions of US dollars.

These cases and others led to an increased awareness of health issues related to the presence of contaminants in soils. As a result, legislation has been adopted that seeks to protect both humans and the environment. Inevitably legislation varies among jurisdictions, but some common strands exist.

1. Initial legislation often focussed on getting rid of contaminants completely or reducing concentrations to a fixed value.
2. Over time legislation has become more sophisticated, due in part to cost issues related to soil clean-up but also to a better appreciation of how to quantify the risks associated with contamination; permissible concentrations of contaminants in soil below which no remediation is deemed necessary now vary depending on land use.
3. There is a requirement at some administrative level to identify contaminated sites, as well as those responsible for the contamination; it is these people who should pay for the clean-up.

Humans require healthy soil in order to flourish. Soil is central to food production, the regulation of greenhouse gases, recreational areas such as parks and sports fields and the creation of an environment pleasing to the eye. But soil is fragile and easily damaged by uninformed management or accidents. One type of damage is contamination by chemicals that provide the lifestyles to which the developed world has become accustomed. Traditional soil “clean-up” has entailed either simple disposal or isolation of contaminated soil. Clearly this is not sustainable. Modern remedial techniques apply mineralogical and geochemical knowledge to clean up contaminated soil and make it good for reuse, rather than simply discarding this precious and finite resource.

Keywords: remediation, contamination, soil, bioremediation, nanoparticles, phytoremediation, adsorption, precipitation

* Soil Research Centre, School of Human and Environmental Science University of Reading, Reading, RG6 6DW, UK E-mail: m.e.hodson@reading.ac.uk

Figure 1 More than 30 years after the evacuation of the community, parts of the Love Canal site are still fenced off due to potential hazards. Image taken from the cover of Environmental Science & Technology, November 2008, volume 42, issue 22, used with permission.
WHAT IS CONTAMINATED LAND AND HOW MUCH OF IT IS THERE?

Formal definitions of what constitutes contaminated land have been developed as part of the legislative process in many countries. The definition used in the UK is typical of many and defines contaminated land as “any land which appears to the local authority in whose area it is situated to be in such a condition, by reason of substances in, on or under the land that:

• significant harm is being caused or there is a significant possibility of such harm being caused; or
• significant pollution of the water environment is being caused or there is a significant possibility of such pollution being caused.”

Harm is defined as “harm to the health of living organisms or other interference with the ecological systems of which they form a part, and in the case of man includes harm to his property” (DEFRA 2006).

The important point in this and similar definitions is that contamination is not defined by the presence of contaminants but by the potential of the contaminants to cause harm. The definition encapsulates the “source–pathway–receptor” concept that is widely used to determine whether a site is contaminated or not (Fig. 2) (Nathanail and Bardos 2004). In this framework the contaminated soil represents the source of contamination, but this is only regarded as a problem if the contaminant can reach a target (the receptor). The means by which the contaminant reaches the receptor is the pathway.

Within this framework it becomes clear that to resolve the contamination issues at any particular site it need not be necessary to remove the contaminant source. Rather it is necessary to break one of the linkages in the source–pathway–receptor model. The adoption of the source–pathway–receptor method of assessing risk and deriving remedial solutions, linked with the sustainability agenda, has led to the development of the remedial methods discussed in this issue of Elements.

Following political acceptance that contaminated soil poses a threat to humans and the environment, and with the development of legislation, many countries have tried to quantify the extent of the contaminated land legacy with which they will have to deal. This has been no easy task as by their very nature sites with harmful levels of contaminants due to accidents or careless management are often poorly documented.

In the UK contaminated land is regulated by the Environmental Protection Act 1990, part 2A (DEFRA 2006). The Environment Agency (EA) assessed industries that could potentially generate contaminants. According to their calculations, around 325,000 sites (~300,000 ha) have had some form of current or previous use that could have led to contamination (EA 2009). To put this in context, the area of England, Wales and Northern Ireland that falls within the remit of the Environment Agency is approximately 165,000 km², so about 2% is potentially contaminated. However, until all these sites are investigated, the true extent of contamination will not be known. To date the EA calculates that about 33,500 sites have been identified as contaminated and of these about 21,000 have required treatment. Overall, inorganic contaminants are found far more commonly than organic contaminants, possibly due to the potential for organic contaminants to degrade naturally over time (Fig. 3).

In the USA two key pieces of legislation cover contaminated soils (LaGrega et al. 2001). Sites contaminated by hazardous waste due to past activities are covered by the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), passed in 1980, and the Superfund Amendments and Reauthorization Act (SARA) of 1986. Sites currently being contaminated or contaminated in the past by still-current activities are covered by the Resource Conservation and Recovery Act (RCRA) of 1976 and subsequent amendments. The United States Environmental Protection Agency (US EPA) is responsible for enforcing these acts. The US EPA states that the total number or extent of contaminated sites is unknown but lists 3746 sites expected to require ongoing remediation, and another 62 are being considered for addition to the Superfund list (US EPA 2010c).

In Germany contaminated land is covered by the Bundesbodenschutzgesetz (the BBodSchG, or Federal Soil Protection Act) and the Bundes-Bodenschutz- und Altlastenverordnung (the BBodSchV, or Federal Soil Protection and Contaminated Sites Ordinance), which became law in 1999 and require the government to locate and remediate contaminated soil. By 2000 the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety had identified about 360,000 sites that were potentially contaminated, but stressed that these sites may not be contaminated and that the area of each site was not known (BMU 2002).
The Dutch Ministry of Housing, Spatial Planning and the Environment (VROM) (now part of the Ministry of Infrastructure and Environment) estimates that “quite a significant part of Dutch soil is polluted” (VROM 2009). It states that some 60,000 sites could be in urgent need of clean-up and in 1997 estimated that costs incurred during remediation of all Dutch contaminated sites would be about 100 billion Dutch guilders (about 500 million euro at current hypothetical exchange rates). The Danish Ministry of the Environment estimates that about 40,000 sites are contaminated in Denmark due to former or current industrial activities (Danish EPA 2009).

Clearly contaminated land is an international problem, with significant areas affected in many different countries. The following methods of remediation are among the most commonly used internationally.

**CURRENTLY POPULAR REMEDIATION METHODS**

Remediation methods are carried out either in situ, with the contaminated soil remaining in place, or ex situ, where the contaminated soil is excavated. Once the soil is excavated, remediation may occur either on or off site. There is always the possibility of returning remediated soil back to its site of origin. Alternatively, once excavated, material may be removed off site and disposed of (most commonly in a landfill). All these methods remove the source from the source–pathway–receptor linkage. An additional method of remediation is simply to isolate the contaminant source, thereby breaking the pathway from the contaminant source to the receptor (Nathanail and Bardos 2004). Although the contaminant is still present, under the UK definition for example, the site would no longer be termed “contaminated” as there is now no threat of harm to humans or the environment.

Perhaps the most common and popular remedial method is that known as “dig and dump”. In simple terms the contaminated soil is dug up, removed from the site, and stored elsewhere, usually in a landfill site (Fig. 4). Depending on development needs, the excavated site is either left as a hole or is filled in with clean material, for example, demolition debris.

The attraction of this technique lies in its simplicity, ease of costing, speed and finality. All contaminated soil can be quickly taken away from the site, leaving it “clean” with no need for future monitoring. This method was particularly attractive when assessment of contaminated soil was carried out by comparing contaminant concentrations to a fixed, legislatively permitted concentration in the soil, rather than on a risk-management basis. However there are important limitations to “dig and dump”. There are practical constraints to the depth of excavation, and the sides of excavations need to be shored up. Also excavation in saturated soils or below the water table presents engineering challenges, and, unless a hole is required at the remediated site, some form of fill has to be found to replace the excavated material. However, perhaps the biggest draw-back to “dig and dump” is the requirement that a site has to be found for disposal of the contaminated soil. There is growing political pressure, for example in Europe through the European Union (EU) Landfill Directive (EU 1999), to reduce the amount of contaminated soil disposed of as waste. Not only are the costs of such disposal being increased to reduce the practise but also legislation is being enacted to control the forms of waste that landfills can accept, thereby reducing the number of landfills available for contaminated soil disposal. Whilst excavation remains a popular remedial measure, there is now far more political and economic pressure to treat the excavated material and return it to the original site or to use an alternative remediation technique.

**Figure 4** A landfill site under construction near Quito, Ecuador, where waste materials, including contaminated soil, can be disposed of. Landfills have to be sited sufficiently close to industry and residential areas that it is economic to transport waste to them, and sufficiently far away that local residents do not complain about noise, smell, visual appearance of the landfill and excess traffic. Other considerations also apply; for example it is good practise to exploit existing holes in the ground rather than create new ones and, in order to reduce potential leakage of liquids from the landfill and subsequent pollution events, the landfill should be underlain by impermeable rocks or sediments (such as clays) and not sited over an aquifer. Photo: iStock

**Figure 5** Impermeable, black sheeting forming part of the basal lining of a landfill site designed to prevent leakage of contaminant-bearing fluids from the bottom of the landfill. The landfill is located in Hungary (South-Transdanubien region) between the villages of Göröcsön and Baksa; construction began in 2008. Typically the basal lining of a landfill site will comprise a series of layers. The uppermost layer of the lining, on which the waste rests, is usually some form of geotextile, i.e. a fabricated material, or graded sand that acts as a filter, permitting the drainage of leachate from the waste but preventing particle transport. This filter layer rests on top of a more porous, free-draining layer that houses a series of collection pipes designed to draw any leachate from the base of the landfill and carry it up to the surface for treatment. The bottom of the free-draining layer takes the form of an impermeable membrane of the type shown in the photo. There may then be a further free-draining layer with collection pipes, underlain by a second impermeable layer as a fail safe. These lining systems are expected to last for the lifetime of the landfill, from the time it receives its first waste to a time after the landfill is full and no longer in operation. At this time, liquids draining through the contents of the landfill should have achieved a composition similar to that of “normal” water, so that any leakage from the landfill has no detectable impact on soil water or groundwater composition; this can take tens to hundreds of years. Underlying the lining systems, in the ideal situation, is a bed of naturally occurring, impermeable clay. Photo: Zsolt Biczó, iStock
Another common and popular remedial method is containment. Containment can be applied off site to excavated materials (i.e. the “dump” end of “dig and dump”), on site to excavated materials, or in situ. The significant advantages of containment are that it is relatively cheap and rapid. The most common methods of containment are the installation of liner systems that form a coating or lining to the holes used for the storage or disposal of contaminated materials (Fig. 5), layers that cover or cap contaminated sites (Fig. 6) and in situ vertical and horizontal barriers (Fig. 7).

Linings typically comprise a series of layers each fulfilling a specific purpose. Examples are impermeable barriers to prevent fluid escape; sorptive layers to reduce contaminant movement; coarse, porous layers to promote fluid collection and removal; and strengthening layers to prevent damage to the lining. As well as synthetic materials, natural materials such as bentonites and zeolites may be used in such layers. Cover layers are usually composite constructions, comprising impermeable layers to isolate the contaminated soil from percolating rainwater from above, drainage layers to direct infiltrating rainwater away from the contaminated site, and vegetated soil layers. In situ, vertical and horizontal barriers may be produced by inserting sheeting – for example, overlapping lengths of steel sheet piling; by excavating and infilling, for example, with a slurry that subsequently solidifies; or by manipulation of the soil – for example, by freezing to produce a cryogenic barrier. Vertical containment systems are more common than horizontal ones due primarily to the relative costs of the associated engineering issues related to their construction.

**WHY BOTHER TO PROTECT THE SOIL?**

If a suite of contamination-remediation techniques exists, why is there a need for new methods? The reason is that the above methods are not sustainable. The concept of sustainability has gained widespread acceptance since its use in the Brundtland report from the United Nations’ World Commission on Environment and Development (WCED), which defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987). Sustainability is commonly stated to have “three pillars”: environmental, social and economic demands (Fig. 8).

Applied to remediation, this means that any remedial treatment should achieve a balance between protecting the environment now and not limiting use of the environment in the future, acceptance by the general population, and not being too expensive. None of the methods outlined above could truly be labelled sustainable. For example, “dig and dump” relies on an infinite provision of holes to put contaminated material in and clean material to fill up voids. In many senses this is not remediation but merely moving contamination from one site to another. Similarly, although containment breaks pathways, the contaminants remain in place and the soil is still not useable by future generations. This is important because soil is a finite resource. The world’s population is growing and much of the food that feeds this population is grown in soil. Soil also stores a vast amount of carbon and sustains the majority of the planet’s animal and plant life. Just as importantly for people’s quality of life, soil supports parks and other recreational areas. However, we are losing soil at a rate estimated at approximately 11.6 ton ha⁻¹ y⁻¹, equivalent to a reduction in soil thickness of about 0.38 mm y⁻¹ (Yang et al. 2003). Estimating the production rate of soil is diffi-

---

**Figures:**
- **Figure 6** A natural cover layer over the Reichs Ford Road landfill site, Frederick, Maryland, USA (www.frederickcountymd.gov/index.aspx?NID=530, accessed November 11, 2010). The tap in the foreground is part of the system for monitoring and releasing any gas that builds up in the landfill. Once a landfill is “full”, the story is not yet over. A cap is placed on the landfill similar in design to the lining systems at the bottom of the landfill. Such caps are designed to isolate the waste in the landfill from the natural environment for visual and safety reasons. The cap is usually covered by a layer of topsoil that can be several metres thick, which is then planted with grass or other vegetation to improve the visual appearance of the landfill site. Although no further waste is being added to the site, the landfill is not “finished”. In particular bacteria will be actively degrading any organic waste present in the landfill. Bacterial degradation of the waste generates various gases, including carbon dioxide, methane and hydrogen. It is important that these latter two gases do not build up in landfills as they can be explosive. Thus after a landfill is “full” it is necessary to continually monitor the evolution of gas from the site and control its release. PHOTO: JOHN KEITH, ISTOCK

- **Figure 7** Vertical sheet piling being inserted at a contaminated site to create a containment cell that isolates contaminated soil. The Escambia Wood Treating Company was located in Pensacola, USA. Prior to going into bankruptcy in 1991, this site had been used for 40 years for treating wood products with creosote and pentachlorophenol. The site was placed on the US EPA National Priorities List in 1995. A variety of organic contaminants were detected at the site. As part of the remedial process, a “containment cell” was constructed for the disposal of about 500,000 m³ of treated, contaminated soil (US EPA 2010c). PHOTO: ESBAMBA TREATING COMPANY CLEANUP (www.etccleanup.org/, accessed November 10, 2010)

- **Figure 8** The three pillars of sustainability. Figure by Johann Dréo (http://en.wikipedia.org/wiki/File:Sustainable_development.svg#file)
cult. However, as it is thought that about 60% of soil erosion is induced by human activity and if we assume that, without human intervention, soil production and erosion would be in some sort of steady state, at least on human timescales, it seems likely that we are depleting the soil resource. Not only should we protect the soil we have but we should bring soil we have previously damaged back into beneficial use, thereby repairing the damage caused by society's previous activities. Disposing of contaminated soil in a hole and sealing it off, or just covering up contaminated soil to isolate it from the environment, does not fulfill this aim.

**SUSTAINABLE REMEDIATION**

The remedial methods detailed in this issue demonstrate how mineralogical and geochemical principles are allowing soils to be remediated and reused in a sustainable fashion (Fig. 9).

The approaches of these methods to inorganic and organic contaminants are somewhat different. The sustainable remediation of inorganic contaminants usually involves breaking the pathway between the source and the receptor. Soil chemistry is manipulated so that, despite the contaminants remaining in the soil, they become immobilised and no longer pose a threat. The chemical processes that these techniques rely on are precipitation and sorption reactions (Jones and Healey 2010 this issue; O'Day and Vlassopoulos 2010 this issue). Either contaminants precipitate out of solution (after, for example, changes in soil pH, oxidation state or the concentration of potential reactants), or they are removed from solution by attaching to the surface of materials, such as clays, zeolites and organic material, via adsorption.

Alternatively, the contaminants can be taken out of the soil altogether, i.e. the source is removed. One means of source removal is phytoextraction – the use of plants to extract contaminant metals from soils. In the ideal end scenario, metal-laden plants become an exploitable metal source, though the usual result is that the plants are just used to concentrate the contaminants for ease of disposal. The problem with phytoextraction is getting a sufficiently high concentration of contaminants into plants of sufficient biomass. High concentrations of contaminants are one thing. However, the plants that typically accumulate high concentrations of metals (i.e. hyperaccumulator plants) are so tiny and so slow growing that they do not remove large quantities of contaminants. Large, fast-growing plants that have a high concentration of metals are required. This has led to the development of assisted phytoextraction, in which soil chemistry is manipulated to help fast-growing plants extract high concentrations of contaminants (Tack and Meers 2010 this issue; Hodson and Donner 2011).

Although the above methods can also be applied to organic contaminants, an important difference between inorganic and organic contaminants is that the latter can often be degraded or broken down, particularly by bacteria, to simple oxides such as water and carbon dioxide. This occurs naturally over time and is accelerated in bioremediation by manipulating conditions to make them favourable for bacterial digestion (Antizar-Ladislao 2010 this issue). Another way to remove organic contaminants is to oxidise them. In many ways this is the abiotic equivalent of bioremediation. The nanoparticle revolution has made possible the production of particles both sufficiently small to mix well with contaminated soil and reactive enough to degrade organic contaminants. Although still in its infancy, the use of nanoparticles in remedial treatments is now being reported (Mueller and Nowack 2010 this issue). Thus sustainable remediation of organic contamination works through removing the contaminant source.

In all cases the end result of sustainable remediation is either the removal of the contaminant source or the immobilisation of the contaminants, so that the soil can be used once again for the benefit of society.

**ACKNOWLEDGMENTS**

I would like to thank Tim Drever, Susan Stipp, and Pierrette Tremblay for their assistance and support in the publication of this issue of *Elements* and the authors who have given their time and effort to produce the articles it contains. I acknowledge the NERC, BBSRC, Royal Society, Leverhulme Trust and STFC for research support.
REFERENCES

Ottawa will host the 2011 joint annual meeting of the Geological Association of Canada, the Mineralogical Association of Canada, the Society of Economic Geologists, and the Society for Geology Applied to Mineral Deposits. Committed to exploring both the scientific and societal aspects of Earth Sciences, Ottawa 2011 will revolve around Navigating Past & Future Change featuring 40 symposia, sessions, field trips and short courses.

JOIN US 25-27 MAY 2011 AT THE UNIVERSITY OF OTTAWA TO MAKE THIS MEETING A SUCCESS!

Abstract submission is now on-line. Details on registration, programs and events are available on our website: www.gacmacottawa2011.ca
Organic Amendments for Remediation: Putting Waste to Good Use

David L. Jones and John R. Healey*

INTRODUCTION

Using organic wastes as a sustainable remediation option not only helps divert another waste stream from landfill but also provides a simple remediation technology that has the potential for widespread adoption. We review the main types of organic waste currently available, the range of contaminants they can treat and their practicality. As the long-term success of any remediation strategy depends on more than just technical factors, we also assess the environmental, economic, social and cultural sustainability of organic wastes in land restoration. Last, we look to the future and speculate on what lies ahead, in particular, the translation of research into industry practice.

ORGANIC WASTES

Organic wastes are produced in large quantities wherever there is human habitation (about 0.1–0.3 t person−1 year−1). With progressive global industrialization, organic waste production has increased year-on-year in most countries and concerns have been raised about the viability (economic and environmental) of current disposal practices. Typically, this problem of disposal is exacerbated by the mismatch between the sites of production (concentrated in towns and cities) and best utilization (e.g. agricultural regions) of these organic wastes. In addition to domestic production, large volumes of biowaste of a more consistent quality are produced by industry (e.g. biosolids, food, textile and paper-processing wastes). All these waste streams can be incinerated for energy recovery; however, safe and efficient infrastructure is rare in many countries, and sustainability may be improved by returning these wastes to the land to close the nutrient cycling loop.

Municipal solid waste (MSW) contains a large amount of biodegradable material (approximately 60%) as well as inert matter that can be recycled (e.g. glass and plastic). This has driven the waste-management sector to develop technologies that convert this material to a more biologically and chemically stable product (e.g. through composting or anaerobic digestion). From a public-health perspective, even source-segregated biowastes are deemed to need sanitization before use as soil amendments to reduce the risk of spreading plant and animal diseases (e.g. prions, norovirus and Salmonella). This treatment is normally a combined thermal and biological process which causes major changes in the biological, chemical and physical properties of the waste material. Composting of a variety of organic materials typically reduces their volume by approximately 50%, increases the concentration of most nutrients and greatly slows the rate of biodegradation, thereby producing a quasi-stable compost end product, though its properties do vary greatly with source material (Fig. 1).

Key questions for risk assessment are what happens to pollutants contained in the waste itself during treatment and do they pose a subsequent risk if the product is applied to land? This contamination typically comes from hazardous material entering the municipal waste stream (e.g. batteries, cleaning products and paints) as a result of poor public awareness about waste treatment. Levels of organic pollutants, such as polyaromatic hydrocarbons (PAHs), dioxins and endocrine-disrupting chemicals, can be dramatically reduced during the biologically mediated aerobic or anaerobic thermal treatment of organic waste materials (at 40–65 °C). In some cases these compounds are completely degraded to CO₂, whilst in others the high temperatures facilitate their volatilization, particularly if air is forced through the material during processing. Additionally, the bioavailable simple carbon compounds are rapidly used by the microbial community during thermal treatment; thus the pollutants remaining at the end of the process tend to be of low bioavailability (stabilized) and not harmful. In contrast, there is little possibility of reducing the levels of potentially toxic metals (e.g. Cd, Cr, Cu, Pb, Ni and Zn) in the material although very small amounts can be lost via volatilization, often in an organo-metallic form (e.g. Hg, As, Bi, Pb, Sb, Te and Sn). The problem of high levels of metals in the waste is increased by mass loss of the organic material during thermal processing, which effectively bioconcentrates the metals further. Some changes in metal speciation do occur during composting; however, this is metal- and waste-specific. For example, during co-composting of biosolids, deinking paper fibre and green waste over a 6-month period, Ni...
Influence of mixing three different organic wastes on the composting process, the quality of the final matured product and its suitability for different remediation purposes. Green waste (GW), paper-processing waste (PP) and biosolids (BS) were composted in-vessel for 2 months and then matured in open air for 3 months. Values represent means ± standard errors (3 replicates). ADAPTED FROM ROBERTS ET AL. (2007)

![Graph showing the influence of mixing three different organic wastes on composting](image-url)

availability reduced, Cu and Zn availability increased and Pb remained unchanged (Tandy et al. 2009).

MSW is highly heterogenous and varies with socio-economic and institutional factors, including wealth, lifestyle, demography, geography, season and legislation. These factors can all impact on treatment-process efficiency and final-product quality. Source-segregation of waste streams (e.g. into green, food and paper waste) can greatly reduce the risk of chemical contamination of the final product. Effective waste screening can also reduce contaminants, such as plastics, metals and glass, which can prohibit the use of the final treated product on aesthetic or health grounds.

Many properties of successfully treated organic wastes are beneficial to soil and plants following application, especially by enhancing soil organic matter content. Organic matter usually contains large amounts of available plant nutrients and enhances water and air movement in soil. This range of positive effects is often not achievable with inorganic fertilizers.

**TREATMENT OF METAL POLLUTION USING ORGANIC WASTES**

While soils can naturally reduce the mobility and bioavailability of metals due to sorption, precipitation and complexation reactions, this attenuation process (natural remediation) can be slow – for example, if the soil on the site is so degraded that it has a low number of microorganisms in it. In this case, remediation can be accelerated by the addition of organic wastes. This option is typically cheaper and easier to implement, can be undertaken over large areas and is generally more acceptable to the public than most alternative remediation strategies. To be successful the application of organic wastes must (1) prevent vertical and horizontal movement of potentially toxic metals and thus protect surface water and ground-water, (2) minimize the entry of such metals into the food chain (through plants, animals or microbes), and (3) minimize wind erosion and dust exposure. Both laboratory and field-scale trials provide evidence that organic wastes such as composts, biosolids and anaerobic digestates can positively address these goals.

Typically, contamination by most metals is a major environmental problem only in acid soils (pH < 6.5), and the migration of metals is largely dependent on the soil’s organic matter content, redox potential and pH. Therefore, organic wastes play several key roles in the remediation and restoration of metal-contaminated sites. First, they can bind metals directly on their highly negatively charged surfaces, making the metals less susceptible to leaching and plant uptake (Farrell and Jones 2010). Second, by increasing the soil’s porosity they help aerate the soil, thereby increasing its redox potential and facilitating the precipitation of metal oxyhydroxides. Third, they typically make the soil more alkaline, inducing metal precipitation. Fourth, they enhance soil quality by improving its structure, reducing nutrient imbalances and increasing microbial growth, which in turn promotes the re-establishment of the soil’s natural ecological cycles. Last, the presence in the organic material of “antagonistic ions” such as Ca$^{2+}$ helps lower the toxicity of certain metal ions by minimizing their uptake in cellular biological transport systems.

Taking all these effects together, while the addition of organic wastes cannot remove toxic metals from soil, it should contribute to stabilizing or immobilizing them on a decadal timescale.

Use of organic wastes with a relatively high content of potentially toxic metals (e.g. biosolids in some countries, and much MSW-derived compost) may be unsuitable for agriculture and horticulture because of metal accumulation in soil and plant tissues. However, the substrate material at contaminated sites frequently has metal concentrations much higher than in these wastes. Application of metal-contaminated organic wastes to such sites may therefore cause a relatively low increase in pollution. This conclusion is supported by an investigation using sequential chemical extraction methods, which found that only small fractions of compost-derived trace elements were bioavailable in comparison with those present in the contaminated substrate (Pérez-de-Mora et al. 2006). Some field trials involving MSW-derived compost, however, have reported an increase in soil and plant metal concentrations (e.g. Ni, Pb, Zn and Cu; Ramos and López-Acevedo 2004). Although an increase in the soil’s overall metal load may be undesirable, organic waste application rarely poses a significant risk of phytotoxicity or high foliar metal contents (Pinamonti et al. 1997). Applying organic wastes carries a risk because their high content of dissolved organic carbon can bind metals into organometallic complexes, facilitating downward migration through the soil (Farrell et al. 2010a). Moreover, organic waste addition to soil typically increases its pH, rendering some metals insoluble and lowering their bioavailability (e.g. Zn, Cu and Pb), but increasing the solubility and mobility of other toxic elements (e.g. As; FIG. 2).

**TREATMENT OF ORGANIC POLLUTANTS USING ORGANIC WASTES**

When incorporated into soil or applied as a surface mulch, organic wastes can directly stimulate microbial activity in contaminated soil. These wastes often contain microorganisms (e.g. bacteria, actinomycetes and lignolytic fungi) which can promote the breakdown of both simple and complex organic pollutants (Semple et al. 2001; Antizar-
Ladislao 2010 this issue) and establish a new and more functionally diverse microbial community in the soil. Indirectly, adding organic waste can also stimulate plant growth and the uptake, decontamination and gaseous loss of organic pollutants (phytoextraction, phytotransformation and phytovolatilization; Tack and Meers 2010 this issue). Similarly, an increase in root growth also promotes soil microbial activity and pollutant removal via the so-called “rhizosphere effect” (rhizoremediation; Kuiper et al. 2004). However, in the absence of plants, remediation is often undertaken using “biopiles”: organic wastes are simply mixed with the contaminated soil; then the material is placed in large heaps and left for several months with or without forced aeration. Depending on the waste-to-soil ratio, these biopiles can self-heat (to 40–70 °C), stimulating microbial breakdown and facilitating gaseous loss of untransformed pollutants. In a comparison, biopiling remediated a different range of PAHs than did incorporation of compost, but both strategies successfully reduced overall PAH contamination of soil (Kriipsalu et al. 2008).

As well as stimulating the breakdown of some pollutants into innocuous compounds such as CO₂ and H₂O, adding organic waste can have other positive results. Composts can chemically immobilize organic pollutants, making them less prone to leaching and plant uptake. This process is particularly important for relatively insoluble pollutants, which become sorbed and trapped in hydrophobic domains in organic matter. While not removing the pollutant from soil, this does minimize the environmental hazard.

Most published reports on the use of organic wastes to remediate organic pollutants in soil have reported favourable results, both environmentally and economically. Simply ploughing green waste–derived compost into a pesticide-contaminated soil resulted in rapid plant establishment and soil remediation (Cole et al. 1995). Similarly, co-addition of earthworms and compost stimulated a threefold reduction in PAHs compared to untreated soil (Hickman and Reid 2008). On-site composting of PAH-contaminated soil with organic wastes followed by landspreading and vegetation establishment reduced the PAH concentration by up to 62% (Fig. 3; Williamson et al. 2009). Contradictory trends, however, have been reported on pollutant fate, with some organic wastes suppressing organic pollutant mineralization while promoting solid-phase immobilization. Responses differ with soil type, concentration and properties of the pollutant, and with the source, age and amount of organic waste applied. This variability makes it difficult to formulate robust guidelines suitable for wide adoption of the technology. Another negative aspect frequently quoted is formation of breakdown products that may be more toxic than the parent compound (Puglisi et al. 2009). However, few studies demonstrate that this is a significant problem. Of greater concern is that after an initial rapid mineralization phase the rate of organic pollutant loss typically reduces, leading to incomplete pollutant removal. Although organic waste amendment may aid pollutant removal, its effect can be unpredictable and it may leave a sufficient concentration of organic pollutants in the soil that the site fails to comply with statutory decontamination limits.

**FIGURE 2** Relationship between soil solution pH and availability of copper (A) and arsenic (B) after addition of a range of organic waste–derived composts (comprising green, catering, paper and municipal solid wastes) to soil from an acidic, metal-contaminated mine spoil site (334 replicates). The natural pH of the contaminated soil was 2.9; it increased to 7.2 after the addition of compost. **ADAPTED FROM FARRELL AND JONES (2010)**

**PUBLIC, REGULATOR AND INDUSTRY PERCEPTIONS OF ORGANIC WASTE APPLICATION TO LAND**

While the benefits of applying farm wastes to land have been recognised since the birth of agriculture, the landspreading of industrial wastes has often had a poor public reception in many countries. Negative perceptions surrounding the use of composts, biosolids and other organic wastes mainly concern the enhanced potential for bioaerosol exposure, odour and insects; but there are also ill-founded fears over increased risk to human health during the treatment, transport and subsequent land application of wastes (Fischer et al. 2008). Environmental effects may be detected up to 5 km from the site of waste use (Aatamila et al. 2010). Opposition to the visual impact of on-site composting may also restrict this cost-effective and environmentally friendly method of creating organic ameliorants. This results in long-distance waste transport to and from existing processing sites prior to landspreading. Are these negatives perceptions justified and how should they be dealt with before they become firmly established? First, unacceptable odour emissions have been proven to cause health complaints, even if the effect is psychologically based. Second, microorganisms released from waste to the atmosphere (bioaerosols) can cause allergies, be infectious and produce toxins. Typically, noxious emissions are greatest during the early stages of waste treatment (e.g. transport and shredding) and are much lower from the final stabilized product destined for land. Further, emissions can be dramatically reduced to acceptable limits by the uses of enclosed (in-vessel) treatment technologies, albeit at additional expense.

Public consultation is highly advisable if waste treatment (e.g. composting) is to be carried out on-site without opposition. However, critically, industry often mistakes public relations for public engagement, the former typically failing as a mechanism for promoting public acceptance (Goven and Langer 2009). Overall, public perception of the use of biosolids (treated sewage sludge) is worse than for green waste–derived compost, although both may be similarly
beneficial and no different in environmental risk. However, Borden et al. (2004) showed that land application of organic wastes to post-industrial land was more socially acceptable than application to agricultural fields growing food crops.

Government regulators’ acceptance of organic waste use to remediate contaminated land is inconsistent in many countries. Some regulatory authorities see this as “land-filling on the cheap” or “high risk” with respect to potential secondary pollution. Legislation has therefore been introduced to prevent waste being applied to land. Many governments are, however, committed to the introduction of new waste-treatment technologies that practically necessitate land disposal of the resulting product. Wastes proven to be effective at a research pilot-scale are sometimes not permitted to be used for land remediation on a commercial scale.

The waste-management industry is willing to find new, workable solutions for treating organic wastes and creating new markets for the end products. Strong engagement by all stakeholders is required for the potential of land restoration to be realized and the perception changed from “organic waste” to “organic resource” (Nason et al. 2007).

LIFE CYCLE ASSESSMENT OF ORGANIC WASTES IN LAND RESTORATION

While the use of organic wastes can provide an effective method for treatment of polluted soil, this type of remediation should not be undertaken to the detriment of other ecosystem services. Of particular concern is the relative size of the carbon footprint of available remediation options and their full life cycle assessment (LCA). For example, blending high-nutrient-content composts with low-nutrient-value mineral wastes might provide an oligotrophic (low-nutrient) habitat highly suited for bioremediation; however, the costs and carbon emissions of transporting dense, low-value mineral wastes make this option undesirable unless it is undertaken close to the site of mineral-waste production (Jones et al. 2009). A wrong decision about where to draw the boundaries (cradle-to-grave) of an LCA can also lead to misleading conclusions about which remediation option is best. In LCA, impacts are classified as primary, secondary and tertiary (Lemming et al. 2010). Primary impacts include local effects of residual contamination left in the subsurface during and after remediation. These will vary among remediation technologies differing in clean-up efficiency and timescale. Secondary impacts include resource use and emissions arising in other stages of the life cycle of the remediation project, while tertiary impacts are related to post-remedial activities (i.e. site end use). An LCA study of the treatment of diesel-contaminated soil indicated that in situ remediation (biopiling) was preferable to ex situ remediation (Cadotte et al. 2007). Critically, however, Lesage et al. (2007) highlighted the uncertainty in LCA, demonstrating that tertiary environmental benefits dominate over other types of impact in the restoration of brownfield sites. Conventional “dig-and-dump” technologies, where contaminants are removed quickly and completely, can permit rapid realisation of the benefits of unimpeded residential and industrial occupation. In contrast, long-term in situ remediation with organic wastes could result in the displacement of construction onto greenfield sites, ultimately resulting in greater environmental damage. These examples typify the challenges of an objective assessment of “sustainability”.

Correct parameterization of an LCA is difficult due to the context-specific nature of remediation schemes, the uncertainty surrounding greenhouse gas emission factors (i.e. CO₂, CH₄ and N₂O emissions, and carbon sequestration) when organic wastes are processed and incorporated into soil and the non-inclusion of underlying groundwater pollution. Currently, too few LCAs have been conducted for in situ remediation technologies, particularly using organic wastes; most of the existing literature focuses on ex situ remediation of contaminated soil.

LOOKING TO THE FUTURE

Land degradation is an increasing problem worldwide, and returning organic wastes to land can play a key role in restoring ecosystem health in both agricultural and industrial settings. Successful restoration may have major food security benefits, especially for communities utilizing marginal land. Further, for the treatment of contaminated land, there is abundant scientific evidence that a broad range of organic wastes can effectively stabilize and reduce most pollutants in soil. In some respects, however, the technology is still in its infancy. For example, many social and legislative barriers to implementation remain (Nason et al. 2007). This is exemplified in Europe, where application of the word waste to organic material signifies that it is of low commercial and social value and should be subject to stringent legislation and bureaucracy. This prevailing attitude has to change if the technology is to be widely adopted. Implementation of the long-delayed European Soil Framework Directive should provide a better integrated structure for soil protection (Blum 2010).

In terms of the fundamental science, although we have a good knowledge of the basic processes from short-term remediation trials, the long-term impacts of organic waste addition to contaminated land require further exploration. For example, the effect of applying lime to acid mine waste is known to disappear over decades, and follow-up intervention may be required to prevent a resumption of acid pollution. Does the same occur for soils ameliorated with organic wastes? Current evidence from coal mine restora-
tion schemes suggests that organic wastes promote plant growth, which in turn results in organic inputs to soil that sustain habitat restoration; however, more information about other remediation schemes is still required.

In order to improve the technology (e.g. speed and cost of remediation), two major factors need more exploration: the optimization of the organic waste and the correct selection of vegetation. Blending different waste streams can yield amendments which achieve radically different results when added to soil. To design optimal waste blends, we need to construct and validate predictive treatment-technology models. Previously scarce organic wastes are becoming available in large quantities as a result of changes in society. One example is chars produced from the pyrolysis of organic wastes (e.g. biosolids or green waste); such chars are known to readily bind metals and organic pollutants (Cao et al. 2009). Although chars show promise in remediation, any benefits over non-pyrolysed organic wastes remain unproven. Similarly, we need to select plants that support and accelerate the remediative power of organic wastes. An example of the potential benefits of new genetic technologies for this purpose is the introduction of the bacterial genes involved in the metabolism of polychlorinated biphenyls (PCBs) into higher plants (a strategy equivalent to the development of transgenic crops) (Van Aken et al. 2010). In addition, genetically modified bacteria have been produced that exhibit improved capabilities for biodegradation and are able to establish stable relationships with plants. Although genetic modification of plants and microorganisms opens the door to an almost infinite number of remediation approaches, uncertainties about public acceptance of transgenic technologies remain (Knight 2009). Further, while microbial inoculants may work in laboratory or pilot-scale remediation trials, they often fail in full-scale field trials, where they are exposed to competition with the resident soil microbial community; this result undermines confidence in the general applicability of the technology (Makris et al. 2010).

Different sources of metals in the environment may vary in isotopic signature (e.g. $^{206}$Pb, $^{207}$Pb, $^{208}$Pb), and several studies have shown that the metal isotope signatures of organic wastes differ from those of contaminated soil (Fig. 4; Teutsch et al. 2001). This indicator can therefore be used to determine the sources of metals entering plants and drainage waters and thereby establish whether metals present in organic wastes exacerbate the risk of pollution.

There will be a continuing need to develop technologies for best use of new and increasing waste streams. The growing combustion of biomass and organic wastes as a renewable form of energy is increasing the production of ash as a “waste product”. Further research is required to establish the most effective use of this ash, including its application to land. Ash can have high concentrations of potentially toxic metals, and the benefits of using organic wastes for remediation of metal-contaminated substrates may extend to mixing such wastes with ash to produce a safer material for land application.

In determining the most effective use of organic amendments in the management of degraded land, the objectives must go beyond basic substrate remediation to the benefits of a restored site (Blum 2010). Restoration objectives should be incorporated into the basic reclamation plan and not treated as an afterthought. Where it is planned to restore semi-natural habitats for ecosystem services such as biodiversity conservation and visual amenity, careful regulation of the fertility of reclaimed soil may be required (Fig. 5). While high nutrient concentrations may aid the initial soil remediation process, they can lead to domination of the site by competitive, weedy vegetation of low value. Once this trajectory of the vegetation succession has become established, it may be hard to reverse. Therefore, successful restoration of acidic, oligotrophic habitats may require

---

![Figure 4](image.png)

**Figure 4** Lead isotope ratios of metal-contaminated (Zn and Pb) soil and of organic waste (MSW-derived compost containing high levels of metals) and the subsequent isotope ratio of plants (*Agrostis capillaris* L.) grown in the contaminated soil alone or amended with the organic waste compost. The isotope ratio indicates that all the metals in the plants came from the contaminated soil and not the compost (Farrell and Jones, unpublished).

![Figure 5](image2.png)

**Figure 5** Restoration of slate rock spoil tips (dumps) at Blaenau Ffestiniog, Wales, using composted organic wastes (biosolids, recycled paper and green waste) and inorganic sulphur in order to create conditions suitable for high-biodiversity, acid grassland. Previously, nothing had grown on this site for over 60 years. Eighteen months after addition of compost (top), acid grassland was successfully established (bottom).
amendment of the applied organic waste, for example with elemental sulphur, to reduce pH. However, this may then increase the availability of phosphorus too much, which could be countered by adding compounds such as iron hydroxide (Farrell et al. 2010b). New research is required to increase the effectiveness of such complex, mixed organic–inorganic soil amendments.

In this article, we have demonstrated the benefits of waste-derived organic products for land remediation through the appropriate use of science and technology. However, remediation practice needs to be better founded on the social sciences. In particular, improved stakeholder engagement is required to assess (1) the size and location of markets relative to waste production volumes and locations, (2) the economic viability of using organic wastes in comparison with alternative materials, (3) other social and institutional restrictions on use, and (4) the ecological/environmental footprints of the different strategies (through full life cycle assessment).

ACKNOWLEDGMENTS

We thank Mark Hodson for inviting us to write this paper, and Daniel Murphy and Mark Farrell for valuable and constructive comments. Julie Williamson, Susan Tandy and Mark Nason researched the site-remediation trials, waste analysis and photographs presented here. Funding was provided by the European Union LIFE-environment programme.

REFERENCES


Farrell M, Perkins WT, Hobbs PJ, Griffith GW, Jones DL (2010a) Migration of heavy metals in soil as influenced by compost amendments. Environmental Pollution 158: 55-64


Hickman ZA, Reid BJ (2008) Increased microbial catabolic activity in diesel contaminated soil following addition of earthworms (Dendrobaena veneta) and compost. Soil Biology and Biochemistry 40: 2970-2976


Mineral-Based Amendments for Remediation

Peggy A. O’Day¹ and Dimitri Vlassopoulos²

Amending soils with mineral-based materials to immobilize contaminants is both old and new. Although mineral amendments have been used for decades in agriculture, new applications with a variety of natural and reprocessed materials are emerging. By sequestering contaminants in or on solid phases and reducing their ability to partition into water or air, amendments can reduce the risk of exposure to humans or biota. A variety of mineral types are commonly used to amend contaminated soils, with different modes of molecular-scale sequestration. Regulatory, social, and economic factors also influence decisions to employ mineral amendments as a treatment technology.

Keywords: contaminated soil, remediation, in situ amendment, metals, metalloids, Portland cement, reactive capping

INTRODUCTION

The use of reactive or stabilizing materials for remediation of metal and organic contaminants in soils has been widely studied and is gaining broader acceptance as a remediation technology. The overall aim of in situ amendment technologies is to sequester and stabilize contaminants in soils or sediments in order to reduce their ability to partition to water or biota, and thus their potential for transport and toxicity. Soil amendments have been employed to treat both organic and inorganic contaminants, although the selection of amendment treatment and the mechanism of hazard reduction differ widely depending on the target contaminant, or mixtures of contaminants, at a given site. Metal and metalloid elements, such as lead, cadmium, arsenic, mercury, chromium, and selenium, are especially problematic because they are potentially hazardous at low bulk solid concentrations (i.e. about 1–500 mg kg⁻¹) and their speciation and mobility are influenced by environmental factors like pH and oxidation-reduction potential (Eh or pe). They are often widespread in surface and shallow subsurface soils at these low concentrations, making removal and disposal of large volumes of impacted material impractical or prohibitively expensive. Remediation of widespread and persistent organic pollutants that are not readily biodegradable, such as polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), and dioxins, may be improved by an amendment treatment that collectively enhances immobilization, chemical attack, and microbiological degradation.

The difficulty and expense of remediating soils and sediments contaminated with dispersed, low levels of problematic organic, metal, and metalloid contaminants calls for applications and technologies that are both effective and cost-competitive. Carbonate, lime, or phosphate amendments have long been used in agriculture to raise soil pH, lower metal toxicity to plants, or add nutrient phosphorus (McBride and Martinez 2000; Bolan and Duraisamy 2003). Other soil amendments in use or under development evolved from stabilization or encapsulation technologies, such as vitrification and cement stabilization, designed for the disposal of radioactive and other hazardous wastes (Conner 1990; Taylor 1997). An important difference between remediation approaches developed for waste streams versus contaminated soils is that waste streams are generally concentrated and spatially contained, and the remediation goal is to limit contaminant dispersal after disposal. For soil contaminants already released and potentially transformed in the environment, the remediation goals are to reduce the risk to humans and biota of exposure, uptake, and assimilation (bioavailability), and to lessen the risk of contaminant leaching or mobilization. Soil amendments can be applied in an “ex situ” process that resembles treatment of a waste stream. In this process, soil is physically removed, in some instances washed to leach soluble contaminants, mixed with a stabilizing amendment, and then returned to its original location. While effective, this type of remediation approach is generally more labor intensive and expensive than the direct addition of an amendment to the soil (“in situ” treatment) (Mulligan et al. 2001; US EPA 2009). A significant challenge to in situ treatments, however, is ensuring adequate mixing, contact, and reaction of amendments with contaminated materials to achieve stabilization.

From a practical standpoint, responsible parties and regulatory authorities have been reluctant to leave contaminated soils and sediments in place for fear of future remobilization (and liability), particularly due to uncertainties in long-term fate after amendment treatment. Several criteria must be met for an amendment technology to be considered successful and safe for remediation of contaminated soils. The treatment must effectively reduce the exposure risk to humans and/or organisms by demonstrating a reduction in bioavailability, potential for mobilization, or transformation to more toxic forms. Treatments generally must have no adverse effects on the reestablishment of biota,
on agriculture, or on land reuse after application. For example, restoration of agricultural lands must ensure that crop yields are not reduced by the application of too much salt or by the addition of amendments that result in high pH (“overliming” of soils) or limit nutrient uptake (McBrine and Martinez 2000; Lombi et al. 2002). Amended soils must be resistant to chemical alteration, bioturbation, and microbiological transformations that may release contaminants as they are buried or aged. Finally, and perhaps most critically for implementation, treatment must be cost-effective when compared with alternative remediation approaches producing a similar degree of risk reduction and must also be acceptable to regulatory agencies and the public.

**TYPES OF AMENDMENTS AND PRODUCT PHASES**

Numerous materials have been investigated for application to surface soils and, to some extent, surface and subsurface sediments (Table 1). The more commonly used amendments include materials such as silicate, aluminosilicate, or clay minerals; forms of phosphate, carbonate, sulfate, oxide, or hydroxide; or organic residues (i.e. various biosolids such as manure or sewage sludge; see Jones and Healey 2010 this issue). For remediation applications, many of these materials have been adapted from agriculture; from industrial processes such as cement making, production of construction materials, and soil stabilization for foundations; or from vitrification and encapsulation technologies associated with the treatment of radioactive and hazardous waste (Mulligan et al. 2001; Guo et al. 2006; Kumpiene et al. 2007). For these borrowed technologies, an important criterion for use in situ is that the material does not require heating or other specialized processing sometimes associated with ex situ treatment. Some mineral amendments, such as clay minerals, zeolites, carbonates, sulfates, and phosphates, may be employed as relatively pure phases, while others, such as Portland cements, are processed materials designed to react with water to produce hardened product phases. Clay minerals (primarily montmorillonite from, for example, bentonite deposits), zeolites, and activated carbon (black carbon and charcoal) have been used traditionally as high-surface-area, adsorbent materials for filtration and water treatment. These materials are effective sorbents for organic compounds and other contaminants, and they have been widely studied and used in remediation. In pure form, however, they can be relatively expensive for large-scale site remediation. Treatments with phosphate-based or carbonate-based materials, lime (sometimes with organic solids), oxides and hydroxides, zero-valent iron, and calcium silicate cements (with or without sulfate) have been among the most studied and commonly used reactive amendments.

Cementitious amendments have been used for ex situ solidification and stabilization of wastes for encapsulation and disposal (Paria and Yue 2006) and employed to some extent for in situ soil remediation. Portland-type cements are composed primarily of calcium silicate and calcium

### Table 1: Summary of Mineral-Based and Related Amendments

<table>
<thead>
<tr>
<th>Amendment Type</th>
<th>Source Material</th>
<th>Primary Contaminant Stabilization Mechanism</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay minerals</td>
<td>Layered aluminosilicates: montmorillonite (bentonite deposits), vermiculite</td>
<td>Adsorption/ion exchange</td>
<td>Natural expandable clays; used in geosynthetic sorptive mats</td>
</tr>
<tr>
<td>Zeolites</td>
<td>Framework aluminosilicates: natural (clinozoelite) and synthesized from coal fly ash</td>
<td>Adsorption/ion exchange</td>
<td>High-surface-area ion exchange; also mixed with cement</td>
</tr>
<tr>
<td>Carbon</td>
<td>Activated carbon [C], charcoal</td>
<td>Adsorption</td>
<td>Very high surface area; most effective for organic compounds</td>
</tr>
<tr>
<td>Silica</td>
<td>Soluble alkali silicate salts: sodium metasilicate [Na₂SiO₃·xH₂O]</td>
<td>Adsorption, encapsulation</td>
<td>Forms amorphous silica or silica gel on aging; also used for permeability reduction</td>
</tr>
<tr>
<td>Phosphates</td>
<td>Solids: natural and synthetic apatite-group minerals [Ca₅(PO₄)₃X, X = F, Cl, OH]</td>
<td>Solid solution</td>
<td>Solid sources include natural rock, bone meal, fertilizers</td>
</tr>
<tr>
<td>Carbonates</td>
<td>Calcite [CaCO₃], dolomite [CaMg(CO₃)₂], magnesite [MgCO₃], siderite [FeCO₃], soda ash [Na₂CO₃·xH₂O]</td>
<td>Solid solution</td>
<td>Acid neutralization, pH buffering</td>
</tr>
<tr>
<td>Sulfates</td>
<td>Gypsum [CaSO₄·2H₂O], ferrous sulfate [FeSO₄·xH₂O], aluminum sulfate [Al₂(SO₄)₃·xH₂O]</td>
<td>Solid solution</td>
<td>Potential formation of ettringite-type phases; also used for permeability reduction</td>
</tr>
<tr>
<td>Iron-based</td>
<td>Zero-valent iron (Fe), iron(III) oxides</td>
<td>Adsorption, solid solution</td>
<td>Potential for oxidation state changes</td>
</tr>
<tr>
<td>Lime</td>
<td>Lime [CaO], portlandite [Ca(OH)₂]</td>
<td>Adsorption, solid solution</td>
<td>Highly soluble; produces alkaline pH and variable reaction products</td>
</tr>
<tr>
<td>Portland-type cements</td>
<td>Mixture of high-temperature calcium silicates [Ca₅SiO₅, Ca₅SiO₄], calcium aluminate [Ca₂Al₆O₁₆], calcium aluminoferrite [Ca₅Al₂FeO₁₆] with Mg, Na, K substitution</td>
<td>Solid solution, encapsulation</td>
<td>Highly reactive with water; products are mixtures of hydrated CaO–Al₂O₃–SiO₂ phases</td>
</tr>
<tr>
<td>Residual and by-product materials</td>
<td>Coal fly ash [35% SiO₂, 20% Al₂O₃, 6% Fe₂O₃, 5–15% CaO, 0–5% MgO, 0–5% SO₃]</td>
<td>Adsorption, solid solution, encapsulation</td>
<td>Amorphous and (micro)crystalline phases, variable compositions; commonly mixed with other amendment material</td>
</tr>
</tbody>
</table>

1 See Figure 1.
2 Typical values for Class C and Class F fly ash from Conner (1990)
3 Typical ranges from Taylor (1997)
aluminate phases formed from the high-temperature reaction of limestone and clay, or other materials of similar bulk composition (Taylor 1997). When reacted with water, they create highly alkaline solutions and form a complex mixture of hydroxides, mainly portlandite [Ca(OH)$_2$], amorphous calcium silicate hydrate phases (C-S-H) of the tobermorite [Ca$_6$Si$_8$O$_{22}$(OH)$_8$·nH$_2$O] or jennite [Ca$_4$Si$_2$O$_{10}$(OH)$_4$·2H$_2$O] types, and siliceous "hydrogarnet" solid solutions [Ca$_3$Al$_2$SiO$_{11}$(OH)$_6$] (Taylor 1997; Matschei et al. 2007). Depending on the starting composition of the cement, variable amounts of iron, magnesium, carbonate, and sulfate can both shift chemical equilibria and affect the kinetics of formation of solid phases to produce calcite (CaCO$_3$), carbonaluminate phases [Ca$_3$Al$_2$ (CO$_3$)$_2$(OH)$_2$·2H$_2$O], gypsum (CaSO$_4$·2H$_2$O), ettringite [Ca$_6$Al$_2$(SO$_4$)$_3$(OH)$_2$·26H$_2$O] or related sulfoaluminate phases, and hydrogarnite-type phases [Mg$_4$(Al$_2$Fe)$_2$(OH)$_4$·nH$_2$O] in addition to C-S-H and hydrogarnet phases (Matschei et al. 2007). Although a vast body of research has examined cement and concrete chemistry for industrial and construction applications, fewer studies have looked in detail at the mineralogy and chemistry of the mineral products formed from the reaction of cement-based amendments with contaminated soils (e.g. Voigt et al. 1996; Miller et al. 2000).

Recycled materials, industrial by-products, or residual materials from treatment processes may serve as low-cost, sustainable alternatives to pure solids as source materials for soil amendment treatments. Examples include residues from alumina extraction from bauxite ("red mud"), fly ash from coal combustion, treated coal combustion products ("beringite"), steelmaking slags, and scrap iron (Lombi et al. 2002; Guo et al. 2006; Kumpiene et al. 2007). These materials are often mixed with a reactive activator or "binder" material such as Portland cement (Taylor 1997), or used in combination with an organic solid such as peat or sludge. The use of recycled materials as additives is potentially a beneficial "green" technology that reduces the amount of material destined for landfills while lowering the overall cost of a remediation project (Dermatas and Meng 2003). Fly ash, which is high in aluminosilicate glass (Table 1), has been added to Portland cements for decades to impart strength and durability (Conner 1990). High-silica materials act as a "pozzolan" (from the Latin pulvis puteolanus, or "powdery ash"), named for the altered volcanic tuff and ash deposits in the Alban Hills used by ancient Roman builders as a highly durable mortar when mixed with hydrated lime (Jackson et al. 2010). During cement hydration, excess silica and alumina react with hydroxyl and, depending on the availability of alkali cations, shift the reaction products to silica-rich zeolite-type phases. Although soil amendments used for large-scale treatments are relatively low-cost commercial products, their composition can be variable and may not necessarily be well characterized, adding uncertainty to their performance and long-term stability under specific field conditions. Furthermore, waste materials and industrial by-products, such as fly ash, mining residues, incinerator wastes, and metallurgical slags, may themselves contain hazardous constituents, such as arsenic, chromium, vanadium, lead, zinc, and other elements, that could potentially leach from amended soils (Cornelis et al. 2008).

**MECHANISMS OF CONTAMINANT IMMOBILIZATION**

Sequestration mechanisms associated with mineral-based amendments to soils fall into two broad categories, surface adsorption and structural incorporation, each of which may have several molecular-scale variations (Fig. 1). In complex mixtures of amendments and soil, both mechanisms may occur and change with time. For many amendment treatments, however, molecular-scale mechanisms have been inferred from laboratory experiments rather than directly verified, which has contributed to a lack of confidence in the long-term effectiveness of amendments to sequester contaminants. For treatments traditionally used to raise the pH of acidic soils, such as the addition of lime or carbonate, reduced leaching or phytoavailability of metal cation contaminants (for example, Cd$^{2+}$ or Pb$^{2+}$) probably results from simple adsorption to oxide and silicate minerals as pH is increased. Metal cations tend to form strongly bound, inner-sphere surface complexes with soil minerals (Fig. 1) such that desorption is suppressed under typical soil conditions as long as pH remains high. However, elevated soil pH can mobilize adsorbed anion and oxyanion contaminants, with effects that vary depending on pH and competing species. Many organic compounds are strongly adsorbed by high-surface-area amendments, such as activated carbon, exchangeable clays, and zeolites. Surface-reactive amendments such as zero-valent iron (Fe$^0$) may provide sites capable of electron transfer with adsorbed species, leading to oxidation state changes for metals or chemical degradation for organic molecules. Since organic contaminants may be degraded by either biological or chemical pathways, an interesting approach is to combine treatments to stimulate both processes by adding, for example, organic carbon to stimulate microbial degradation and zero-valent iron to promote reductive dehalogenation of chlorinated compounds (Boparai et al. 2008). Although adsorption can be an effective immobilization mechanism for metal contaminants, which may undergo changes in speciation but do not degrade, there is an inherent risk that future changes in pH, Eh, ionic strength, or solution composition could shift surface complex equilibria and desorb contaminants. Some amendments react with soil water and minerals to alter the composition, pH, or Eh of the system, causing dissolution of solids and precipitation of new phases that can structurally incorporate contaminants (Fig. 1). This class of sequestration mechanisms has the potential for more permanent immobilization, compared to surface adsorption or ion exchange, since mineral dissolution is required to partition the contaminant into water. However, the host phase for the contaminant must be stable under the given environmental conditions. Of the amendments summarized in Table 1, phosphate-based treatments, particularly for lead contamination of soils, have been among the most widely studied and used. Application of phosphate minerals or soluble forms of phosphate to soils (Table 1) is intended to sequester toxic divalent cations such as Pb$^{2+}$ by precipitation of pure or substituted phosphate phases of the apatite group [Ca$_5$(PO$_4$)$_2$X, X = F, Cl, OH] (Miretzky and Fernandez-Cirelli 2008). This type of treatment tries to take advantage of differences in the solubility of phosphate minerals to precipitate the contaminant into a more stable phase. For treatment of lead, for example, dissolution of more solubleapatite-group minerals, such as hydroxylapatite [Ca$_5$(PO$_4$)$_2$(OH)] (a primary component of bone meal) or substituted apatites [Ca$_5$(PO$_4$)$_2$(CO$_3$)$_2$POF] from natural phosphate-bearing rocks, adds dissolved phosphate to soils and leads to the precipitation of highly insoluble phosphate minerals such as pyromorphite [Pb$_5$(PO$_4$)$_3$Cl] (Ma et al. 1995; Miretzky and Fernandez-Cirelli 2008). A potential negative consequence of phosphate remedial amendments, however, is excessive phosphate leaching from soils and runoff to water bodies, which can promote algal blooms and eutrophication.
Cement-based treatments, sometimes together with ferrous sulfate, have been studied as an amendment for immobilization of problematic oxynion contaminants such as arsenate (Voigt et al. 1996; Miller et al. 2000). Ettringite-type minerals [Ca–end member: $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_12\cdot26\text{H}_2\text{O}$], which form at high pH, have been proposed as a potential host phase for oxyanions (Chrysochoou and Dermatas 2006), as well as for cations (substituting for $\text{Ca}^{2+}$). This mineral class has a channel structure that may allow substitution of sulfate by oxynions of similar structure and size, such as chromate, borate, arsenate, vanadate, and selenate (Poellmann et al. 1993) (Fig. 2). In the presence of $\text{Fe}^{3+}$, $\text{Fe}$-ettringite (where $\text{Fe}$ substitutes for $\text{Al}$) has been synthesized experimentally and forms an incomplete solid solution with Ca-ettringite (Möschner et al. 2009). Field samples of arsenic-contaminated soils, collected more than 10 years after treatment with a combination of Portland type-V cement and ferrous sulfate, indicate the formation of ettringite and a close association of arsenic with calcium and iron (Illera et al. 2006) (Fig. 2). Comparison of field samples with laboratory control experiments suggests that arsenic (present only as arsenate) is associated with ettringite, possibly within arsenic-rich domains that locally resemble calcium-arsenate phases.

Microencapsulation (Fig. 1) refers to a mechanism whereby contaminants are bound physically in nano- to microscale inclusions or as sorbed or precipitated nanoparticles within another resistant medium. This mechanism may be more prevalent than currently recognized due to the lack of microscale characterization of reaction products in prior studies. Silica- and cement-based amendments provide an example of microencapsulation that reduces contaminant partitioning into porewater. During hydration of ordinary Portland cement added to soil, abundant neoformed C-S-H gel coats and binds arsenic-contaminated soil particles, thereby acting as a physical barrier to porewater leaching (Voigt et al. 1996). Microencapsulation may also be an effective mechanism for relatively unreactive contaminants such as mercury if a two-step treatment process is employed—for example, sorption to activated carbon or precipitation as insoluble mercury sulfide, followed by microparticle encapsulation with a more chemically or physically resistant treatment such as a cement-based amendment. Encapsulation-based remedies may also result in permeability reduction, thereby decreasing the flux of water through treated soil and the potential for leaching of stabilized contaminants.

**METHODS OF APPLICATION**

Mineral-based remediation strategies rely on adequate contact between amendments and contaminants to promote contaminant transformation and immobilization reactions. As such, delivery and uniform distribution of amendments within the targeted soil volume are often the most significant engineering challenge for successful in situ application. Selection of an appropriate delivery method is dictated by both the physical state of the amendment (e.g. solid phase versus liquid or slurry) and the physical and hydraulic properties of the soil medium. For shallow applications, mixing of amendments using conventional earth-moving equipment has been widely used. Direct subsurface injection of liquid or slurry amendments is commonly used for deeper applications. However, nonuniform amendment distribution can be a problem for subsurface injection, especially in heterogeneous soils or sediments containing low-permeability regions. This can be mitigated to some extent by controlling the injection pressure, pulsing, or adjusting the injectate fluid viscosity to site conditions. Subsurface barriers containing reactive solid phases have been used where contaminant mass-flux reduction is desired. A potential pitfall of this technology is clogging due to infilling of pore spaces by the formation of secondary precipitates or biological fouling over time, which can lead to mobile contaminants bypassing the

**FIGURE 1** Conceptual models of molecular-scale sequestration mechanisms for representative contaminants and mineral-based amendments. **In surface adsorption,** “inner-sphere” refers to direct bonding of an ion to atoms on the mineral surface, whereas “outer-sphere” indicates the presence of water or hydroxyl ligands between the metal center and the surface. **Ion exchange** is typically associated with the exchange of cations in clay mineral interlayers with species in solution. **Surface reduction-oxidation** processes may involve either microbial biodegradation of organic compounds coupled to mineral reduction, or the oxidation (or reduction) of adsorbed inorganic contaminants. Structural incorporation of contaminants by the precipitation of new phases may involve the formation of either amorphous or crystalline solids and contaminant substitution, or the encapsulation of micro- or nanoscale precipitates containing contaminants into new phases.
Another problem is the potential for adverse biogeochemical reactions that may shift pH or redox conditions and thus remobilize contaminants.

In situ soil mixing using specially designed, large-diameter augers has proven to be one of the more successful methods for uniform delivery of chemical amendments to soil depths in excess of 10 m (Fig. 3). Soil is treated by simultaneous mechanical mixing and injection of fluidized amendments in overlapping cells 60 to 140 cm in diameter in 1.5 m depth increments until the desired total treatment depth is attained. A final mixing pass over the entire cell thickness ensures uniform amendment distribution. After amendment application, soils may be covered with an impermeable cap to limit infiltration and leaching, or with clean soil, and then stabilized with vegetation.

The use of reactive amendments to treat subaqueous or subsurface sediments presents significant challenges, and this is an area of considerable research. A crucial difference for the subaqueous environment is the method of amendment delivery, for which site considerations such as water depth, currents, bottom topography, and nature of the contaminants determine method feasibility (Bailey and Palermo 2005). Delivery methods, including release, spreading, broadcasting from the water surface, and the use of subaqueous diffusers, must be designed to minimize sediment resuspension. Amendments must have sufficient contact with contaminants in the sediment, and the intended reactions must proceed under saturated, often reducing, conditions. In shallow marsh or tidal areas, mixing of amendments directly into shallow subaqueous sediments with large-scale mixers or slurry injection from barge- or crawler-mounted equipment is potentially feasible, as demonstrated in a recent pilot study in which an activated carbon amendment was added to PCB-contaminated mudflat sediments (Cho et al. 2009).

Another promising technology for subaqueous sediments is the use of amendment media within an engineered cap to create a reactive geochemical barrier system. New research is examining a variety of reactive materials for this application, including adsorptive media, such as expansive clay minerals, zeolites, or activated carbon, or reactive materials, such as Portland cement or siderite (FeCO$_3$). Reactive amendments are emplaced either between layers of conventional capping material, such as gravel or coarse sand, or in geosynthetic composite or textile mats. The treated area is then covered with a clean sediment layer for long-term, active contaminant attenuation, physical isolation, and erosion control (Bailey and Palermo 2005).

**REGULATORY FRAMEWORK, ACCEPTANCE, AND ECONOMICS**

Development of science and technology for the remediation of contaminated soils and sediments has been driven by environmental regulations enacted in many countries, beginning mostly in the 1970s. Legislation was initially created in response to environmental disasters such as Love Canal (USA) and Minamata Bay (Japan), with the goal of restoring contaminated sites and impacted natural resources to pristine conditions. With the realization during the 1980s and 1990s that such a goal was economically and sometimes technically unfeasible given the sheer number and complexity of contaminated sites, the paradigm has shifted to one of risk management. In many developed countries (e.g. United States, United Kingdom, Canada, Australia, and others), complex, risk-based regulatory policies for site remediation are often implemented at the state or regional government level, and sometimes tailored to specific geographic and political factors. Because standards tend to be site-specific and regulated locally, the use of soil stabilization technologies has increased slowly over the
last few decades. For example, at U.S. Superfund sites, the use of an in situ treatment of any kind for source control of contaminants increased from 47% of sites during the period 1982–2005 to 60% of sites during 2002–2005. Solidification–stabilization constituted only about 10% of the in situ technologies applied at all Superfund sites, with the dominant application being remediation of metal and metalloid contaminants (US EPA 2007). These trends suggest increasing interest in using in situ treatments for site remediation, but also some reluctance to employ them, probably because of an inability to demonstrate effectiveness, uncertainty in long-term performance, or economic factors.

The effectiveness of soil treatment has traditionally been assessed primarily by extraction-based tests such as the Toxicity Characteristic Leaching Procedure (TCLP), the Waste Extraction Procedure (WET), and the Synthetic Precipitation Leaching Procedure (SPLP). These are usually short-term (<24 hours) batch procedures that evaluate contaminant partitioning between the solid and a leaching fluid. Some of these protocols were developed for specific regulatory purposes and thus are not necessarily appropriate for evaluating contaminant fixation under a variety of field conditions. For example, the TCLP, which employs an acidic acetate solution as the leachate, was developed to simulate leaching by dissolved organic compounds in order to determine whether specific waste types are legally acceptable for landfill disposal in the United States. Nevertheless, the TCLP continues to be a widely used test for a range of organic and inorganic contaminants. In Europe, significant effort has been directed toward standardization or “harmonization” of a number of different extraction tests. Post-treatment monitoring of groundwater and surface water is typically conducted to confirm that remediation has reduced contaminant mobility. Although such assessments are useful for evaluating contaminant sequestration following treatment, they do not directly address whether amendments are effectively reducing the risk of contaminant exposure at a site for a sufficiently long period of time. More recently, there has been a regulatory shift towards performance evaluations that are more closely tied to contaminant bioavailability and exposure risk. This effort includes development of extraction tests, such as the Physiologically Based Extraction Test (PBET). The PBET and similar protocols evaluate partitioning between contaminated solids and simulated gastric fluids to assess bioaccessibility, and are compared against relative bioavailability tests that employ animal models, such as swine or mice (Kelley et al. 2002; NRC 2003). More direct evaluations of toxicity reduction include the survival and growth of soil biota (e.g. earthworms) in treated versus untreated soil, the use of plant bioassays as a measure of metal phytoavailability in soil, and the development of methods for using microorganism assays and biomarkers as monitoring tools in the field. Alternative assessment metrics are important for the acceptance and evaluation of mineral amendments as a remediation option.

Another potential barrier to the use of mineral amendments for soil remediation is the overall cost of treatment relative to other methods that provide similar risk reduction. Expenses for mineral-based remediation vary widely depending on the site, contaminants, and ex situ versus in situ treatment. The cost of ex situ treatment of excavated soils depends on the processing rate and volume of soil treated. For example, in the United States, the cost typically ranges from US$90 to $190 per cubic meter (m³). In situ treatment using auger-based equipment ranges from US$50/m³ for shallow contamination to more than US$300/m³ for deeper applications (US EPA 2009). When selecting an appropriate remedy for a particular site, the estimated cost for in situ treatment is compared with that of more traditional methods, such as excavation and off-site disposal. The long-term effectiveness and permanence of risk reduction are also factored into the selection process.

**SUMMARY AND OUTLOOK**

Remediation approaches need not be restricted to a “one-size-fits-all” methodology in which convenient or inexpensive amendment materials are used regardless of whether the treatment is compatible with the environmental characteristics of a particular site. Rather, remedia-
tion strategies can and should be tailored to site-specific biogeochemical and hydrologic factors where existing conditions can modify or enhance the remediation method. Although the effectiveness of mineral amendments in reducing contaminant mobility has been demonstrated in many instances by operational tests, detailed knowledge of sequestration mechanisms is still lacking, particularly over timescales of years to decades. Better understanding of the chemical and physical controls on contaminant immobilization, together with a framework for site assessment, would aid in selecting amendments that are compatible, with and optimized for, a specific site. Because many amendment technologies were originally developed for the treatment of waste streams before disposal, it can be a challenge to adapt them for in situ treatment of soils and sediments where contaminates have already been released to the environment and where the goal is to limit further dispersal and exposure to humans or biota. Amendment stabilization technologies are particularly useful when combined with conventional methods, such as source-area removal, pump-and-treat, or vapor extraction, or with other in situ technologies, such as bioremediation, phytoremediation, reactive barriers, capping, or monitored natural attenuation in an overall risk-management approach. Better knowledge of contaminant sequestration mechanisms would improve confidence in the use of mineral-based amendments for soil remediation and promote the use of reprocessed and recycled materials as amendments, thereby making this technology more sustainable and economically competitive.

ACKNOWLEDGMENTS

The authors thank the guest editor, Mark Hodson, for the opportunity to contribute to this issue. Synchrotron X-ray data were collected at the Advanced Light Source, supported by the Office of Basic Energy Sciences, U.S. Department of Energy, under Contract No. DE-AC02-05CH11231. The authors gratefully acknowledge financial support for their remediation research from the US-NIH/NIEHS Superfund Research Program (RO1ES016201).

REFERENCES


Interested in Remediation? We have publications for you!

SC 25 Biological-Mineralogical Interactions
Editors: Julie M. McIntosh and Lee A. Groat (1997)
ISBN 0-921294-25-2, 239 pp

SC 31 Environmental Aspects of Mine Wastes
ISBN 0-921294-31-x, 496 pp

SC 34 Mercury: Sources, Measurements, Cycles, and Effects
Editors: Michael B. Parsons and Jeanne B. Percival (2005)
ISBN 092129434-4, 298 pages

TI 47-3 Minerals in Contaminated Environments: Characterization, Stability, Impact
Editors: Karen A. Hudson Edwards, Heather E. Jamieson, Kaye Savage, and Kevin G. Taylor
ISSN 0008-4476, 208 pp

ISBN 0-921294-43-3, 496 pp, now only $75

Order online at www.mineralogicalassociation.ca

Anchor QEA - Seeking Geochemists to join our staff!

Anchor QEA is an environmental and engineering consulting firm that specializes in aquatic, shoreline, and water resource projects. Our business philosophy is to provide technical leadership, excellent client service, and quality products with personal and professional integrity. With more than 250 employees in offices across the United States, Anchor QEA has extensive experience and expertise in water resources, water quality, coastal development, habitat restoration, and contaminated sediment management. Our company culture promotes professional development - with a small company “vibe” that is supportive, fun, and close-knit. We work together across disciplines and across the country to help our clients with all phases of some of the most complex and challenging sites in the nation - from the conceptual stage to permitting, design, and construction.

We are currently expanding our capabilities in environmental geochemistry and invite applications from talented and highly motivated individuals with strong analytical abilities and excellent communication skills. Reactive transport modeling and/or laboratory experience are a plus. You can also visit our website to view other openings in offices across the nation. We hire only the best and brightest - and we hope you will consider joining our crew!

Please submit resumes to: careers@anchorqea.com

www.anchorqea.com
INTRODUCTION

Soil contamination occurs worldwide. Remediation is a challenge, not only from a technological viewpoint, but also because of the large costs involved. Many contaminated sites comprise wide areas of relatively low, but significant, concentrations of contaminants. Examples of large contaminated areas include regions affected by metal smelters or mining activities and agricultural land affected by long-term use of metal-containing fertilizers or agrochemicals. The incident at the Aznalcóllar mining site in Andalusia, Spain, in 1998 is an example where a single accident – the failure of the mine's dam, which held several million tons of pyrite-rich slurry – caused contamination with metals over an area of about 2500 ha (López-Pamo et al. 1999). The scale of such contamination renders cleanup with conventional engineering-based soil remediation techniques prohibitively expensive, even though the ecological risk and potential hazards may be highly significant. Using plants to remove or at least control metal contamination in cases like these is potentially an economic and less invasive solution.

PHYTOMANAGEMENT AND PHYTOREMEDIATION

Phytoremediation is defined as “the use of green plants to remove pollutants from the environment or to render them harmless” (Cunningham and Berti 1993). It includes a range of approaches to treat soil, waste water and air. In a broader context, phytomanagement involves the manipulation of soil–plant systems to affect the fluxes of trace metals in the environment, with the goal of remediating contaminated soils, recovering valuable metals, or increasing micronutrient concentrations in crops (Robinson et al. 2009).

Applications of phytoremediation for soil cleaning can be subdivided into different approaches (Fig. 1). In phytoextraction, plants are used to move soil contaminants to the harvestable plant tissues. The contaminants are subsequently removed by harvesting the plant. Some elements, such as mercury and selenium, can be transformed into volatile compounds by the plant and are released into the atmosphere. This phenomenon is exploited in phytovolatilisation. Phytoimmobilisation, or phytoimmobilisation, is defined as the breakdown of contaminants either in the root zone or through metabolic processes within the plant. Phytostimulation, or plant-assisted bioremediation, involves the stimulation of microbial and fungal degradation of organic pollutants by the release of exudates/enzymes into the root zones. In phytostabilisation, plants are used to reduce the mobility of contaminants and to prevent their migration to groundwater (leaching) or air (wind transport) and their entry into the food chain.

The lower cost of phytoremediation compared to that of conventional soil remediation techniques is a major advantage. Conventional techniques typically cost around $1 million/hectare, compared with an estimated $60,000–$100,000/hectare for phytoremediation (Robinson et al. 2003). Phytoremediation offers several other advantages. As an in situ technique, it causes less disturbance at the contaminated site than civil engineering earth-moving techniques and enjoys a high level of public acceptability. It can be applied over extended areas of land and primarily targets the more bioavailable fractions of metals in soils, which are the most relevant from an environmental risk perspective. Removal of the available fractions is proposed in the concept of “bioavailable contaminant stripping”, where the aim is to target the extraction of only the most labile, bioavailable metal pools (Hamon and McLaughlin 1999). Finally, there is a huge potential for phytoremediation in the contexts of biomass energy, improved biodiversity, watershed management, soil protection, carbon sequestration and improved soil health, applications that remain underexploited (Dickinson et al. 2009). Phytoremediation encompasses a whole array of approaches to contain, abate and manage contamination of land. However, it remains a challenge to achieve an acceptably fast removal of metal contamination from soils using plants (Vangronsveld et al. 2009). Approaches involving phytoextraction are explored in the subsequent sections.

PHYTOEXTRACTION

Phytoextraction involves the uptake of metals from the soil and their translocation to harvestable plant parts. Metals are then removed from the site though harvesting of the plant biomass (Fig. 2). For an efficient and fast operation, metal concentrations in the above-ground plant parts should be elevated, and biomass production should be high.
and fast. Phytoextraction is successful if the soil is cleaned to a level that complies with environmental regulations and, from an economic viewpoint, at a lower cost than an alternate technology or the cost of inaction (Robinson et al. 2006).

Hyperaccumulator plants can accumulate very high levels of a specific element, such as nickel or zinc – up to levels of 1–5% of their dry weight (Baker and Brooks 1989). Unfortunately, their usefulness in metal phytoextraction from soils is limited by their high metal selectivity, very slow growth and low biomass production.

Metal concentrations in non-hyperaccumulating plants are commonly orders of magnitude lower. Moreover, the extent of metal accumulation and distribution within different plant parts is highly variable among plants, even among clones of the same plant species. For example, 19 inbred lines of maize (Zea mays L.) grown in identical conditions had shoot cadmium concentrations ranging from 0.9 to 9.9 mg kg\(^{-1}\) dry weight (Florijn and Van Beusichem 1993). In well-controlled solution cultures, metal levels in shoots of different clones of a single species of willow, Salix viminalis, varied greatly. Cadmium ranged from 0.3 to 8.5, copper from 0.75 to 7.8 and zinc from 64 to 1200 mg kg\(^{-1}\) dry weight (Greger and Landberg 1999). This variability in the capability to accumulate metals substantially limits the number of candidate plants available for phytoextraction. Also, as with hyperaccumulators, enhanced uptake by a plant is generally limited to only a few elements. Therefore, phytoextraction may only be an option if just one or a few metals are of concern.

In addition to the above constraints, phytoextraction is limited by basic plant physiology. The contaminated area has to be amenable to plant growth. Soil conditions and climate are primary factors, but the type and levels of contamination can also affect the success of plant cultivation. The depth to which contamination is removed is governed by the rooting depth of the plants.

Because of the above limitations, phytoextraction currently is viable only when combined with the production of biomass with an economic value for non-food applications, e.g. paper production and renewable energy (Lebeau et al. 2008; Dickinson et al. 2009). Current research therefore focuses on enhancing phytoremediation. One method of doing this is via genetic modification. Hyperaccumulating capabilities might be introduced into fast-growing, high-biomass plants, or hyperaccumulator species might be modified to become fast-growing, high-biomass varieties. This article deals with another direction of research, in which phytoextraction is aided by agronomic and/or forestry practices that involve manipulating plant growing conditions. This is referred to as assisted phytoextraction or enhanced phytoextraction and requires an in-depth knowledge of soil–plant interactions.

**UPTAKE OF METALS BY PLANTS**

For their growth, plants acquire nutrients, including metals and other trace elements, from the soil. Although a direct exchange between plant roots and soil particles is possible, it is mostly the concentration in the soil solution (the water and its solutes present in soils) that determines the availability of metals to plants. Generally the effective availability of metals to plants is limited because of low metal solubility in the soil solution. Metals are distributed over different soil compartments, where they exist in a variety of chemical forms that strongly differ in reactivity (Fig. 3). A major fraction of the total metal content is usually associated with the solid phases. Elements that are sorbed to solid-phase components such as clay minerals, iron and manganese (oxy)hydroxides and organic matter are exchangeable with the soil solution to varying degrees depending on, amongst other things, the sorption mechanism. When occluded within soil solids, they are at least temporarily unavailable for exchange with the soil solution, unless the solid phase concerned is dissolved or otherwise destroyed. Trace elements structurally incorporated into soil minerals are not likely to become available. They may be released over long timescales as the minerals weather. Physical, chemical and biological processes in soil will determine the speciation, redistribution, mobility and ultimately the bioavailability, i.e. the availability for uptake by organisms, of trace elements. The timescale by which
the different processes occur in soils can vary between nanoseconds and centuries or more.

Any factor that affects the solubility of trace metals in soils will also tend to influence their uptake by plants. Plant roots absorb trace metals mainly from the soil solution. Eventually their concentrations in the rhizosphere, the volume of soil in the immediate vicinity of the roots, can be depleted. Metals can be resupplied to the roots through advection and diffusion. Advection is where the dissolved metals are transported along with the soil water flow. Diffusion involves the spontaneous migration of metals from an area with higher concentrations to an area with lower concentrations. Metals can also be resupplied via the dissociation of metal complexes present in the solution, e.g. organic complexes, and through the release of metals that are weakly bound to the soil solids. The extent of this resupply can differ greatly among soils. It is determined by numerous factors, including the concentration of total metals in solution and their chemical forms, the rate at which the metals diffuse through the soil solution to the roots, and the rate at which metals are released from the soil solids to the soil solution.

The effective uptake of metals by plants is largely controlled by plant-specific mechanisms of metal tolerance and homeostasis. These physiological mechanisms regulate the concentrations of essential trace elements such that they remain within physiological limits, and they intervene to minimize the toxic effects of metals. Largely because of this active involvement of plants in regulating metal uptake, there is no straightforward relation between metal contents in the soil – not even the easily extractable fractions – and metal concentrations in the plant. Trace metal accumulation rates in plants are dependent, consecutively, on mobilization and uptake from the soil, compartmentalisation and sequestration within the root, efficiency of xylem loading and transport, distribution between metal sinks in the aerial parts of the plant, and sequestration and storage in leaf cells (Clemens et al. 2002).

Within the plant root, there are two parallel pathways for uptake of water and nutrients: the apoplastic and the symplastic pathways (Fig. 4). The apoplastic pathway passes through cell walls and spaces between the individual cells. It involves passive transport by advection and diffusion. The symplastic pathway proceeds from cell to cell. It involves active transport across membranes. In these membranes and within the cell, biological structures including transporters, chelators and chaperones regulate the uptake, transport and storage of elements within the plant.

The apoplastic pathway is discontinuous. It is interrupted by the root endodermis, where the Casparian strip obstructs the passive transfer of solutes to the stele, i.e. the central part of the root, and thus also to the rest of the plant. However, the endodermis is not a perfect barrier. There are passage cells and sites along the root axis where this barrier is “leaky”. At the root tip, the Casparian strip is not fully developed. For these reasons, some nutrients can reach the stele by apoplastic transport (Nowack et al. 2006).

To increase the uptake of nutrients, plants actively change the soil environment in the rhizosphere by exuding substances that are involved in the uptake mechanism. The processes responsible for changes in the rhizospheric pH involve the production of carbon dioxide gas, the release of root exudates, the excretion or uptake of protons and bicarbonate, and the production of organic acids by microbes.

Factors that limit the solubility and mobility of metals in the soil solution will also generally tend to limit their uptake by plants. Soil pH is one of the most significant factors influencing the concentration of metals in solution and also has a major effect on plant uptake. The influence of organic matter is complex and depends on the element and the specific soil environment. Nutrient interactions will also affect the patterns of metal uptake by the plant. In assisted phytoextraction, attempts are made to favour metal bioavailability and subsequent metal uptake by suitably influencing the growing conditions of the plant. This can be accomplished by the use of soil amendments or natural soil microorganisms.

**USE OF SOIL AMENDMENTS**

Soil amendments influence the physico-chemical characteristics of the soil environment, and thereby the distribution and chemical forms of metals in the soil. In contrast to the use of amendments as remedial agents in themselves (O’Day and Vlassopoulos 2010 this issue), in assisted phytoextraction amendments are used to increase the concentration of metals available for uptake and translocation into harvestable plant parts by bringing metals into solution. There are three main categories of amendments: (1) inorganic amendments, (2) organic acids and amino acids, and (3) complexing agents, in particular, aminopolycarboxylic acids (APCAs) (Meers et al. 2008).

Among the inorganic amendments, chloride is widely studied. It forms soluble chlorocomplexes that contribute to increasing the overall solubility and availability of some metals. It is particularly effective for cadmium, and to a lesser extent for mercury, zinc and lead. The impact of elemental sulphur on metal mobility and increased availability to plants is currently being investigated. Sulphur is expected to enhance the uptake of metals by plants because acidity is produced when it is oxidised by soil microorganisms. This in turn mobilises metals from soil solids into the soil solution. Hydrogen peroxide treatments have also been tested. These destroy organic compounds, allowing...
for increased metal availability, in particular, of copper and zinc. Other inorganic additives, such as thiocyanate, cyanide and iodide, have been evaluated to a lesser extent (Meers et al. 2008).

Organic acids and amino acids occur naturally in the soil. Some of them increase metal mobility and bioavailability by forming soluble organo-metallic complexes. A wide variety of small organic acid molecules, such as oxalic acid and citric acid, are excreted by plant roots. They function as natural chelating agents capable of solubilising mineral soil components such as metals. Citric acid is most widely studied in the context of phytoextraction.

Various amino acids, such as histidine and nicotianamine, play a role in metal transport within plants (Krämer et al. 1996). Higher plants respond to potentially toxic metals by synthesizing phytochelatins and related cysteine-rich polypeptides. For example, plants can tolerate a 10–1000-fold higher amount of phytochelatine-bound cadmium than free ions (Zenk 1996). The high degree of biodegradability of organic acids means that their use as a soil amendment in assisted phytoextraction entails a lower risk for leaching after removal of the vegetative cover because of the stability and persistence of the chelating agents, leaching is practically unavoidable. Preferential flow, where soil water preferentially moves through more permeable zones in the subsoil, leads to fast downward movement of metal complexes and chelant. This is likely to increase groundwater pollution and metal toxicity for plants and soil organisms in the wider environment (Nowack et al. 2006).

**PHYTOEXTRACTION ASSISTED BY MICROORGANISMS**

A different strategy to enhance the uptake of metals by plants involves the use of natural soil microorganisms. This approach is sometimes referred to as bioaugmentation-assisted phytoextraction. Soil microorganisms can enhance the growing conditions of plants, thus facilitating biomass production and in particular root growth. At the same time, the plants may become more resistant to elevated levels of metals (Glick 2010).

Soil microorganisms can increase the bioavailability of metals in soil through the production of microbial chelates such as siderophores. This approach has several advantages over the addition of chemical chelates. First, microbial chelates will be produced predominantly in the vicinity of the roots. Second, their persistence will be shorter than that of synthetic chelates (White 2001). The microorganisms of interest are able to survive in adverse environmental conditions where they have a favourable influence on plant growth and metal uptake (Rajkumar et al. 2010). Although bioaugmentation has not been shown to enhance the performance of phytoextraction as much as chelating agents, the lower risk of leaching and possibly also cost factors warrant further exploration of the potential of bioaugmentation-assisted phytoextraction (Lebeau et al. 2008).

**AGRONOMIC ASPECTS OF ASSISTED PHYTOEXTRACTION**

Research up to now has focused mostly on the geochemical side of metal removal. Agronomic practices may also impact on phytoextraction performance. Crop breeding can improve the biological characteristics of the plant and enhance their remediation potential. Seed-coating technology may promote the germination of seeds in contaminated sites. The use of crop culture technologies may accelerate growth, increase biomass and enhance metal uptake (Wei et al 2008). For example, plant density can play a role in the distribution between above-ground and below-ground biomass in turnip. Depending on metal accumulation in the turnip shoot and root, the optimal plant density for phytoextraction purposes might be different from that for agronomic production aimed at maximizing turnip yield.
Rooting patterns are inherently dependent on plant choice. Some plants have clustering roots whereas others have tapping roots. Conditions such as water content, nutrient limitations, soil compaction and root-zone aeration also influence the rooting patterns. These factors can affect the effective depth to which phytoextraction can be applied.

The optimal rotation schedule for biomass is another aspect requiring further study. Some studies propose multiple short cropings rather than a single crop over the duration of the growing season because young plants tend to accumulate higher metal loads. However, total annual biomass yield might be reduced. The most effective schedule therefore needs to be determined. In addition, an optimal sequence for plant selection during the growing season and for cover during autumn and winter needs to be assessed.

**PREVENTING METAL LEACHING FOLLOWING MOBILISATION**

Mobilising metals in a contaminated soil entails a significant risk that elements leach and move through the subsoil into groundwater, rather than being taken up by plants. This is currently a major obstacle for the application of chelate-assisted phytoextraction. Physical processes such as preferential flow may strongly increase the amount of leaching. Assisted phytoextraction using mobilizing agents will become acceptable only when contamination of subsoil by vertical migration of the contamination is absolutely prevented. This would require a thorough control of the hydrological balances in chelate-amended soils to cause a net upward movement of soil moisture. So far, a satisfactory solution to this key issue has not been found (Evangelou et al. 2007). Research is ongoing into combining appropriate doses and application of the amendments and developing precautionary measures to avoid metal and nutrient leaching from the site.

More precise placement of soil amendments in the root zone, rather than evenly spreading it over the field, might enhance extraction efficiency, reduce the required dosage per hectare and ultimately decrease the risk of leaching. This could potentially be achieved by direct injection into the root zone or by drip irrigation of the dissolved treatment at the plant base. Furthermore, this method could be combined with partial sheltering of the soil at the locations of amendment applications to reduce the impact of rainfall on leaching through the soil.

Strategies might be envisaged where the activity of the chelate is controlled through the properties of the active compounds or chemical measures. The ‘chemical hand-brake’ aims to chemically reestablish chelate-assisted mobilization, for example, to prevent leaching after harvest or in case of excessive rainfall. Application of a sulphide solution has resulted in instantaneous precipitation of chelated metals (unpublished data). Another example is the alternating application of acidifying agents (e.g. organic acids) during the growing season and liming agents to prevent leaching in autumn and winter. Finally, application of organic matter may partially restabilize mobilized metals through sorption and complexation (see Jones 2010 this issue). Organic matter can also increase the amendment degradability and thus shorten its effect.

Treated soil could be mechanically sheltered in case of excessive rainfall. Another option involves the implementation of a horizontal permeable barrier consisting of a mixture of sorbing materials, such as apatite, vermiculite and sawdust, under the plough layer to provide additional safeguards against leaching (Kos and Leštan 2004). Technical and financial impediments to this procedure remain to be evaluated.

The use of foliar amendments, i.e. products directly applied on plant leaves, offers prospects for complementing or substituting for soil amendments (Meers and Tack 2004). Over the last decades, foliar application of nutrients has become common practise in agriculture and horticulture. Foliar application tends to result in a larger uptake of nutrients compared to when the same amount of fertilizer is applied to the soil, because it promotes additional nutrient uptake by roots. Further research is required with different plant species, with different technical means of foliar application, with different compositions of amendment medium (e.g. use of surfactants) and with different soil treatments in combination with foliar application.

**PERFORMANCE**

A major bottleneck of phytoextraction is the time factor. Assisted phytoextraction aims to reduce the time span needed for remediation. Much experimental research into assisted phytoextraction has shown potential to achieve substantial increases in the transfer of metals from soil to plants over normal phytoextraction. In a sandy soil from Balen, Belgium, contaminated by metal smelter activities, removal of cadmium by the willow clone *Salix dasyclados* Loden was increased by a factor of 2 to 5 using the synthetic complexing agent EDDS (ethylene diamine disuccinate), leading to an estimated removal rate of 0.15 mg kg\(^{-1}\) y\(^{-1}\) (Meers et al. 2007). In a paddy soil in South China, application of EDTA increased lead uptake by *Viola huoshanensis* on an agricultural soil contaminated by nearby mining activities by a factor of 10. This performance theoretically could allow a decrease from 1000 to 500 mg kg\(^{-1}\) lead in a period of about 50 years (Zhuang et al. 2005). If all lead released using EDTA could be taken up by the plant, between 128 and >1200 high-transpiration days or between 8 and 100 crops would be needed to halve the metal concentration to 200 mg kg\(^{-1}\) of soil (Nowack et al. 2006). At best, remediation would take about ten years.

Various factors cause typical estimations of phytoextraction performance to be over-optimistic. First, there is the bioavailability of the metals. Of the total metal concentration, only some fraction, a bioavailable pool, is available for plant uptake. In assisted phytoextraction, attempts are made to increase this bioavailable pool. Phytoextraction would be limited to this pool if there were no resupply from less available pools. Over the years, the bioavailable pool, and accordingly plant concentrations and removal rates, will decrease. The bioavailable pool is likely to be replenished with time, but such resupply processes may be very slow and not significant within the phytoextraction period.

Many studies investigating assisted phytoremediation involve the use of amended soils in pot experiments. This leads to gross overestimations of realistic field performance of phytoextraction. Metals artificially added to soils in the form of soluble salts are highly available and readily taken up by plants, unlike metals in most contaminated sites. Based on this, overenthusiastic interpretations and promises have been made concerning the possibilities of metal phytoextraction. This causes a risk that the technology will be dismissed without proper evaluation (Vangronsveld et al. 2009).

A second factor that is not accounted for in basic performance calculations is that plant biomass production might decrease with time because of nutrient depletion in the soil after several harvests or pest infections. To account for this, assisted phytoextraction will likely need to be...
complemented by fertilizer use, pest control and crop rotation. Moreover, plant growth might be limited by other environmental factors, such as inadequate pH, salinity, poor soil structure or low water availability (Van Nevel et al. 2007).

Many sites are contaminated with more than one element. This might strongly affect the productivity of plants, especially considering that, in assisted phytoextraction, the plants experience even more stress because of the enhanced availability of the contaminants. The distribution of metals is typically highly heterogeneous both spatially and temporally. Roots in the field may not be in intimate contact with the contaminated material, thus resulting in lower-than-expected metal uptake. Areas of high metal contamination, so-called “hot spots”, may inhibit plant growth, rendering phytoextraction ineffective in these zones (Robinson et al. 2006).

CONCLUSIONS

Although the concept of phytoextraction is attractive for the effective removal of metals from contaminated soils, the removal rates currently achieved are not adequate for phytoextraction to be a fast and efficient clean-up technology. Phytoextraction is slow to the extent that it is viable only when combined with biomass production with economic value. Options for a more rapid and effective removal of metals by plants using enhanced phytoextraction are being explored, yet no market-ready technologies have emerged so far. Many approaches yield improvements in phytoextraction rates, which, while sometimes substantial, remain too limited to provide acceptably fast metal extraction rates. The greatest increases in plant uptake have been achieved using chelating agents. A major obstacle for approaches based on increasing metal solubility is a lack of control of metal leaching, which could result in groundwater contamination. Alternative approaches based on bioaugmentation are still in an early phase of research. Modes of application and site management at the field scale remain to be further developed and tested. Despite the current lack of convincing field experience after years of research, interesting aspects of the concept of phytoremediation still remain to be explored. We can therefore still expect that effective plant-based technologies for removal of metals from contaminated soils will eventually emerge.

REFERENCES


Bioremediation: Working with Bacteria

Blanca Antizar-Ladislao*

1811-5209/10/0006-0389$2.50 DOI: 10.2113/gselements.6.6.389

INTRODUCTION

Bioremediation is defined as the acceleration of the natural metabolic process whereby microorganisms alter and break down organic molecules into other substances. In situ bioremediation involves the placement of amendments directly into contaminated media, whereas ex situ bioremediation transfers the contaminated media to a selected site for treatment. Acceleration of the process is achieved by adding amendments to stimulate contaminant biodegradation by indigenous microbial populations (biostimulation). Amendments include air (oxygen), added by bioventing; oxygen-releasing compounds, which keep the contaminated media aerobic; and reducing agents, such as carbon-rich vegetable oil and molasses, which promote growth of anaerobic microbial populations. Bioremediation partly overlaps a form of phytoremediation called phyto-stimulation, or plant-assisted bioremediation, which involves the stimulation of microbial and fungal degradation of organic pollutants by the release of exudates/enzymes into the root zones, or rhizosphere (Tack and Meers 2010 this issue).

Bioremediation can also be accelerated through injection of native or non-native microbes (bioaugmentation) into a contaminated area. Numerous attempts have been made to design genetically modified microorganisms for environmental release as agents for the bioremediation of pollutants. However, these microorganisms do not behave in a predictable fashion under conditions that are quite different from the controlled ones of the laboratory. Recently, the onset of synthetic biology (i.e. the design and construction of new biological parts, devices and systems and the redesign of existing, natural biological systems for useful purposes; Chopra and Kamma 2006) has led to renewed interest in creating laboratory-designed microorganisms with superior catalytic abilities for use with recalcitrant pollutants. The issue at stake is whether the opportunities provided by synthetic biology will be converted into more vigorous biological agents that – once they are delivered to a target site for enhanced bioremediation – perform the clean-up with high efficiency and acceptable risks (de Lorenzo 2008).

But metabolism is not the only aspect of bioremediation. Bioaugmentation may also involve prior addition of biostimulation amendments to create favourable conditions for microbial activity. Additionally, a number of processes upstream (e.g. diffusion in solid matrixes, bioavailability, weathering, abiotic catalysis of pollutants) and downstream (e.g. stress, predation, competition) of the metabolic process constrain the outcome of the remediation.

Bioremediation is one of the treatment technologies extensively used at US Superfund sites. In fact, 12% of the in situ projects and 11% of the ex situ projects have used bioremediation (US EPA 2010). Table 1 presents the evolution of the use of bioremediation during the last three decades. The main in situ technology used more frequently than bioremediation is soil vapour extraction (51%), while ex situ technologies used more frequently than bioremediation are stabilization/solidification (34%) and incineration (19%).

THE HISTORY OF BIOREMEDIATION

Bioremediation is not a new concept: microbiologists have studied the process since the 1940s (Zobell 1946). The first commercial use of naturally occurring microbes to safely and effectively clean up a toxic environmental disaster occurred in the late 1960s following an accidental oil spill in Cat Canyon (located in Santa Barbara, California, USA) after an oil pump shaft broke loose. The spillover went into the drainage system, into a stream and eventually into the nearest drinking water supply. George M. Robinson, assistant county petroleum engineer, treated the oil spill sumps with bacterial cultures that he had isolated in home experiments begun in the 1960s. The new treatment technology of bioremediation grew out of these early studies on petroleum hydrocarbon degradation.

One of the first scientific papers with a focus on the application of bioremediation was published in the 1980s (Sloan 1987), when a 3 ha lagoon near Houston (USA) contaminated with 20 million litres of organic chemical waste...
Biodegradable: they undergo a biological transformation.

Persistent: they do not undergo biodegradation in certain environments.

Recalcitrant: they resist biodegradation in a wide variety of environments.

Bacteria can play a significant role in the mitigation or removal of contaminants in the environment, both organic and inorganic. Their metabolism is dependent upon the availability of electron donors and acceptors, essential nutrients, and ions necessary for growth. Bacteria have evolved a wide range of mechanisms for the uptake and transformation of contaminants, and also for their immobilization or mobilization (Antizar-Ladislao and Galil 2004, 2006).

The oil spill in the Gulf of Mexico is currently receiving significant media attention. According to the latest US government figures, this oil spill has become the worst spill in US history, easily surpassing the Exxon Valdez environmental disaster (Clark 2010). Unfortunately, lessons learned from the Exxon Valdez oil disaster were difficult to apply to the oil spill in the Gulf of Mexico, since there are substantial differences between the two. The differences include the amount of oil spilled into the environment, the characteristics of the spill site and of the oil source, and the oil’s mode of dispersion. But what is clear is that the use of dispersants that break down the oil, employed extensively in the Exxon Valdez oil spill, is not appropriate. Dispersants make the oil less visible but not less toxic. The main problem, however, is that oil treated with dispersants is more likely to get past booms protecting critical shoreline because it is not floating as a mass on the water surface.

Prior to the Exxon Valdez spill in Alaska, bioremediation was mainly applied to the treatment of contaminated soils (for example, resulting from leaking underground oil storage tanks). Numerous commercial products have been developed for use as bioremediation agents, such as microbe-containing products derived from the biotechnology industry and fertilizers. Many bioremediation agents were used to clean up the Exxon Valdez spill. Particular attention was given to two types of fertilizers applied to contaminated shorelines in Prince William Sound: Inipol EAP22™, an oleophilic (strong affinity for oil) fertilizer formulation, and Customblen™, a granular slow-release fertilizer (Lindstrom et al. 1991).

### Table 1

**BIOREMEDICATION TREATMENT TECHNOLOGY BY FISCAL YEAR APPLIED AT US SUPERFUND SITES (1982–2008)**

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>Bioremediation Treatment Technologies</th>
<th>Ex situ</th>
<th>In situ</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982-85</td>
<td></td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1986</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1987</td>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1988</td>
<td></td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>1989</td>
<td></td>
<td>1</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>1990</td>
<td></td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>1991</td>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1992</td>
<td></td>
<td>4</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>1993</td>
<td></td>
<td>4</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>1994</td>
<td></td>
<td>5</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>1995</td>
<td></td>
<td>4</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>1996</td>
<td></td>
<td>6</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>1997</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1998</td>
<td></td>
<td>6</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>1999</td>
<td></td>
<td>4</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td>4</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>2001</td>
<td></td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>2002</td>
<td></td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2003</td>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td>2</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>2005</td>
<td></td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2006</td>
<td></td>
<td>6</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>65</td>
<td>64</td>
<td>130</td>
</tr>
</tbody>
</table>

*Total in situ control technologies 1982–2008: 537
Total ex situ control technologies 1982–2008: 598
Source: US EPA 2010*
Most of the information available on the biodegradation of organic contaminants concerns oxidative degradation, since aerobic culture techniques are relatively simple compared with anaerobic culture methods. Also, aerobic processes are considered the most efficient and generally applicable (Adriaens and Vogel 1995). Availability of oxygen can increase the growth rate and yield of aerobic organisms. Aerobes have mono- and dioxygenases, which are uniquely effective enzymes in the oxidation of hydrocarbons. The presence of oxygen, however, can suppress anaerobic processes, such as the degradation of halogenated pollutants, through the inhibition of reductive dehalogenation. In the case of hydrocarbon degradation, oxygen is rapidly depleted at heavily contaminated sites, resulting in anaerobic conditions (Donald and Freeman 1991). Anaerobic activity is widespread and has been reported under nitrate-, iron-, manganese- and sulphate-reducing conditions, as well as under methanogenic conditions (Foght 2008).

**WHAT INFLUENCES BIOREMEDIATION?**

The successful bioremediation of contaminated soils depends on factors such as contaminant characteristics, local climatic conditions, site hydrogeology, and the type of technology used for bioremediation. Of these, the selection and deployment of appropriate site-specific and contaminant-specific bioremediation technologies are the only factors controlled by bioremediation professionals.

The chemical characteristics of a contaminant play an important role in determining its susceptibility to biodegradation. Hydrophobicity, as measured by the octanol–water partition constant (i.e. the ratio of concentrations of a compound in the two phases of a mixture of octanol and water at equilibrium) or the inverse of aqueous solubility, is a key property that provides information about the bioavailability of a given contaminant, with increasing hydrophobicity leading to reduced bioavailability and therefore susceptibility to biodegradation. Bioavailability processes are defined as the individual physical, chemical, and biological interactions that determine the exposure of plants and animals to chemicals associated with soils and sediments (NRC 2003). The concept of bioavailability has recently attracted the interest of the hazardous waste industry as an important consideration in deciding how much waste to clean up. The rationale is that if contaminants in soil and sediment are not bioavailable, then more contaminant mass can be left in place without creating additional risk (Diplock et al. 2009).

Other characteristics relevant to predicting the fate and biodegradation of a contaminant include (1) its volatility, which determines its distribution between air and water, and (2) its charge, or polarity, which determines whether the compound sorbs primarily to the inorganic or organic soil fractions. Uncharged solutes will sorb mainly to the organic fraction, while charged or highly polar molecules will associate primarily with mineral surfaces of opposite charge or polarity.

Extreme conditions, including temperature, salinity and altitude, also influence contaminant biodegradation (Antizar-Ladislao et al. 2007; Godoy-Faúndez et al. 2008). For example, desert mining soils, typically with a low organic matter content, high mineral content and high salinity, have been little investigated (Rhykerd et al. 1995; Mader et al. 1997). In situ landfarming, bioventing and composting treatment technologies were implemented to treat more than 20 × 10^6 m^3 of oil that accumulated in the desert soil during the Iraqi invasion of Kuwait in the early 1990s (Al-Awadhi et al. 1996; Al-Daher et al. 2001). Research on Kuwait’s desert soils indicates that biodegradation of more than 60% of the total petroleum hydrocarbons initially present could be achieved after 8 months of composting in soil piles. By using a bulking agent (wood chips) and nitrogen–phosphorus–potassium fertilizers and by controlling the moisture content of the composting mixture, the biodegradation rate of heavily contaminated desert soils from Kuwait was significantly enhanced (Rhykerd et al. 1999).

Contaminated soils and sawdust were produced during the repair and maintenance of machinery and as a result of accidents during mining operations in the Atacama Desert of Chile (Fig. 1A). Soils and sawdust have been used routinely as cheap, readily available sorbent materials after spills of fuel oil, which consists of complex mixtures of aliphatic and aromatic hydrocarbons. Experiments on aged, contaminated mixtures of sawdust and soils have shown that more than 40% biodegradation of heavy hydrocarbons with initial concentrations in the range of 50,000–225,000 mg kg^-1 can be reached by 2 months of in-vessel composting (Fig. 1B) (Godoy-Faúndez et al. 2008).

Examples of bioremediation in extremely cold environments have also been reported (Filler et al. 2008). Indigenous Antarctic bacterial communities have recently been found to exhibit a high potential for bioremediation, even at low temperatures. Delille et al. (2009) reported that temperature had only a limited influence on petroleum
degradation in Antarctic seawater. They observed a similar number of hydrocarbon-degrading microorganisms in seawater samples treated at 4, 10 and 20 °C. They also found that the addition of nutrients increased the rate of petroleum biodegradation.

**BIOREMEDIATION STRATEGIES AND THEIR POTENTIAL**

An appropriate bioremediation strategy for treating a contaminated site needs to consider three basic principles: (1) biochemistry, or the amenability of the pollutant to biological transformation to less toxic products; (2) bioavailability, or the accessibility of the contaminant to microorganisms; and (3) bioactivity, or the opportunity for optimization of biological activity. Nevertheless, there are other factors that might slow down or even prevent biodegradation. An example is an imbalance in the carbon:nitrogen:phosphorus (C:N:P) ratio caused by high carbon and low nitrogen levels following, for example, an accidental spill of hydrocarbons. An imbalance in the C:N:P ratio reduces the capacity of microbes to form viable biomass using hydrocarbons as a carbon/energy source.

Several remediation technologies have been developed to clean up contaminated wastes and overcome the aforementioned limitations. We briefly review these below.

**Biosparging** is an in situ remediation technology that utilizes naturally occurring microorganisms to degrade organic contaminants within the saturated zone (Fig. 2a). The rate of remediation is enhanced by injecting air into the saturated zone. **Bioventing** is another in situ remediation technology that uses indigenous microorganisms to biodegrade organic constituents adsorbed to soils in the unsaturated (vadose) zone (Fig. 2b). The activity of indigenous bacteria is enhanced by inducing air/oxygen flow in the unsaturated zone and, if necessary, by adding nutrients.

**Bioaugmentation** refers to the addition of specialized nutrients to the contaminated site so that indigenous microbes that are present in sufficient numbers and types are able to break down the waste materials effectively. This accelerates the naturally occurring biodegradation process under favourable environmental conditions, such as appropriate oxygen/air, temperature, pH, and water content conditions, the addition/presence of suitable microbial populations, and proper mixing. **Bioaugmentation** is a significant in situ and ex situ treatment process in which indigenous microbes are added to a contaminated site in order to eliminate toxic contaminants (Bragg et al. 1994; Foght 2008).

**Anaerobic biotransformation** is used for the degradation of organic compounds that are resistant to aerobic bioremediation, such as chlorinated hydrocarbons, polychlorinated phenols and nitro-aromatics. Anaerobic treatment processes produce much smaller quantities of biomass (Antizar-Ladislao and Galil 2004). Moreover, anaerobic biotransformation of polychlorinated hydrocarbons is of particular interest in the bioremediation of contaminated soils and groundwater, since dechlorination rates are generally faster under these conditions. Substrate concentration, availability, temperature, pH, co-factor supply, concentration of cells, viability of cells and type of operation are some of the major factors responsible for successful anaerobic biotransformation processes (Märshner et al. 2001).

**Biological fixation** occurs naturally when bioremediation is connected to the development of microbes provided with dual functions: contaminant biodegradation and nitrogen fixation. Biological fixation is involved in nutrient cycles such as carbon, nitrogen, sulphur and phosphorous to maintain ecological balance.

**Figure 2** Schematic diagrammes illustrating (A) biosparging and (B) bioventing. Sources: (A) redrawn from www.csiro.au/science/Hot-Microbes.html; (B) redrawn from www.afpee.af.mil/resources/technologytransfer/programsandinitiatives/bioventing/index.asp

Bioremediation is an effective, continually evolving and improving technology for the management of a large variety of pollutants. One such improvement is the use of enzymes produced from microorganisms, plants, and animals in the removal of toxic compounds from industrial waste-water streams. In most microbial bioremediation treatment technologies, toxic compounds are converted into non-toxic end products. This occurs via enzymatic reactions which take place within or outside the cell by means of the secretion of intracellular or extracellular enzymes. However the use of enzyme-catalyzed treatment has several limitations, such as its high cost and the potential formation of toxic residual products that remain in the aqueous phase. In addition, enzymes can be inactivated permanently by the formation of various undesirable side products during the treatment process (Aitken et al. 1994). **Landfarming** is a bioremediation technology in which contaminated soils are mixed with soil amendments such as soil bulking agents and nutrients; these amendments are initially tillied into the earth, and the soil is subsequently periodically tilled for aeration. Contaminants are degraded, transformed, and immobilized by microbiological processes and oxidation. **Composting** is an aerobic process that utilizes naturally occurring microorganisms to degrade organic contaminants within the unsaturated zone. Composting is enhanced by injecting air into the unsaturated zone (Fig. 2b). The activity of indigenous bacteria is enhanced by inducing air/oxygen flow in the unsaturated zone and, if necessary, by adding nutrients.
process in which organic materials are biologically decomposed. Conventional composting processes typically comprise four major microbiological stages in relation to temperature: mesophilic, thermophilic, cooling and maturation. During these stages, the structure of the microbial community also changes, and the final product is compost.

Natural attenuation is the term used for all natural processes that are responsible for the remediation of pollutants in contaminated sites. Naturally occurring physical, chemical and biological processes can transform contaminants into harmless forms or immobilize them in the subsurface, thereby reducing the concentration of contaminants in the environment.

Each technology possesses inherent characteristics that make it appropriate for application at a particular site; for example, natural attenuation methods would be appropriate for handling comparatively dilute waste streams. In the last 20 years, significant research efforts have led to a detailed process-based understanding of the ecological, biochemical and genetic bases of microbial contaminant degradation, with a view to enhance microbial capabilities and design more effective bioremediation processes.

Most failures of bioremediation occur when introduced organisms do not thrive in the natural environment or when they cannot access the contaminant. These failures can be due to a lack of nutrients, predation or parasitism, competition, the immobility of introduced bacteria, contaminant concentrations below threshold for organism survival, or organisms feeding on alternative substrates. Furthermore, each contaminated site represents a different set of physico-chemical and environmental conditions, and technologies that work at the laboratory scale may not work in the field. This is often because laboratory experiments can be carefully controlled, while such optimal conditions may not be possible at the contaminated site.

**COST**

Three site-specific examples of project costs are shown in Table 2 (FRTR 2010). Factors contributing to the costs include site type, type of contaminants, concentrations of contaminants, extent of the contamination, and any challenges that may occur during remediation. The factors that were included in the total cost for the Kelly Air Force Base project in Texas included microcosm testing, capital costs for full-scale study, and operation and maintenance (O&M).

The technology implemented in this field demonstration project was bioaaugmentation, tested to treat groundwater contaminated with chlorinated solvents. This study indicated that the microbes added (KB-1 culture) were robust and able to compete with, and survive among, the indigenous microbial population. The cost estimate for the phased remediation plan at Beaches Laundry and Cleaners at Jacksonville Beach, Florida, includes capital costs, construction costs, O&M costs, and monitoring costs. The treatment consisted of soil excavation and soil vapour extraction (SVE) to address volatile organic compounds (VOCs) in soil at the site. Enhanced bioremediation was the technology selected to remove VOCs in the groundwater associated with a large contaminant plume at the site. Excavation and SVE were included in the remedial design to accelerate the removal of mass from the source area. The SVE system was designed to address soil contamination in the unsaturated ( vadose) zone of the site and portions of the site that could not be excavated due to building structural concerns and the shallow groundwater table. In situ enhanced bioremediation was used to expedite the bioremediation process in the dissolved phase (down-gradient) portion of the contaminated area (plume) through the addition of nutrient amendments. The nutrient amendment consisted of potassium lactate and denatured ethanol to serve as a carbon and energy source to support the growth and activity of chlororespiratory microbes at the site. The factors that were included in the total cost of the Newark Air Force Base project in Ohio included monitoring and injection wells and sampling events over 49 months. This full-scale project was based on enhanced in situ anaerobic bioremediation using a vegetable oil substrate. This provided the environment required for the dechlorination of ethenes, and clean-up goals were achieved in all treated locations.

**NEW TRENDS IN BIOREMEDIATION**

In 2006, a group of remediation professionals formed the Sustainable Remediation Forum (SURF). “The mission of SURF is to establish a framework that incorporates sustainable concepts throughout the remedial action process while continuing to provide long-term protection of human health and the environment and achieving public and regulatory acceptance” (SURF US 2009). Sustainable remediation is a term adopted internationally (SURF US 2009) and encompasses sustainable approaches to the investigation, assessment and management (including institutional controls) of potentially contaminated land and groundwater. Sustainable remediation is defined by SURF-UK as “the practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of undertaking remediation is greater than its impact, and that the optimum remediation solution is selected through the use of a balanced decision-making process” (SURF UK 2009).

To accomplish this, SURF embraces the following sustainable approaches: (1) minimize or eliminate the consumption of energy or other natural resources, (2) reduce or eliminate releases to the environment, (3) mimic a natural process, (4) result in the reuse or recycling of land, and (5) encourage the use of remedial technologies that permanently destroy contaminants.

The increasing awareness of sustainability within the remediation industry has provided a new impetus not only to develop new technologies but also to improve existing techniques that are considered to be mature in terms of their design, scope of use and cost. One way that bioremediation will evolve in the future to reduce its environmental footprint is the minimization of energy consumption and maximisation of the use of renewable energy. Often the breakdown products of organic contaminants include greenhouse gases such as carbon dioxide and various oxides of nitrogen. Another future trend will therefore be the minimisation of emissions of pollutants and greenhouse gases during bioremediation.
REFERENCES
Sloan R (1987) Bioremediation demonstrated at hazardous waste site. Oil and Gas Journal 85: 61-65

This conference will take an all-embracing look at gold—from mineralogy, to geology, to inputs, to coinage, to jewelry—and at all stages of its production and use. We will explore the contemporary focus on sustainable and environmentally conscious extraction and the increasing use of reclaimed metal by contemporary artists in gold. We will look at collections of gold throughout history and, looking beyond gold’s role as a repository of value, we will consider its symbolism, and how that has evolved over time.

This 2-day conference in New York April 7 – 9, 2011

For further information:
Initiatives in Art and Culture
Tel: 646-485-1792
E-mail: info@artinitiatives.com
Online registration: www.acteva.com/goi/gold
Remediation with engineered nanomaterials (ENMs) promises more effective and cheaper approaches than conventional methods due to the increased reactivity of nanoparticles and the possibility of in situ treatment. Three examples of the use of ENMs in soil remediation are nanoscale zero-valent iron for the degradation of halogenated organic compounds, nanoscale calcium peroxide for the destruction of organics (e.g. gasoline) and nanoscale metal oxides for the adsorption of metals. However, these methods are very new, and more research is needed on the mobility of ENMs in the soil and their impact on the environment.

Keywords: engineered nanomaterials, nZVI, adsorption, reduction, in situ remediation

INTRODUCTION

Maintaining and restoring the quality of air, water and soil is one of the great challenges of our time. Most countries face serious environmental problems, such as the availability of drinking water, the treatment of waste and wastewater, air pollution and the contamination of soil and groundwater. In many cases, conventional remediation and treatment technologies have shown only limited effectiveness in reducing the levels of pollutants, especially in soil and water (Rickerby and Morrison 2007). Nanotechnology promises a potential revolution in approaches to remediation.

Nanotechnology is a broad and interdisciplinary field dealing with structures and particles at the nanoscale. Nanotechnology can be defined as “research and technology development at the atomic, molecular, or macro-molecular levels using a length scale of approximately one to one hundred nanometers in any dimension; the creation and use of structures, devices and systems that have novel properties and functions because of their small size; and the ability to control or manipulate matter on an atomic scale” (US EPA 2007, p 5).

The terms nanoparticle (NP) and nanomaterial (NM) are used in the scientific literature to describe these small particles, and some confusion exists with respect to their exact definition; different organizations have come up with different definitions (Som et al. 2010). The term engineered nanoparticles (ENPs) is most often used as a collective term for all discrete particles that have one or more external dimensions at the nanoscale, while the term engineered nanomaterials (ENMs) is a collective term for ENPs and nanostructured materials. Nanostructured materials may be composed of discrete functional materials with one or more external dimensions at the nanoscale (e.g. polymer composites that contain ENPs), or they may be free of ENPs (e.g. nanoporous polymers, nanostructured bulk materials and nanoscale coatings).

Nanoparticles are not only produced deliberately for specialized materials and processes, they can also form as accidental by-products of industrial processes. They also occur naturally and are found in air, water, soil and sediments. Natural NPs can have an atmospheric, geogenic or biogenic origin (Banfield and Zhang 2001).

Since the 1990s the use of ENMs in a variety of environmental applications, such as water purification, wastewater treatment, indoor and outdoor air cleaning, and soil and groundwater remediation, has been investigated (Mueller and Nowack 2009). Various applications have been successfully demonstrated at the laboratory scale, but most of them still require verification of their efficacy and safety in the field. It is thus not surprising that to date few nanotechnological applications for environmental use have been commercialized. The high costs involved in developing materials and running pilot and field trials have also delayed progress.

However, some environmental applications of nanomaterials have entered the market or are under close investigation. These include:

- Nanoscale TiO$_2$ for the photocatalytic degradation of contaminants in air (e.g. NO$_x$, VOCs) and water (e.g. microorganisms, organic materials)
- Nanofiltration for wastewater treatment and drinking water purification (e.g. removal of hardness and desalination)
- Nanoscale zero-valent iron for soil and groundwater remediation

There is considerable commercial potential in environmental nanotechnologies. Boehm (2006) projected that the world market for applications of environmental nanotechnologies would reach approximately $6 billion by 2010. The market for soil and groundwater remediation is expected to grow to around $23.6 billion worldwide; the UK and Japan are expanding near-term markets, and central and eastern Europe countries will be important mid-term markets (Rickerby and Morrison 2007).
NANOPARTICLES: NEW PROPERTIES DUE TO SMALL SIZE

Nanoparticulate materials are new but not new. The chemical composition of nanomaterials may be the same as an equivalent material in bulk form (particle size in the micrometre to millimetre range), but nanoparticles can display totally new characteristics due to their high surface-to-volume ratio and because, at their small size, quantum effects come into play (Hochella and Madden 2005). For example, TiO$_2$ has been used as a white pigment in high-opacity paints for a long time. By contrast, nanoscale TiO$_2$ particles are transparent to visible light (wavelength 400–800 nm). Aluminium in cans is harmless, whereas nanoscale aluminium is highly explosive and can be used in rocket fuels. Hematite particles with a diameter of 7 nm adsorb Cu ions at lower pH values than particles with a diameter of 25–88 nm, illustrating one way in which surface reactivity of iron oxide particles varies with decreasing diameter (Madden et al. 2006).

Nanomaterials may be significantly more reactive than larger particles because of their much greater surface area per unit of mass (Rickerby and Morrison 2007), and this effect is made use of in environmental remediation. Zero-valent iron (ZVI) has been used in reactive barriers at numerous sites all over the world for the removal of organic and inorganic contaminants (Nowack 2008). ZVI effectively dechlorinates many halogenated hydrocarbon compounds (Gillham and O’Hannesin 1994). The degradation is based on redox reactions, in which iron donates electrons to the contaminants, reducing them to less toxic compounds. ZVI can also decrease dissolved concentrations of nitrate, perchlorate, selenate, arsenate, arsenite and chromate (Nowack 2008).

The reaction rates of nanoscale zero-valent iron (nZVI) are 25–30 times faster than the reaction rates of granular iron in the micrometre to millimetre range, and the sorption capacity is also much higher (Li et al. 2006). nZVI particles can have surface areas per unit of mass up to 30 times greater than larger-size powders of granular iron and can be 10 to 10,000 times more reactive (US Navy 2010). Figure 1 illustrates the very high reactivity of nZVI: when it comes into contact with air, it ignites spontaneously. In contrast, the reactivity of granular iron with oxygen is very slow, leading to slow oxidation (rusting) of the surface.

SOIL AND GROUNDWATER REMEDIATION WITH NANOPARTICLES

Environmental remediation methods can be classified as adsorptive or reactive and as in situ or ex situ (Tratnyek and Johnson 2006; Hodson 2010 this issue; Table 1). The use of nanomaterials in all these scenarios has been investigated. In soil and groundwater remediation, in situ applications seem to be most promising as they are in general less costly. For in situ treatment, it is necessary to create either an in situ reactive zone with relatively immobile nanoparticles or a reactive nanoparticle plume that migrates to contaminated zones. For applications in topsoil, nanoparticles can be worked into the surface of contaminated soil using conventional agricultural practices. These different approaches are shown in Figure 2.

Soil and groundwater contamination are closely linked. Methods targeting soil contamination indirectly affect the quality of the groundwater, and vice versa. We therefore summarize the nanotechnologies used for soil and groundwater remediation. Little work is being carried out on topsoil remediation using nanoparticles.

Contamination of soil and groundwater with carcinogenic organic substances and/or metals occurs all around the world. Groundwater sources are also frequently contaminated with pesticides or halogenated compounds. Landfill leakage, agriculture and chemical accidents are the main sources of these pollutants.

Conventional remediation technologies include ex situ soil washing and pump-and-treat operations, and in situ thermal treatment, chemical oxidation and use of reactive barriers with iron (Hodson 2010 this issue). Soil and groundwater remediation is generally very expensive, and conventional methods are not always successful or they take a long time for the remediation to become effective. Karn et al. (2009) state that pump-and-treat methods require 18 years of operation on average, compared to 1–2 years for a treatment with nZVI. New and more effective applications are therefore needed. Table 2 gives examples of the current use of nanoparticles in remediation. Photocatalysis could be used in a pump-and-treat operation to purify groundwater, but this article will focus on in situ soil remediation via adsorption and redox reactions.

Table 1: Classification of remediation methods involving nanoparticles

<table>
<thead>
<tr>
<th>Method</th>
<th>In situ</th>
<th>Ex situ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adsorptive</td>
<td>In situ sequestration of contaminants by adding binding agents, e.g. iron oxides</td>
<td>Extraction of contaminated solution, which is then treated with adsorbents, as in nanofiltration</td>
</tr>
<tr>
<td>Reactive</td>
<td>In situ reaction of nanomaterial, e.g. nZVI, with target contaminant</td>
<td>Extraction of contaminated solution, which is then treated with reactants, as in TiO$_2$ photo-oxidation</td>
</tr>
</tbody>
</table>

Figure 1: Nanoscale zero-valent iron ignites spontaneously when it comes into contact with air.

© AquAtest, Czech Republic
**Adsorption**
Iron oxides can strongly adsorb metals in soils. Adding nanoscale metal oxides to soils will thus immobilize soil metals (Schorr 2007). A mixture of iron and iron oxide has also been shown to be effective in phosphate removal – even more effective than higher-cost products such as activated alumina – while being active for even longer periods (Schorr 2007). Green rust – a very reactive iron oxide – can be used to reduce Cr(VI) to Cr(III), which is not soluble and much less toxic than the mutagenic Cr(VI) (Rickerby and Morrison 2007). Carbon-based nanomaterials, such as dendrimers and polymers, are also currently being explored for the removal of metals and organics from soils and groundwaters (Mueller and Nowack 2009).

Iron oxide minerals can be used to adsorb not only metals but also arsenic (Rickerby and Morrison 2007). Arsenic in groundwaters in the Bengal region of Southeast Asia and elsewhere constitutes a major hazard to the health of millions of people who use these waters for drinking, cooking and irrigation (Smedley and Kinniburgh 2002). Iron oxide NPs can bind arsenic 5–10 times more effectively than larger particles (Rickerby and Morrison 2007). In laboratory tests, more than 99% of the arsenic in water was bound by 12 nm diameter iron oxide nanoparticles.

**Redox Reactions**

**Nanoscale Zero-Valent Iron (nZVI)**
The use of nZVI in groundwater remediation is the most widely investigated environmental nanotechnological technique (Nowack 2008) and has considerable potential benefits (Tratnyek and Johnson 2006; Klimkova et al. 2008). Field-scale commercial applications of nZVI have been conducted on nanosorbents, and although the results are promising, there are only a few commercial applications so far. The problems with using nanosorbents in soils are similar to those encountered with conventional adsorbents (O’Day and Vlassopoulos 2010 this issue).

**Table 2** Examples of the use of nanoparticles in remediation

<table>
<thead>
<tr>
<th>Process exploited</th>
<th>Nanomaterials used</th>
<th>Target compounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocatalysis</td>
<td>TiO₂</td>
<td>Organic pollutants</td>
</tr>
<tr>
<td>Adsorption</td>
<td>Iron oxides, dendrimers</td>
<td>Metals, organic compounds, arsenic</td>
</tr>
<tr>
<td>Redox reactions</td>
<td>Nanoscale zero-valent iron (nZVI), nanoscale calcium peroxide</td>
<td>Halogenated organic compounds, metals, nitrate, arsenate, oil</td>
</tr>
</tbody>
</table>

This method is thus some 2500 to 25,000 times more efficient than current systems, at least at the laboratory scale. A new study by Pan et al. (2010) found that nanoscale magnetite particles can be used successfully to immobilize phosphate in soil by adsorption. They compared the immobilization efficiency of micro- and nanoscale particles stabilized by a coating of carboxymethyl cellulose and found that only nanoscale particles were able to penetrate the soil column. Non-stabilized ‘nanomagnetite’ could not pass through the soil column under gravity because it quickly agglomerated into microparticles. The coated NPs were more transportable due to their small size and the increased negative charge associated with the carboxymethyl groups. Consequently, a large proportion (72%) of the coated NPs could pass through the column due to their charge repulsion with the negatively charged soil particles. Transport over a certain distance is needed to achieve a good distribution of the reactive particles in the soil matrix and therefore an even adsorption capacity for phosphate.

Much research has been conducted on nanosorbents, and although the results are promising, there are only a few commercial applications so far. The problems with using nanosorbents in soils are similar to those encountered with conventional adsorbents (O’Day and Vlassopoulos 2010 this issue).
already become common in the United States (Karn et al. 2009), but there have been only a few projects in Europe so far (Mueller and Nowack 2010). A web-based list of the sites where nZVI has been applied is available at www.nanotechproject.org/inventories/remediation_map/.

Competition among suppliers (Tratnyek and Johnson 2006) has led to a significant drop in the price of nZVI materials. nZVI can be produced by top-down (milling) or bottom-up (chemical synthesis) processes (Li et al. 2006). Due to its high reactivity (Fig. 1), nZVI must always be handled as a slurry (Fig. 3). This requires some additional infrastructure above ground because the suspension has to be remixed immediately before its injection (Fig. 4).

There are two ways to use nZVI in groundwater and soil remediation (Tratnyek and Johnson 2006; Nowack 2008), as shown in Figure 2.

- nZVI is injected to form a reactive barrier of iron particles.
- nZVI is injected in surface-modified form (e.g. coated with polyelectrolytes, surfactants or cellulose/polysaccharides) to establish a plume of reactive iron, which destroys any organic contaminants within the aqueous phase.

Several studies have shown that nZVI as a reactive barrier is very effective in the reductive degradation of halogenated solvents, such as chlorinated methanes, brominated methanes, trihalomethanes, chlorinated ethenes, chlorinated benzenes and other polychlorinated hydrocarbons, in groundwater (Zhang 2003; Schorr 2007). nZVI has also been shown to be effective against pesticides and dyes (Zhang 2003). Efficient removal by nZVI of polycyclic aromatic hydrocarbons (PAHs) adsorbed to soils has been reported at room temperature (Chang et al. 2005, 2007), while under the same conditions only 38% of the polychlorinated biphenyls (PCBs) were destroyed because of the very strong sorption of PCBs to the soil matrix (Varanasi et al. 2007).

According to Tratnyek and Johnson (2006), nZVI used in real-world groundwater remediation has a particle size larger than 100 nm and is thus strictly speaking outside the standard definition of NP size. These authors also state that the mobility of nZVI will be less than a few metres under almost all relevant conditions as nZVI tends to aggregate, producing clusters that may approach several micrometres in size and thus be easily removed from the porewater. Companies are therefore functionalizing nZVI particles to stop them from aggregating, for example, with surfactants or polymers. Other approaches combine the nZVI with carbon platelets or embed the nZVI in oil droplets to facilitate particle delivery into the contaminated area (Mueller and Nowack 2010). In the United States, it is common to combine the nZVI with other metals, such as palladium, to increase the reactivity. In Europe such bimetallic particles are not used due to their possible toxicity and the limited additional benefit (Mueller and Nowack 2010).

Tratnyek and Johnson (2006) state that high reactivity tends to correlate with low selectivity. For this reason, remediation with nZVI may be inefficient because nZVI particles may react with non-target substances, including dissolved oxygen, sulphate, nitrate and water. This also implies that nZVI will have a limited lifetime in porous media and reinjections of nZVI may be necessary, which makes the treatment more costly. On the other hand, the short in situ lifetime of nZVI may be beneficial by preventing unwanted exposure of the environment and humans to nZVI.

A field test at a site in Germany contaminated by chlorinated hydrocarbons was carried out by the Federal Institute for Geosciences and Natural Resources (Houben et al. 2006). Injection of nZVI particles caused significant changes in redox chemistry, while other physico-chemical and hydrochemical parameters of the groundwater were not negatively affected. The limited penetration depth and lateral dispersion of the nZVI resulted in the clean-up of only a small part of the test site. Results from other pilot sites have shown that the oxidation-reduction potential in a soil decreases significantly following nZVI addition, while the pH increases slightly (US EPA 2005).

In the United States, many of the contaminated sites are on military bases. The US Navy and NASA have used nZVI in remediation for a number of years and have had positive experiences. Information on different case studies (supervised by government bodies) and background information on nZVI can be found in US EPA (2005) and Mach (2004). Examples of stages in the field application of nZVI are shown in Figures 4, 5 and 6.

The use of nZVI has been shown to be successful in the remediation of groundwater in porous soils. However, not much is known about the efficiency of the treatment in soils that are not saturated with water. The main challenge...
to date is the limited mobility of the particles. The actual efficiency of nZVI remediation depends on the geo- and hydrochemistry of the site.

**Nanoscale Calcium Peroxide**

Nanoscale calcium peroxide has recently been used for the clean-up of oil spills (Karn et al. 2009). Several projects have been conducted in New Jersey, USA. Two American companies are using nano-sized calcium peroxide as an oxidant in the remediation of soils containing various organic contaminants, such as gasoline, heating oil, methyl tertiary butyl ether (MTBE), ethylene glycol and solvents. Nanoscale calcium peroxide is claimed to be highly efficient in removing aromatics and is also used in enhanced bioremediation. The oxygen produced in the reaction of calcium peroxide with water leads to an aerobic environment that supports natural bioremediation by aerobic organisms present in the soil.

**Risks Associated with the Use of Nanomaterials**

Decreasing particle size and increasing reactivity are properties that may render a substance more toxic. Thus the very properties that make nanoparticles technologically interesting may place them in a novel category of potentially toxic substances. A number of studies exist concerning the toxicity of nanoparticles. Generally these studies suggest that smaller particles are more toxic than larger ones, although large differences among different particle types exist (Oberdörster et al. 2007). It is thus not possible to easily extrapolate toxicity data from bulk material to nanoparticles.

Nanoparticles may be ingested, inhaled or taken up through the skin. Several studies have shown that nano-sized particles can be taken up by a wide variety of mammalian cell types (Oberdörster et al. 2007). However, much is still unknown about the toxicity of nanoparticles to humans and the environment. Factors such as composition, structure, molecular weight, the melting/boiling point, the octanol–water partition coefficient, water solubility, activity, the particle aggregation/disaggregation potential, and surface coatings and structure may be important variables influencing the toxicity of different particles and their behaviour in the environment (Nowack and Bucheli 2007).

The issue of toxicity and ecotoxicity is especially important for all nano-remediation techniques because in most of them free NPs are directly added to soil or groundwater, and thus environmental exposure definitely occurs.

Only a few studies are available on the toxicity of nZVI. Li et al. (2009) found that nano-iron can induce oxidative damage in fish embryos and disturb the antioxidative balance in fish adults. The risk associated with nZVI depends not only on its toxicity but also on the extent of exposure. Tratnyek and Johnson (2006) have concluded that exposure to nZVI will be minimal due to rapid agglomeration of the particles, limited particle mobility and fast oxidation to iron oxide. Phenrat et al. (2009) investigated this nZVI “ageing” effect and found that 11-month-old nZVI was less toxic to rodent microglia (a type of cell in the brain and spinal cord) and neurons than fresh nZVI. Fresh nZVI induced mitochondrial swelling and apoptosis (controlled cell death) and reduced the levels of adenosine triphosphate. They further found that the redox activity of aged nZVI was minimal and that fresh nZVI tended to sediment and agglomerate faster than aged nZVI.

**CONCLUSIONS**

Nanoparticles can potentially be used for the remediation of soil and groundwater. The small particles are highly reactive and have great sorption capacity. However, technical challenges, such as the delivery of the particles to the target area, have to be solved. There are also concerns regarding the release of large quantities of manufactured nanoparticles into the soil prior to extensive human and ecological toxicity testing.

So far nZVI is the only application of nanomaterials in soil and groundwater remediation that has been successfully commercialized – at least in the United States. Possibly in a few years, remediation with nanoscale calcium peroxide will also be common, whereas soil and groundwater remediation methods relying on the adsorption of contaminants to nanoparticles are still far from market.

**ACKNOWLEDGMENTS**

This paper is based on work carried out within the EU-FP7 project “ObservatoryNano” (www.observatorynano.eu).
REFERENCES

On 13–15 September, Ferrara hosted the 89th Congress of the Italian Society of Mineralogy and Petrology (SIMP), in partnership with the Italian Society of Geochimistry (SoGeI), the Italian Association of Volcanology (AIV), and the National Institute of Geophysics and Volcanology (INGV). The meeting, entitled “The Evolution of the Earth System, from Atoms to Volcanoes,” represented a great opportunity for the geological science disciplines to share ideas and research results, with the goal of advancing the collective knowledge for the benefit of the wider scientific and nonscientific communities.

The congress, which lasted three days and was organized into 16 sessions, focused on the origin and evolution of the Earth; volcanic events and related risks; the atmosphere and hydroosphere in relation to natural and human phenomena; resources and geomaterials (including gemology); and the impact development has on the whole Earth system. Each day featured three oral sessions running in parallel, a comprehensive poster session, and two plenary lectures. Invited speakers were William McDonough (U of Maryland), Mauro Rosi (U of Pisa), Chiara Cardaci (DPC, Roma), Antonio Navarra (INGV, Bologna), Roberta Rudnick (U of Maryland), and Daniela Rubatto (Australian National U, Canberra).

About 300 people – a record for national SIMP meetings – participated in the meeting, thus demonstrating a strong desire to collaborate among scientists in the various branches of Earth science. Global climate change and large geological disasters are constantly under the spotlight, and a deeper knowledge of the Earth system is more important than ever. The big challenge for the Earth science disciplines is to cooperate and share results, in order to minimize investments and provide effective solutions. The approach has to be synergistic and multidisciplinary. Another point stressed during the congress is the need for science to manifest itself in everyday life. Technological progress should be sustainable and, through science, the safety of the people living on this planet should be guaranteed. In this respect it is important to develop a common language and to cooperate with institutions, such as the Department of Civil Protection (DPC), that establish the rules and act for our safety and protection.

Particular attention was paid to young researchers: their participation was encouraged by a reduced registration fee and their oral presentations were favored whenever possible.

During the meeting an exhibition of meteorites was also set up, keeping in mind that two of the most famous chondritic meteorites, the Vigarano and Renazzo, fell on Ferrara in 1824 and 1910, respectively. The exhibition was made possible thanks to the contributions of the Museo di Storia Naturale di Ferrara, the Museo di Mineralogia di Bologna, the Museo di Storia Naturale e del Territorio dell’Università di Pisa, the Museo di Scienze Planetarie di Prato, the Museo del Cielo e della Terra di San Giovanni in Persiceto and the Museo Nazionale dell’Antartide.

The organizers wish to express their gratitude to all participants, who made the congress a very stimulating and lively event. Special thanks go to the University of Ferrara and the Department of Earth Sciences, which provided financial support and human resources.

Massimo Coltorti
(U of Ferrara)
Chair of Organizing Committee

Two informal groups of the Italian Society of Mineralogy and Petrology, GNM (National Group of Mineralogy) and GABeC (Earth Resources, Environment, and Cultural Heritage), will hold on 27–30 September 2011 an international school titled “Minerals and Biosphere” in the fascinating setting of the Parco Archeominerario di San Silvestro in southern Tuscany, Italy (www.parchivaldicornia.it/parco.php?codex=sil-gen). The school is aimed at young researchers in mineralogy, geochemistry and related fields, and will introduce a current “hot” topic in the Earth sciences: the interactions, interrelationships and interchanges between the geosphere and the biosphere. The topics addressed will include fundamental aspects, such as the interaction between mineral surfaces and organic matter, new techniques for investigation of mineral–biosphere interactions, minerals and the origin of life, and geomicrobiology. Other subjects will be of an applied nature, such as biogenic ore deposits, bioleaching, biodeterioration of stone artifacts, and biomaterials. Lecturers will include mineralogists and biologists. A preliminary list includes Chiara Alisi (ENEA, Roma, Italy), Elena Belluso (Torino, Italy), Karim Benzerara (Paris, France), Giovanni De Giudici (Cagliari, Italy), Marco Giovine (Genova, Italy), Robert M. Hazen (Washington, DC, USA), Piero Lattanzi (Cagliari, Italy), Pietro Marescotti (Genova, Italy), Richard Patbrick (Manchester, UK), Gabriella Salvio (Padova, Italy), Annarossa Sprocati (ENEA, Roma, Italy), and Giovanni Valdré (Bologna, Italy). For further information, write to Pierfranco Lattanzi (lattanzp@unica.it) or visit www.socminpet.it/minbio2011/index.html.
My, how the times have changed! Many of our members have fond (perhaps becoming “fond” only after many years) memories of late evenings spent in the library, poring over articles in *American Mineralogist*. And we did this only after spending considerable time manually browsing and searching for references to the most important papers. In my younger days, I would often catch up on the most recent *American Mineralogist* at home in the evening while my wife read a novel, looking askance at me for my habit. As recently as 2000, more than 90% of our members received the print copy of our journal. Longtime members of MSA had bookshelves filled with copies of *American Mineralogist*, almost a badge of honor. As Alex Speer’s report below shows, personal subscriptions to the printed journal have dropped from about 90% of members to approximately 20% in only ten years. The fledgling electronic subscriptions have grown to 20–30% since 2002. Surprisingly, this number seems to have leveled off, perhaps because many of our home institutions purchase an electronic subscription. Thus, it is important to ensure that your libraries continue to subscribe to *American Mineralogist*, at least in electronic form.

Clearly, the nature of *American Mineralogist* access is evolving, and 80–90% of our new members subscribe to neither the hardcopy nor the electronic version. Indeed, the way in which we obtain information from our society is changing. GeoScienceWorld (GSW) has become an important purveyor of our scientific communications, and RIMG volumes and *American Mineralogist* preprints are now available online. It is possible to set up alerts from GSW, even if your institution does not subscribe. I encourage you to access *American Mineralogist* and our other publications through GSW, as this is the best way to ensure that MSA receives income every time our articles are downloaded.

We are currently discussing the production of electronic versions in e-book format of virtually everything we publish, including the RIMG volumes, and we anticipate that these will initially be in pdf format to allow presentation of high-resolution tables, graphs, and figures. All of these changes to our journal and our other publications have been driven by our readers and subscribers. But those of you who like to read a hard copy of the journal will also be accommodated. Modern technology allows us (at least for the near future) to produce a paper copy, one of the significant benefits of the option of print on demand. And, of course, all members receive hard copies of the popular journal *Elements*, with unique topical discussions in every issue.

Given the changes to our journal in the past decade, it is easy to imagine a world with virtually no hard copies of *American Mineralogist*. It is not difficult to imagine an entire generation of young graduate students and professionals curling up in bed or in front of their fireplaces with an e-book reader, studying the latest research published in our journal. These same young professionals will have few hard copies of books on their shelves, and certainly no bound journals. I am a bit nostalgic for the “good old days,” but I have to admit that searching and finding the best research in a field is so much easier today than it was even ten years ago. Enjoy this efficiency! Now, I just have to figure out what to do with all those hard copies of *American Mineralogist* filling my shelves!

As I write, I am completing my term as vice-president of MSA. One of the interesting tasks of the VP is chairing the Committee on Committees, which is charged with identifying volunteers to staff virtually all of our operations. This committee provides a glimpse into the wide array of things going on in MSA, and it gave me a great opportunity to witness the strength of our volunteer community around the world. There is room for anyone who wishes to have a more active role in MSA.

Upcoming MSA activities in 2011 include the Tucson Gem and Mineral Show, to be held in Tucson, Arizona, on February 10–13. I had my first opportunity to attend the show in 2010 and I assure you that it is well worth a visit. If you go, be sure to check out the myriad of satellite venues before the “official” show; at these events you can often find the best deals on just about any mineral. The show is a great place to stock up on mineralogy lab specimens. Also, be sure to stop by the MSA booth at the convention center. Our summer meeting will be held on August 14–19, in conjunction with Goldschmidt 2011 in Prague, Czech Republic, where Ross Angel of Virginia Tech will receive the Dana Medal. Michael Carpenter, Alan Woodland, and Tiziana Boffa-Ballaran are busy organizing a special session entitled “Structure, Elasticity and Thermodynamics of Minerals” to accompany Ross’s award.

I am excited about the changes currently occurring with our publications, and our managing editor, Rachel Russell, has instituted modifications that should plant us firmly in the electronic publishing world. Most of the changes will be invisible to you. I look forward to hearing from many of you this year, and I encourage you to take advantage of everything MSA has to offer and to give MSA your active participation.

Dave Bish, President
bish@indiana.edu

---

**NOMINATIONS SOUGHT FOR 2012 AWARDS**

Nominations must be received by June 1, 2011

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.

Society **Fellowship** recognizes a member’s significant scientific contributions. Nomination is undertaken by one member with two members acting as cosponsors. Form required; contact the committee chair or visit the MSA home page.

Mineralogical Society of America

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

---

**IN MEMORIAM**

Peter G. Hill – Member, 1994
Kurt E. Lowe – Life Fellow, 1938
NOTES FROM CHANTILLY

- All 2009 and 2010 MSA members have been contacted by mail, electronically, or both about renewing their membership for 2011. If you have not renewed your MSA membership, please do so. If you have not received a notice by the time you read this, please contact the MSA business office. You can also renew online at anytime.

- In 2010, 41% of MSA members subscribed to the American Mineralogist in some form, with roughly half of those receiving print + electronic and half having electronic access only. Since the journal was decoupled from dues in 1995 and with the advent of electronic institutional subscriptions, increasing numbers of members no longer receive personal copies but depend on their institutions for access to the journal. This trend is not surprising. For some time the newest members of MSA had been giving us an indication of where member journal subscriptions were headed, with up to 80% of new members in some years being nonsubscribers. This makes it imperative that institutions be convinced to subscribe to the journal, to make the journal available to users and to ensure its financial health.

![Graph of MSA member journal subscriptions]

![Graph of New MSA member journal subscriptions]

J. Alex Speer, MSA Executive Director
jaspeer@minsocam.org

MSA AWARDS AT THE ANNUAL MEETING, DENVER, COLORADO

Dr. Robert C. Newton, University of California, Los Angeles, has been awarded the 2010 Roebling Medal, given for a lifetime of outstanding original research in mineralogy. Dr. Newton is widely recognized for three achievements. The first was conceiving and applying the concept of a reversed mineral reaction in the experimental study of mineral stabilities. The second was obtaining the thermodynamic properties of minerals that are widely used today in calculations of the stabilities of minerals ± fluid or melt under various conditions. Third, Dr. Newton helped solve the riddle of the composition of the fluids present during the formation of the high-temperature, very dry granulite facies metamorphic rocks of the lower continental crust.

![Photo of Dr. Robert C. Newton]

Dr. Benjamin Gilbert, Lawrence Berkeley National Laboratory, Berkeley, California, is the 2010 recipient of the Mineralogical Society of America Award. This award is given for outstanding contributions by a scientist beginning his or her career. Dr. Gilbert is recognized for his work on nanoparticle–environment interactions. His work is of great significance to fields such as the remediation of natural resources using nanoparticles and the evaluation of biological responses to nanoparticles. His contributions include some of the first studies on the characterization and theory of mineral nanoparticle interactions. His publications provide important insights into the mechanisms of nanoparticle interactions in ZnS and similar mineral systems, such as the effect of strain and surface-water interactions. Dr. Gilbert is now studying aggregation in these systems and the consequences on structure and reactivity, a subfield where few quantitative results have been assembled thus far.

![Photo of Dr. Benjamin Gilbert]

The Mineralogical Society of America
2012 Grants for Research in Crystallography
from the Edward H. Kraus Crystallographic Research Fund with contributions from MSA members 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 described in a written proposal; and the likelihood of success of the project. There are three US$5,000 grants with no restrictions on how the funds may be spent, as long as they are used in support of research. Application instructions and online submission are available on the MSA website, www.minsocam.org. Completed applications must be submitted by June 1, 2011.
I’m sitting in my office about to undertake the review of a manuscript that looks interesting because it delves into the exciting (at least to me) topic of clays and a biologically important element. The authors are from a well-respected Chinese university. According to our trusty chief editor, Joe Stucki, *Clays and Clay Minerals* is experiencing an increase in submissions from clay scientists around the world. It is wonderful to know that the global network of clay science is growing, not only in China but also on all continents.

The life-blood for promoting and sustaining high-quality publication runs through the veins of associate editors and their army of reviewers. Reviews take a great deal of time, and the peer-review system is currently under stress as we are asked to “do more with less.” The increase in submissions presents a challenge for which I’d like to propose a solution: it’s time to embrace more people into the reviewer pool. This runs through the veins of associate editors and their army of reviewers. The life-blood for promoting and sustaining high-quality publication runs through the veins of associate editors and their army of reviewers. Reviews take a great deal of time, and the peer-review system is currently under stress as we are asked to “do more with less.” The increase in submissions presents a challenge for which I’d like to propose a solution: it’s time to embrace more people into the reviewer pool. This runs through the veins of associate editors and their army of reviewers.

The Clay Minerals Society (CMS) held its 47th annual meeting in conjunction with the Clay Science Society of Japan (CSSJ) and the Spanish Clay Society (SEA) in Spain on June 6–11, 2010. The organizing committee was chaired by Eduardo Ruiz-Hitzky, Yoshiaki Fukushima, and Ray Ferrell were cochairs. Pilar Aranda and Patricia Aparicio served as general secretary and general treasurer of the meeting, respectively. The trilateral meeting on clays (2010TMC) provided a unique atmosphere for the presentation and discussion of over 200 technical reports on innovations in the study of clays and clay minerals. The 2010TMC began with a one-day workshop on clays and materials in Madrid, followed by a symposium on sepiolite. The symposium included a field trip to Mg-clay deposits close to Madrid and one half-day technical session in Seville with papers describing the origin and technical applications of sepiolite. The general meeting, also in Seville, was followed by a field trip to the Rio Tinto Mines area.

The workshop focused on the development and use of advanced materials based on clays and clay minerals. It was held at the Materials Science Institute of Madrid (National Research Council of Spain, ICMM-CSIC, www.icmm.csic.es), located on the Autonomous University of Madrid (UAM) campus. The chairs, Pilar Aranda, Makoto Ogawa, and Lawrence Drummy, were assisted by Margarita Darder, M. Angeles Martin-Luengo, Carolina Belver, Francisco M. Fernandes, and Bernd Wicklein. Ten speakers reviewed conventional and innovative aspects of industrial and medical applications of clay and related materials. The proceedings will be published online by the CMS as a monograph in their Workshop Lectures Series.

The visit to the sepiolite quarries and the symposium provided unique insights into the origin and applications of this important industrial mineral. Field trip participants also had ample sampling opportunities at the Vicalvaro (Madrid) and Cabañas (Toledo) mines operated by TOLSA. Sepiolite activities were organized by Santiago Leguey and Jaime Cuevas (UAM) and by Emilia García-Romero, José Fernández-Barrenechea, and Javier Luque (Complutense University Madrid), with help from Javier Berrio and Antonio Álvarez (TOLSA) and Daniel Tejela (Sud Chemic).

A high standard of excellence for technical presentations at the general meeting was established during the plenary lectures. These were delivered by J. M. Serratosa (CMS Bailey Award recipient), R. T. Cygan (CMS Brindley Lecturer), T. Kogure (CMS Jackson Award recipient), S. Takagi and E. Narita (recipients of CSSJ special awards for contributions to clay science), and distinguished scientists E. Ruiz-Hitzky, J. Cornejo, and A. Inoue. Keynote speakers provided special insights for the general sessions, namely, Structural Features and Crystal Chemistry, Mineralogy and Geology, Soil and Sediments, Environment and Energy, Biological Aspects and Health, Industrial and Other applications, and Clays in Education Programs. Abstracts of all oral and poster presentations during the general meeting are available online at www.sea-arcillas.es/2010TMC/Book_of_abstracts-2.pdf. A tour of the Real Alcázar followed by cocktails and a gala closing banquet with flamenco-style entertainment at the Triana Abades Restaurant provided spectacular opportunities for social interaction among the participants. The general meeting was chaired by M. Carmen Hermosa, seconded by cochairs P. Schroeder and H. Yamada. They were assisted by J. Cornejo, C. Maqueda, E. Morillo, L. Cox, R. Celis, T. Undabeytia, F. Bruna, J. Gonzalez, and P. Aparicio. Members of the local scientific advisory committee included J. Cornejo, E. Galán, S. Leguey, F. Nieto, J. L. Pérez-Rodríguez, J. M. Serratosa, M. Suárez, and V. Rives. International members included A. Thomas, D. Bain, J. Stucki, W. Huff, K. Okada, T. Sakamoto, R. Kitagawa, E. Narita, M. Shishime, and A. Inoue. The high quality of the technical presentations is due in part to their efforts.

Paul Schroeder
President, The Clay Minerals Society
schroe@uga.edu
A highlight of 2010TMC was the presentation of the best paper award and travel grants to student participants. Francisco M. Fernandes (Instituto de Ciencia de Materiales de Madrid) was recognized with the best oral presentation award for his communication, coauthored by E. Ruiz-Hitzky, entitled “On the Synergy between Sepiolite and Carbon Nanotubes in Bionanocomposites.” Sara Moron (University of Minnesota) received the best Earth science poster award for her communication entitled “Middle Miocene in Panama, Wet or Dry?” It was coauthored by C. Montes, A. Cardona, C. Jamarillo, and D. Fox. Yohei Ishida was given the best poster presentation award in clay technology for the paper (coauthored by S. Takagi, D. Masui, T. Shimada, H. Tachibana, and H. Inoue) “Efficient Excited Energy Transfer Reaction between Porphyrins on Clay Surfaces: The Effects of Adsorption Conditions.” Eight students received travel awards from CMS: Marek Szczesna (Institute of Geological Sciences, Poland), Tom Naumann (Georgia State University), Autur Kuligiewicz (Institute of Geological Sciences, Poland), Ali Hooshiar (University of Alberta), Ines Mulder (University of Heidelberg), Sara Moron (University of Minnesota), Irshad Bibi (University of Sydney), and Elena Kuznetsova (Lomonosov Moscow State University). Student travel stipends were also provided by CSSJ and SEA.

The meeting ended with a trip to the Rio Tinto pyrite mines in the province of Huelva, about 80 km northwest of Seville. The mining operations (since prehistoric times), which produce gold, copper, silver, zinc, lead, and other metals, have created a world of reddish hues and a wide range of other colors. Waters draining the region are extremely acidic. The history of the region was told through exhibits at a government-supported tourist facility. The trip was organized by Isabel González and Antonio Romero (University of Seville).

Financial support for 2010TMC was provided by the Spanish Ministry of Science & Innovation, the Government of Andalucia, the Consejo Superior de Investigaciones Científicas, the Universidad de Sevilla, Bruker, Bel Japan Inc., IESMAT, SHAYANO Ltd., Chevron Energy, Wyo-Ben Inc., Oil-Dri, and Thiele Kaolin Company. Thanks to our sponsors for their generous contributions.

Ray Ferrell, Louisiana State University

Dr. Randall T. Cygan, who delivered the 2010 George W. Brindley Lecture

Prof. Toshihiro Kogure (right), recipient of the 2010 Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist Award, and his mentor, Prof. Victor A. Drits (1996 Bailey Distinguished Member awardee)

Prof. J. M. Serratos, recipient of the 2010 Marilyn and Sturges W. Bailey Distinguished Member Award

Participants in the PL1 field trip beside the statues of the Saint Apostles, damaged by Kraków air pollution

Field trip PL1, “Mineral deposits of the Fore-Carpathian region and weathering processes of monuments in the polluted atmosphere in Kraków (SW Poland),” took participants to a variety of interesting places in and around Kraków: building stones used in historical monuments and weathering processes in a polluted urban atmosphere (leaders: Wanda Wilczyńska-Michalik and Marek Michalik); a historical salt mine in Wieliczka situated in the Carpathian Foredeep (leader: Andrzej Ślączka); and a Mississippi Valley-type (MVT) lead and zinc deposit at the Pomorzany Mine, with its flotation waste and metallurgical slag dumps (leader: Harry Kucha).

Field trip PL2, “Mineralogy of Lower Silesia, Poland,” visited famous mineralogical localities in Lower Silesia. These were: the pegmatites of the Karkonosze and Strzegom-Sobótka granite massifs, the Sowie Mountains gneiss block and the Szklary serpentinite massif; the skarns of the Izera metamorphic massif; and the rodingites and nephrites of the Karkonosze and Strzegom-Sobótka granite massifs, the Sowie Mountains gneiss block and the Szklary serpentinite massif. Many nice samples were collected, and the best examples of pegmatite and nephrite will find their way to the Mineralogical Museum of the Eötvös L. University (ELTE) in Budapest. The leaders were Eligiusz Szleć and Irina Galuskina.

Field trip PL3 was entitled “Late Paleozoic volcanism in the Sudetes Mountains and the Kupferschiefer-type ore deposits in the Fore-Sudetic Monocline, Poland.” On the way from Budapest to Wałbrzych (Sudetes), participants enjoyed the scenery of the Bohemian Massif. On the next day the Carboniferous-Permian postorogenic volcanism and associated postmagmatic mineralization were observed within continental molasse successions of two big intramontane troughs: the Intra- and the North-Sudetic basins. Selected volcanic structures (mafic to felsic lavas, subvolcanic intrusions, pyroclastic deposits) were visited (leader: Marek Awdankiewicz). Typical ore sections, as well as unique Au-enriched barren zones and sandstone-hosted massive ores, were seen in two enormous underground mines, Polkowice and Rudna, along with its flotation plant (leader: Zbigniew Sawłowicz, with the collaboration of Jadwiga Pieczonka and Adam Piestrzyński).
The 74th meeting of the Meteoritical Society will be held in London, United Kingdom, August 8–12, 2011. The organizers invite you to attend the meeting and visit marvelous London. We expect to have a wide variety of interesting sessions. In addition to an exciting program of science, the early results of the Dawn mission in orbit around asteroid 4 Vesta will just be coming back. We are pleased to announce that Martin Rees, the Astronomer Royal (and current president of the Royal Society), will deliver the Barringer Lecture. Wednesday afternoon will also be available for sight-seeing or an organized outing. There may also be a field trip before the meeting in the highlands of Scotland.

The meeting will be held at the University of Greenwich, located in southeast London. Accommodation will be provided by local hotels and on-campus housing. Greenwich is easily accessible from the center of London and the five airports that serve the greater London area. Full details given in the first announcement are available on the Lunar and Planetary Institute (LPI) website (www.lpi.usra.edu), and more information is available on the meeting website (www.metsoc2011.org). For information not available on the websites, please contact the organizers, Gretchen Benedix (g.benedix@nhm.ac.uk), Phil Bland, Sara Russell, or Caroline Smith.

CALL FOR AWARD NOMINATIONS

Please consider nominating a colleague for one of the Society’s awards. Nominations for Meteoritical Society awards should be sent by January 15 (January 31 for the Pellas-Ryder Award), preferably by e-mail with electronic attachments, to the incoming secretary, Greg Herzog (herzogsec@rutchem.rutgers.edu); Dept. Chemistry, Rutgers Univ., 610 Taylor Road, Piscataway, NJ 08854, USA). For more information and details on how to submit a nomination for any of these awards, please see the latest newsletter on the Society website or e-mail the secretary.

The Leonard Medal honors outstanding contributions to the science of meteoritics and closely allied fields.

The Barringer Medal and Award recognize outstanding work in the field of impact cratering and/or work that has led to a better understanding of impact phenomena.

The Nier Prize recognizes outstanding research in meteoritics and closely allied fields by young scientists (under 35).

The Service Award honors members who have advanced the goals of the Meteoritical Society to promote research and education in meteoritics and planetary science in ways other than by conducting scientific research.

The Paul Pellas – Graham Ryder Award is given for best student paper in planetary science and is awarded jointly by the Meteoritical Society and the Planetary Geology Division of the Geological Society of America.

IN MEMORIAM

Ardis Nier (1921–2009)

Ardis Nier was a great friend of the Meteoritical Society. Ardis, who worked in the Department of Physics and Astronomy at the University of Minnesota, was married to Alfred O. Nier, a major player in the development of mass spectrometry and a meteoriticist. After her husband’s death in 1994, Ardis established the Nier Prize for young scientists in the area of meteoritics, which was first awarded at the Berlin meeting in 1996. Ardis was “by nature curious, intelligent, and good spirited.” She traveled to many of the Meteoritical Society meetings to meet the winners of this award, which has become a significant achievement for young meteoriticists. Ardis will be much missed by the members of the Meteoritical Society.
LETTER FROM THE PRESIDENT

Dear Members of the DMG,

In September a very successful and enjoyable annual DMG meeting was held at the Prince-Bishops’ residence of the University of Münster. The scientific program was composed of a number of well-received sessions on “hot” mineralogical topics, as well as three plenary lectures on crystal growth, mantle processes, and mineral evolution. It was particularly encouraging to see that many student members of our society contributed to the scientific sessions. On behalf of the DMG, I would like to congratulate and thank the local organizers in Münster, Claudia Meyer, Timm John, and Andrew Putnis, for the organization of this marvelous meeting. The following three DMG awards for 2010 were presented during the meeting.

Abraham-Gottlob-Werner Medal in Silver to Hans-Rudolf Wenk

The recipient of the Werner Medal in Silver was Hans-Rudolf Wenk from the University of California, Berkeley. Rudy was honored for his outstanding scientific achievements in the field of characterizing and interpreting the textures of rocks that result from deformation, both under laboratory conditions and in geological environments. One of his major achievements was to establish the link between crystallographic preferred orientation and underlying deformation mechanisms in crystals. His books, *Electron Microscopy in Mineralogy* and *Minerals – Their Constitution and Origin*, are examples of his seminal contributions to the mineral sciences.

Victor-Moritz-Goldschmidt Prize to Sandro Jahn

The Victor-Moritz-Goldschmidt Prize was given to Sandro Jahn from the Geoforschungszentrum Potsdam. Sandro was honored for his fundamental contributions to the atomistic modeling of the structures and properties of minerals, melts, and fluids. His electronic structure calculations, classical molecular dynamics work, and metadynamics simulations have substantially improved our understanding of the atomic structure, thermodynamics, and transport properties of silicate melts, as well as of the polymorphism of mantle minerals.

Paul-Ramdohr Award to Bastian Joachim

The Paul-Ramdohr Award is an honor bestowed on young graduate and postgraduate students who have given outstanding presentations at annual DMG meetings. Bastian Joachim from the Geoforschungszentrum Potsdam was honored for his talk entitled “Diffusion-controlled growth of monomineralic åkermanite reaction rims in the ternary system CaO-MgO-SiO$_2$,” which he presented at the 2009 DMG meeting in Halle.

At the general assembly of the DMG it was agreed to add two student members to the DMG board. Further, it was reported that the electronic membership catalogue is now available to DMG members (visit www.dmg-home.de/mitgliedschaft.html) and that the DMG intends to establish a new endowment fund for young female researchers in honor of Beate Mocek. The planning for future meetings is already underway. In 2011, we will meet at the University of Salzburg, together with the German Society of Crystallography (DGK) and the Austrian Mineralogical Society (ÖMG), and in 2012, we look forward to the European Mineralogical Conference at the University of Frankfurt (http://emc2012.uni-frankfurt.de). I hope to meet you at these meetings and wish you all the best for the new year.

Sincerely yours,

Falko Langenhorst, President

CALL FOR NOMINATIONS FOR THE 2011 DMG AWARDS

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

![Abraham-Gottlob-Werner Medal](image)

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

![Georg-Agricola Medal in Bronze](image)

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

Nominations for the DMG awards should include the curriculum vitae and publications 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 18, 2011, 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.
Mineralogical Society of Great Britain and Ireland

www.minersoc.org

LONDON NEWS

And so we arrive at the end of another ‘Elements’ year. The Elements calendar is a bit different from the regular Gregorian calendar. The end of the year happens when this text is written in late September/early October!

The Mineralogical Society has had a busy and successful year.

- Three books in the EMU Notes in Mineralogy series, now co-published by the Society, will have been released.
- Our membership numbers are up noticeably, and our student numbers are very healthy (this is partly related to our free student membership offering for year 1 and partly due to the good work put in by departmental representatives who encourage their students to become members).
- Our Annual Meeting was a good success – see the report below.
- Our third Nature’s Treasures event is building up to be the most successful so far.
- Our journals have performed well, both scientifically and financially.

And all of this has taken place against the background of a gloomy international recession. Many thanks to all who make it possible: editors, Council members, those who serve on the committees of our special interest groups, departmental representatives, all who volunteer their time in service of the Society (e.g. this year two volunteers helped with the proofreading of the journals, giving their time and expertise to raise the bar still further) and, of course, the staff!

To what do we look forward next year?

Richard Harrison’s project to establish a list of the ‘100 most important questions in the mineral sciences’ will be one of the most interesting topics of discussion at the coffee table/water cooler in 2011, in my view. More information about this soon. Support from the IMA and from Elements will make this a truly international venture.

The Society hopes to become involved in the provision of educational material suitable for use in second-level schools in the UK and elsewhere. We will work with appropriate teaching professionals to make this possible, and the results will be available on the Society’s website for all to use.

There will be another EMU volume. Our online bookshop and new-look website will be functional. We expect to publish one if not two more books in our Landmark Papers series. Our Annual Meeting promises to be an exciting one: it will have an environmental theme and will be located in Aberystwyth, Wales, a stone’s throw from a perfect location to study some classic environmental geochemistry problems in the field.

The Society is applying to become a licensed body of the Science Council, entitled to award chartered status to its Fellows. CSci is recognized not only in Britain but also throughout Europe. For some with long careers in academia behind them, this will not be a necessary title, but for those looking to join the ranks of professional mineralogists, academic or commercial, then we believe the right to confer chartered status will be an attractive feature in the Society’s arsenal.

There will be much focus on our journals in the coming year. They are the scientific and financial mainstay of the Society and our primary raison d’être. At the time of writing, interviews are about to be held for one or two new Principal Editors for Mineralogical Magazine. Mark Welch steps down in the middle of 2011.

Best wishes for the New Year!

Kevin Murphy, Executive Director

“NUCLEAR WASTE MANAGEMENT: RESEARCH CHALLENGES FOR THE FUTURE”

A joint meeting of the Mineralogical Society of Great Britain & Ireland and the Geological Society – Report

Some 120 delegates gathered for two days in late September in Cambridge, UK, for this meeting. There was a healthy crop of students (50%) in attendance, as befits the title of the meeting. The meeting was divided into five sessions:

- Stabilization of high-level waste
- Long-term behaviour of engineered barriers (containers, buffers, backfills) in geological conditions
- Retention, retardation and reactive transport of radionuclides
- Total system performance, models and uncertainties
- Careers panel discussion

The keynote speakers and the titles of their talks are as follows:

- Andy Felmy (Pacific Northwest Laboratories): Interfacial reactivity: Emerging paradigms from molecular-level observations
- Francis Livens (The University of Manchester): Why chemistry matters in radioactive waste management (especially for actinides!)
- Bernard Kienzler (Karlsruhe Institute of Technology, Germany): Retention, retardation and reactive transport of radionuclides
- Scott Painter (Los Alamos National Laboratory, New Mexico): Modeling geosphere transport in performance assessments of geologic disposal
- The Mineralogical Society’s 41st Hallimond Lecture was delivered by Rod Ewing (University of Michigan): The nuclear fuel cycle: Role of mineralogy and geochemistry in the safe management of nuclear waste.
As suggested by these titles, a wide range of material was covered. There were no parallel sessions; all delegates were encouraged to attend presentations and discussions on all aspects of the conference. A recurring comment was that people were learning a lot by going to talks outside of their usual area. A longer report, more photographs, and copies of some of the presentations are available on the Society’s website. A thematic set of papers arising from presentations made at the meeting will be published in *Mineralogical Magazine* in early–mid 2011.

**Experimental Aspects**

Two novel aspects of this meeting, at least as far as the Mineralogical Society was concerned, were:

- Preview presentations of posters. Each presenter of a poster was invited to show one slide and speak for two minutes about the content of their poster. This was successful in so far as it allowed delegates the opportunity to decide which posters to study in detail in the poster session held immediately afterwards. It also gave more profile to the poster session, often the poor relation at conferences.

- At the end of the meeting, there was a two-hour panel discussion about research requirements, training needs, and possible career options for students and others in the audience. The panel included Sarah Vines from the Nuclear Decommissioning Authority, Ian Barraclough from the Environment Agency, Fiona Rayment from the National Nuclear Laboratory, and the meeting convenors. There was much useful input from the audience, including industry people, consultants and academics.

**Quality**

There was an excellent selection of talks, and the poster presentations, including a batch of 17 given by 'EMPower' students, were of very high quality. The EMPower award for the best poster was given to Kate Norman.

**Success?**

Often the measure of success of a conference is whether those present considered that it would be an exercise worth repeating. There was a general feeling that this meeting could be repeated in a couple of years’ time. Britain needs a revitalized nuclear industry; clearly, research is required in many areas, which should lead to careers in a couple of years’ time. Britain needs a revitalized nuclear industry; Britain needs a revitalized nuclear industry; Britain needs a revitalized nuclear industry.

I gave a presentation on the first day of the conference entitled ‘Metals in earthworm casts are more mobile but earthworm mucus reduces mobility.’ It attracted a lot of attention, perhaps due to the bold statement made in the title. The presentation went well, and several delegates approached me to discuss aspects of my current research that may link with or complement their own or to tell me about similar work that they have in the pipeline.

I spent the rest of the week in a more relaxed frame of mind (!) as I skipped from room to room watching presentations on subjects that interested me. I also spent time during the poster sessions to find out what other students from various European countries were doing. Of particular help to me was speaking to students who use techniques unknown to me; these methods might be useful in my research, and collaborations might happen in the future as a result of these conversations.

Tom Sizmur

University of Reading, UK

**Bursary Report**

I thank the Mineralogical Society for the travel bursary that enabled me to travel to Seville, Spain, and attend the 20th Society of Environmental Toxicology and Chemistry (SETAC) Europe Annual Meeting. This large conference was attended by delegates from academia, business and government, and a wide range of presentations were made on the theme of the environmental chemistry of organic and inorganic toxicants in sediment, soil water and the atmosphere. It was an ideal setting to meet and network with professionals from all over the world, to the benefit of both my current research project and the advancement of my career.

Two new volumes in the EMU series are now available: go to www.minersoc.org/pages/EMU-notes/EMU-notes.html for information and to order.

**OCTOBER ISSUE OF MINERALOGICAL MAGAZINE**

A. N. ZAITSEV, C. T. WILLIAMS, S. N. BRITVIN, I. V. KUZNETSOVA, J. SPRATT, S. V. PETROV and J. KELLER: Kerimisite, Ca₂Zr₂(Fe³⁺,Cr⁴⁺)₅O₈, a new garnet from Kerimaisi volcano and surrounding explosion craters, northern Tanzania

S. V. KRIVOVICHEV, V. N. YAKOVENCHUK, E. S. ZHITOVA, A. A. ZOLOTAREV, Y. A. PAKHOMOVSKY and G. YU. IVANYUK: Crystal chemistry of natural layered double hydroxides. 1. Quintinite-2H-3c from the Kovdor alkaline massif, Kola Peninsula, Russia

S. V. KRIVOVICHEV, V. N. YAKOVENCHUK, E. S. ZHITOVA, A. A. ZOLOTAREV, Y. A. PAKHOMOVSKY and G. YU. IVANYUK: Crystal chemistry of natural layered double hydroxides. 2. Quintinite-1M: first evidence of a monoclinic polytype in M₆²⁺M₈⁴⁺ layered double hydroxides

E. S. ZHITOVA, V. N. YAKOVENCHUK, S. V. KRIVOVICHEV, A. A. ZOLOTAREV, Y. A. PAKHOMOVSKY and G. YU. IVANYUK: Crystal chemistry of natural layered double hydroxides. 3. The crystal structure of Mg,Al-disordered quintinite-2H

LIDONG DAL, HEIPING LI, CHUNHAI LI, HAIYING HU AND SHUANGMING SHAN: The electrical conductivity of dry polycrystalline olivine compacts at high temperatures and pressures

CNMNC Newsletter 5: P. A. WILLIAMS, F. HATERT, M. PASERO and S. J. MILLS: New minerals and nomenclature modifications approved in 2010

S. J. MILLS, A. R. KAMPE, P. A. WILLIAMS, P. LEVERETT, G. POIRIER, M. RAUDESEPP and C. A. FRANCIS: Hydroniumpharmacosiderite, a new member of the pharmacosiderite supergroup from Cornwall, UK: structure and description

M. NAGASHIMA, T. ARMBRUSTER and T. HAINSCHWANG: A temperature-dependent structure study of gem-quality hibonite from Myanmar

L. MELLUSO, S. CONTICELLI and R. DE’GENNARO: Kirschsteinite in the Capo di Bove melilitic leucite lava (ecclitite), Alban Hills, Italy

S. J. MILLS, S. A. WILSON, G. M. DIPPLE and M. RAUDESEPP: The decomposition of konyaite: importance in CO₂ fixation in mine tailings

P. BAYLISS, U. KOLITSCHE, E. H. NICKEL and A. PRING: Alunite supergroup: recommended nomenclature

M. S. RUMSEY, S. J. MILLS and J. SPRATT: Natropharmacosiderite, NaAl[(OH)₃(AsO₃)₃]-4H₂O, a new mineral of the pharmacosiderite supergroup and the renaming of aluminopharmacosiderite to pharmacosiderite
PRESIDENT’S LETTER

Impending Revolution in Science Publishing and Its Predicted Effect on the Geochemical Society’s Bottom-line

The escalating cost of producing professional journals and the changing landscape in publishing have brought the dissemination of scientific information to the precipice of a new paradigm. We are reminded of other previous transformative milestones, such as going from typewriters to computers or from journals on shelves in the library to electronic access in the comfort of one’s office. Escalating journal prices have all but wiped out personal subscriptions, and entire journal genres are disappearing from institutional libraries as hard budgetary choices are made.

Moreover, there is a growing movement in the US Congress against double charging for science information: first, in the form of taxes, which underwrite government funding agencies and most of the research done in academic institutions, and second, through journal subscriptions, which provide access to research already paid for by taxes. Hence, the open-access-to-journals mantra now has enough forward momentum to sweep away the traditional concept of subscription-based access at the institutional and personal levels. A news article by Jocelyn Kaiser in the August 20, 2010, issue of Science reported that between 7% and 11% of all peer-reviewed scientific journals now offer an open-access publishing model, and this percentage is likely to increase dramatically over the next few years. Already some 20% of peer-reviewed articles across all disciplines are now available free of charge through various open-access portals, and this percentage is increasing steadily.

Against that backdrop, the Geochemical Society, in partnership with the Meteoritical Society, is currently engaged in contract negotiations with Elsevier for continued publication of Geochimica et Cosmochimica Acta (GCA), the flagship journal in the field of geochemistry. These negotiations were triggered by Elsevier terminating the previous GCA contract, last negotiated in 1991 with provisions for roll over every five years under the same terms. While these negotiations have continued to be cordial, they have not been without tensions, largely stemming from recognition by both sides that the global journal-publication enterprise is in transition, engulfed by uncertainties, and not likely to survive in its current form much longer.

A sizeable component of the Geochemical Society’s operating budget comes from the royalties we receive for publishing GCA. With those royalties shrinking, at least in the near term, as stipulated by the draft contract now in discussion, we need to craft a new business model and find other income streams in order to sustain the same level of engagement and help our organization expand its activities and influence. Obvious possible changes in our operations include running meetings like the Goldschmidt Conference with a modest but significant profit margin and growing an endowment through membership and corporate donations. Our membership renewal web page solicits donations to cover Society expenses, such as running our business office at Washington University in St. Louis, student travel grants, publications, award medals and honorariums, legal and professional counsel, the meeting assistance program and outreach activities. Please consider donating to the Geochemical Society as you renew your membership for 2011. Let me take this opportunity to thank those of you who have already made a generous contribution with your membership renewals and those who are perennial donors to our Society.

Professional societies, like ours, and publishers, like Elsevier, can reap mutual benefits if they join forces and work collaboratively in defining the future of research information dissemination before it is defined for us by lawmakers. Toward this goal, we should embrace the micro-economic concept of the economy of scale. With few exceptions, the geochemistry community remains centered in North America and Europe. To scale up the community, expand journal markets, and involve populations which have not always been represented in our science, robust outreach programs need to be created and nurtured, particularly in developing nations where hunger for scientific knowledge is high. We seek active partners to work with us to fulfill this vision of the future.

Samuel Mukasa
GS President 2010–2011

NOTES FROM ST. LOUIS

GS at GSA-Denver Meeting

The 2010 F. Earl Ingerson Lecturer, Patricia Dove, with GS President Samuel Mukasa at the Geochemical Society exhibit booth.

Photo by Seth Davis

2011 Membership Drive

The 2011 membership drive, launched in October, has had an overwhelming number of responses. 2009 was our largest year ever with 3087 members in our Society, and with your help 2011 is poised to exceed this. If you have not yet renewed for 2011, please take a moment to do so now (www.geochemsoc.org). Membership in 2011 costs only US$30 for professionals and US$10 for students. If you have already renewed, thank you for your continuing support!

Knoxville Goldschmidt Membership

Delegates who attended the 2010 Goldschmidt Conference at the nonmember rate received a two-year Geochemical Society membership as part of their registration. Welcome to the Geochemical Society! A full list of member benefits can be found on our website at www.geochemsoc.org/society/benefitsofmembership.htm.

All the best,

Seth Davis
GS Business Manager
Washington University in St. Louis
Earth & Planetary Sciences
One Brookings Drive, CB 1169
Saint Louis, MO 63130-4899, USA
Tel.: 314-935-4131; fax: 314-935-4121
E-mail: seth.davis@geochemsoc.org
Web: www.geochemsoc.org
European Association of Geochemistry

21st Annual
Goldschmidt Conference
Prague | Czech Republic | August 14-19, 2011
www.goldschmidt2011.org

Prague, City of a Hundred Spires and capital of the Czech Republic, hosts the 21st annual V.M. Goldschmidt Conference, August 14-19, 2011. One thousand years ago Prague was the third-largest European city. Today it is Europe’s fourth-largest tourist destination, after Paris, London and Rome.

The Scientific Program has over 130 sessions covering every aspect of geochemistry, including high- and low-temperature geochemistry, biogeochemistry and environmental topics. The last European Goldschmidt conference attracted almost 3000 delegates, and we expect a similar number in Prague.

The Prague Congress Center overlooks the historical town quarters and the 1100-year-old Royal Castle. Once you enter the Congress Center you can reach any of the 20 lecture halls, the poster sessions and the exhibition in less than a minute. The Congress Center is conveniently located near an underground station, and Prague’s public transport system will take you there in less than 30 minutes from anywhere in the city. Budget accommodation has been negotiated at student dormitories for over 1600 conference participants.

Social highlights include the conference banquet, half-day city sightseeing tours and two-day pre- and post-conference field trips. Enjoy a visit to some of the nation’s 12 protected UNESCO World Heritage castles and country houses, as well as cities like Český Krumlov and Telč, and nature reserves.

We look forward to welcoming you all to Prague in 2011.

Bernard Marty
Martin Novak
Bernard Bourdon

Abstract Submission opens: 1 February 2011
Abstract Submission closes: 15 April 2011
Early Registration closes: 15 June 2011
www.goldschmidt2011.org
Mélanie Cousineau completed her BSc (honors) in environmental science at the University of Ottawa in 2001, graduating with the highest standing in the program. During these studies, she worked as a research assistant in soil science research at the Central Experimental Farm in Ottawa and as an environmental officer at the Thurso Pulp Mill. In 2001 she enrolled in the MSc (environmental science) program at Memorial University of Newfoundland under the supervision of Drs. Moire Wadleigh and David Schneider. Her research there focused on the use of sulfur isotopes in lichens to trace atmospheric sulfur sources. After graduating in 2003, Mélanie moved to Québec City, where she worked for Environment Canada’s Canadian Wildlife Service and was responsible for the national coordination of a program on the impact of wind turbines on migratory birds and a research project on the use of radar to track bird migrations. In 2008, she returned to the University of Ottawa to begin a PhD in Earth sciences under the supervision of Drs. Danielle Fortin and Boswell Wing (McGill University). In her research, she uses pure cultures of acid-tolerant strains of sulfate-reducing bacteria to determine the role of pH in sulfur fractionation during bacterial sulfate reduction (BSR). This has implications for understanding geochemical conditions prevailing in ancient ocean and freshwater environments. Archean oceans, which are believed to have been acidic, supported the beginning of life on Earth and the appearance of BSR metabolism. Additionally, because sulfate-reducing bacteria have the potential to remediate acid mine drainage, understanding the metabolism of these organisms at low pH conditions may benefit research into large-scale bioreactor applications for remediation purposes.

Luke Hilchie received his BSc with first class honors in Earth sciences from Dalhousie University in 2009, earning him the University Medal in Earth Sciences. He studied experimentally generated surface textures of diamond oxidized in chloride-bearing fluids under the supervision of Dr. Yana Fedortchouk. He then began his MSc at Dalhousie under the supervision of Drs. Yana Fedortchouk and Sergei Matveev (University of Alberta). Luke is comparing the hydrogen-related infrared spectra of olivine in xenoliths and diamond surface morphologies produced in fluid-bearing and fluid-free experiments to determine the linkage between hydrogen in olivine, diamond quality, and the presence or absence of aqueous fluid. This investigation will establish whether the hydrogen-related infrared spectra of xenocrystic or norecristic olivine in kimberlites can be reliably used as proxies for diamond quality and magmatic water oversaturation. This study may also elucidate the causes of variations in diamond quality among kimberlites.

**MAC FOUNDATION SCHOLARSHIP WINNERS**

Mélanie Cousineau (University of Ottawa) and Luke Hilchie (Dalhousie University) are the recipients of the 2010 MAC Foundation Scholarships. Congratulations to these deserving students!

**MAC UNDERGRADUATE AWARD WINNERS**

The MAC Undergraduate Awards are given annually to undergraduate students for excellence in one of the fields covered by MAC (mineralogy, crystallography, petrology, geochemistry, and economic geology). The award consists of a gift certificate for MAC publications and one-year subscriptions to *Elements* and the online version of *The Canadian Mineralogist*. We congratulate the 2009–2010 awardees:

- **MICHAEL A. ANTONELLI**, University of Alberta
- **JESSICA BALDWIN**, Memorial University
- **ANNE-MARIE BEAUCHAMP**, Université Laval
- **ANNE C. BÉLANGER**, Dalhousie University
- **MATTHEW BRZOZOWSKI**, University of Windsor
- **KEVIN M. CANNON**, Queen’s University
- **MARTINE CHABOT**, Université du Québec à Chicoutimi
- **BRADY KEVIN CLIFT**, UBC Okanagan
- **ADAM CLOUGH**, Carleton University
- **KENDALL L. CULLIGAN**, University of British Columbia
- **MATEA DRJIJEPAK**, Brock University
- **ASHLEY MARIE EMMS**, Mount Royal University
- **STEPHANIE FRIEDRICH**, Acadia University
- **EVAN R. GLADNEY**, St. Mary’s University
- **AMY M. KENWELL**, University of Waterloo
- **ELLEN LEASK**, McGill University
- **JASON LÉVESQUE**, University of New Brunswick
- **RYAN BREAUX LIBBEY**, The University of Western Ontario
- **TRAVIS J. A. McCARRON**, St. François Xavier University
- **JALISSA C. McMULLEN**, University of Regina
- **GREG F. PAJU**, Lakehead University
- **DANICA FRANCINE PASCUA**, University of Toronto
- **MEGHAN C. TOMLIN**, University of Victoria
- **RYAN BREAU LIBBEY** (University of Ottawa)

**ADVANCES IN EARTH SCIENCES RESEARCH CONFERENCE 2010**

This year’s AESRC conference, “Geosciences: A World beyond Textbooks,” was held at the University of Ottawa, Ontario, on March 26–28, 2010. It had a record attendance of 83 people, including 61 students, 12 faculty, 5 industry sponsors, and 5 keynote speakers. This bilingual, graduate student–run conference is the only one of its kind in central Canada and attracted students from eight universities across Ontario and Quebec. Participating universities included the University of Ottawa, Carleton University, Queen’s University, the University of Toronto, the University of Montreal, the Université du Québec à Montréal, the University of Waterloo, and McMaster University.

The conference began with a welcoming reception and poster session, where 13 graduate and undergraduate posters were on display. Over the following two days, 31 oral presentations were given by students, who discussed their latest research findings covering a variety of geo-science topics. Each session began with a lecture by a prominent keynote speaker; these were Drs. Jeffrey Hedenquist, Bill Arnott, Alexandre Poulain, Liam Keiser, and Ian Clark. The MAC was the official cosponsor of two coffee breaks. Saturday-night attendees enjoyed a conference dinner hosted by Jazzy Restaurant at the University of Ottawa. During the closing ceremony, several awards were announced. The AESRC 2010–CSEG best undergraduate poster award was given to Jamie Cutts (Carleton University). The first and second runners-up were Allison Enright and Nicole Williamson (both from the University of Ottawa). The AESRC 2010–CSEG award for best graduate poster went to Leena Davis (University of Ottawa). The first and second runners-up were Viktor Terlaky and Jamil Sader (both from the University of Ottawa).

The AESRC 2010–Imperial Oil award for best MSc talk honored Mélanie Mercier (Carleton University). The first runner-up was Kristen Feige (University of Ottawa) and the second runner-up was Joanna Northover (Carleton University). Finally, the AESRC 2010–CSEG award for best PhD oral presentation was given to Deanne van Rooyen (Carleton University). The first and second runners-up were Erika Revesz and John Jamieison (both from the University of Ottawa). This conference benefited greatly from MAC’s generous contribution.

*Leena Davis* and *Matt Herod* (University of Ottawa)
ANNUAL SEM MEETING IN MADRID

The 30th meeting of the Spanish Mineralogical Society was held in Madrid from September 13 to 16. The meeting was organized jointly by scientists from the Complutense University (UCM) and the Polytechnical University of Madrid, the Spanish National Research Council (CSIC), and the Geological and Mining Institute of Spain (IGME). Financial support was provided by the Spanish Ministry of Science and Innovation, the Spanish National Research Council, and industrial sponsors.

The meeting was preceded by a biominerals and biomineralization workshop on Monday, September 13. The 46 participants listened to six lectures by Wolfgang Schmahl (Ludwig-Maximilians-Universität of Munich), Erika Griesshaber (Ludwig-Maximilians-Universität of Munich), Alberto Pérez-Huerta (University of Alabama), Paolo Montagna (Columbia University), Concepción Jiménez-López (University of Granada), and Alejandro Rodríguez-Navarro (University of Granada). These lectures are collected in the 7th volume of the Seminarios de la Sociedad Española de Mineralogía series.

The meeting opened on Monday evening with a welcoming ceremony in the Mining Engineering School Auditorium, followed by an icebreaker reception at the Gómez-Pardo Foundation. Tuesday and Wednesday (September 14 and 15) were devoted to the scientific sessions. The scientific program included four plenary lectures and nine special sessions (oral and poster) arranged around the following topics: general mineralogy and petrology, ore deposits mineralogy, biomineralization, environmental mineralogy, cultural heritage and applied mineralogy, crystal growth, and mineral–fluid interaction. The plenary lectures were given by Lia Addadi (Weizmann Institute of Science), David Millward (British Geological Survey), Santiago Leguey (Autonomous University of Madrid), and Mercedes Suárez (University of Salamanca). A total of 146 participants attended the meeting, which comprised 53 oral and 58 poster presentations. The oral sessions were held at the Auditorium of the Gómez-Pardo Foundation and in the Mining Engineering School (UPM), while the posters were on display at the IGME.

Concurrently with the poster sessions on Tuesday and Wednesday afternoons, guided visits to the impressive collections of minerals and fossils housed at the IGME and the Mining Engineering School were arranged for small groups. On Tuesday evening, participants had the chance to attend the projection of the film *The Mystery of Giant Crystals*, directed by Javier Trueba and written by Juan Manuel García-Ruiz.

A postmeeting field trip to La Cabrera (Guadarrama Range, Madrid) was held on Thursday, September 16. The field trip, led by Rafael Lozano and Ramón Jiménez, included visits to numerous mineralized sites associated with the granites and pegmatites of La Cabrera, as well as to the open-air Stone Museum (El Berrueco, Madrid). Further information about the meeting will be posted on the SEM website (www.ehu.es/sem).

Venegas del Valle (Astrobiology Center, CSIC-INTA) was recognized for her interesting poster entitled “Caracterización mineralógica de la alteración supergénica de El Jaroso mediante espectroscopía Raman.”

A NEW SEM PRESIDENT

During the SEM general assembly in Madrid on September 15, Carles Ayora was elected as the new president of the SEM for a period of four years. He takes over from Manuel Prieto, who has generously served the Society since 2006. Carles Ayora holds a PhD in geological sciences (University of Barcelona, 1981) and is currently a research professor at the Institute of Environmental Assessment and Water Research (IDAEA) of the Spanish Research Council. His main areas of interest are experimental water–rock interaction, modeling, and the coupling of hydro-geological and geochemical processes. Manuel Prieto’s presidency was marked by actions to make the SEM more modern and dynamic. Among the challenges for the new president will be to enlarge the SEM’s field of activities and to foster cooperative interactions within Spain’s geochemical community.
2011


January 23–28 35th International Conference and Exposition on Advanced Ceramics and Composites, Daytona Beach, FL, USA. Web page: www.ceramics.org/icac-11

January 24–27 Source to Sink Systems around the World and through Time: Recent Advances in Understanding Production, Transfer and Burial of Terrestrial and Marine Materials on the Earth Surface, Oxford, CA, USA. E-mail: chapman-source@sink.agu.org; web page: www.agu.org/meetings/chapman/2011/acall

January 25–46 4th Meeting of the Small Bodies Assessment Group, Washington, DC, USA. Web page: www.lpi.usra.edu/baag/meetings


February 21–February 26 International School: Diamonds, the Mantle Petrologist’s Best Friends, University of Padua, Bressanone, Italy. Details: Fabrizio Nessori, e-mail: fabrizio.nessori@unipd.it

February 25 Focused Ion Beam 2011, Baltimore, MD, USA. Details: Ken Livi, e-mail: klivi@jhu.edu; website: www.fibsem.org

February 27–March 3 The Minerals Metals & Materials Society (TMS) Annual Meeting, San Diego, CA, USA. E-mail: mtgservice@tms.org; web page: www.tms.org/meetings


March 21–25 Chapman Conference on Climates, Past Landscapes and Civilizations, Santa Fe, NM, USA. E-mail: chapman-climate.society@agu.org; web page: www.agu.org/meetings/chapman/2010/eall

March 27–31 241st American Chemical Society (ACS) National Meeting & Exposition, Anaheim, CA, USA. Web page: www.acs.org


April 10–13 AAGP Annual Convention & Exhibition, Houston, TX, USA. Web page: www.aagp.org/meetings


May 2–4 Congreso Geologico Argentino, Neuquén, Republic of Argentina. E-mail: info@congresologico.org.ar; web page: www.congresologico.org.ar

May 2–7 Workshop on Submarine and Emergent Volcanic Arcs and Associated Volcano-Sedimentary Basins, Cabo de Gata, Spain. Web page: www.ija.csic.es/cabogegata

May 15–19 12th European Workshop on Modern Developments and Applications in Microbeam Analysis, Angers, France. Web page: www.emas-web.net

May 16–19 6th Annual International Symposium on Environment, Athens, Greece. E-mail: atiner@atiner.gr, web page: www.atiner.gr/environment.htm

May 22–27 IUMAS-V: 5th Meeting of the International Union of Microbeam Analysis Societies, Incho, South Korea. E-mail: saong@samsung.com; web page: www.microprobe.org/events/iumas-v


May 29–30 GIA Symposium 2011: Advances in Gemological Research, Carlsbad, CA, USA. E-mail: symposium2011@gia.org; website: http://symposium2011.gia.edu


June 21–24 The Mineralogical Society’s Annual Meeting: Frontiers in Environmental Geoscience, University of Aberystwyth, Wales, UK. Details: N. Pearce, e-mail: njp@aber.ac.uk; web page: www.minesoc.org/pages/meetings/frontiers-2011/frontiers-2011.html


June 27–July 7 XXVIth International Union of Geodesy and Geophysics (IUGG) and IAVCEI General Assembly, Melbourne, Australia. E-mail: ray.casi@sci.monash.edu.au; web page: www. iugg2011.com

July 3–7 International Conference on the Biogeochemistry of Trace Elements, Florence, Italy. Details: Dr. Giancarlo Renella, e-mail: giancarlo.renella@unifi.it; website: www.icobte2011.com

July 4–9 Seventh Hutton Symposium on Granites and Related Rocks, Avila, Spain. E-mail: hutton@ugr.es; web page: www.seventh-hutton.org/meeting/Welcome.html


July 10–20 EMU School – Bulk and Surface Structures of Layer Silicates and Oxides: Theoretical Aspects and Applications, Rome, Italy. Web page: www.univie.ac.at/Mineralogy/EMU


July 20–27 International Union for Quaternary Research (INQUA) XXVIII Congress, Bern, Switzerland. Website: www.inqua.tci.de/congress.html


August 28–September 1 242nd American Chemical Society (ACS) National Meeting & Exposition, Denver, CO, USA. Web page: www.acs.org


September 4–7 8th European Conference on Mineralogy and Spectroscopy (ECMS 2011), Potsdam, Germany. Details: Prof. Dr. Monika Koch-Mueller, e-mail: mkoch@ gfu-potsdam.de; web page: www.physchemgeo.com/ECMS/index.html

September 4–7 FRAGILE EARTH: Geological Processes from Global to Local Scales and Associated Hazards, Munich, Germany. Web page: www.geosociety.org/meet/2011/munich

September 20–24 GEOMED2011 – 8th Hemispheric Conference on Medical Geology, Bari, Italy. Details: Saverio Fiore, e-mail: fiore@maea.cn.it; web page: www.geomed2011.it

September 26–29  11th Biennial Society for Geology Applied to Mineral Deposits (SGA) Meeting, Antofagasta, Chile. E-mail: sga2011@ucn.cl; web page: www.sga2011.ucn.cl

September 27–30  International GNM-GABeC School on Minerals and Biosphère, Campiglia Marittima (LI), Italy. E-mail: lattanzp@unica.it; web page: www.socminpet.it/minbio2011/index.html

October 9–13  Geological Society of America Annual Meeting, Minneapolis, MN, USA. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings/2011

October 16–20  Materials Science & Technology 2011 Conference and Exhibition – MS&T ‘11 combined with the ACerS 113rd Annual Meeting, Columbus, OH, USA. Web page: www.tms.org/Meetings/meetings.asp

November 21–24  Conference on Arsenic in Groundwater in South Asia, Hanoi, Vietnam. E-mail: vietcetads3@yahoo.com; web page: vietas.er.dtu.dk


2012

March 4–7  XIV EMPG (Experimental Mineralogy, Petrology and Geochemistry) Meeting, Kiel, Germany. E-mail: empg2012@min.uni-kiel.de

March 11–15  The Minerals Metals & Materials Society (TMS) TMS 2012: Linking Science and Technology for Global Solutions, Orlando, FL, USA. E-mail: mtgserv@tms.org; web page: www.tms.org/meetings/annual-12/AMT12home.aspx


April 22–25  AAPG Annual Convention & Exhibition, Long Beach, CA, USA. Web page: www.aapg.org/meetings

May 28–30  Geological Association of Canada and Mineralogical Association of Canada Annual Meeting, St. John’s, NL. Web page: www.gac.ca/activities


July 28–August 2  American Crystallographic Association (ACA) Annual Meeting, Boston, MA, USA. Web page: www.amercrystalas.org


August 19–23  IAVCEI General Assembly 2013: Forecasting Volcanic Activity, Kagoshima, Japan. Details: Masato Iguchi, e-mail: iguchi@svo.deri.kyoto-u.ac.jp; web page: www.iavcei.org/IAVCEI.htm


October 9–12  Geological Society of America Annual Meeting, Minneapolis, MN, USA. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings

October 16–20  Materials Science & Technology Conference and Exhibition – MS&T ‘11 combined with the ACerS 113rd Annual Meeting, Columbus, OH, USA. Web page: www.tms.org/Meetings/meetings.asp

November 21–24  Conference on Arsenic in Groundwater in South Asia, Hanoi, Vietnam. E-mail: vietcetads3@yahoo.com; web page: vietas.er.dtu.dk


2013

April 7–11  245th American Chemical Society (ACS) National Meeting & Exposition, New Orleans, LA, USA. Web page: www.acs.org

May 19–22  AAPG 2013 Annual Convention & Exhibition, Pittsburgh, PA, USA. Web page: www.aapg.org


July 7  IAVCEI General Assembly 2013: Forecasting Volcanic Activity, Kagoshima, Japan. Details: Masato Iguchi, e-mail: iguchi@svso.deri.kyoto-u.ac.jp; web page: www.iavcei.org/IAVCEI.htm

August 19–23  IAVCEI General Assembly 2013: Forecasting Volcanic Activity, Kagoshima, Japan. Details: Masato Iguchi, e-mail: iguchi@svso.deri.kyoto-u.ac.jp; web page: www.iavcei.org/IAVCEI.htm

September 9–13  EMC2012: Planet Earth – from Core to Surface, Frankfurt, Germany. Web page: emc2012.uni-frankfurt.de

The meetings convened by the societies participating in Elements are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol (more meetings are listed on the calendar she maintains at http://homepages.udayton.edu/~akoziol1/meetings.html). To get meeting information listed, please contact her at Andrea.Koziol@notes.udayton.edu.

The meetings convened by the societies participating in Elements are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol (more meetings are listed on the calendar she maintains at http://homepages.udayton.edu/~akoziol1/meetings.html). To get meeting information listed, please contact her at Andrea.Koziol@notes.udayton.edu.

---

**PARTING QUOTE**

Be clear • Be concise • Be correct

**Bob Sheppard**

---

**PERALK-CARB 2011**

This workshop, to be held during

16-18 June 2011

The Institute for Geoscientists, Tübingen, Germany, will address the generation and evolution of peralkaline rocks and carbonatites from their source to their last stages of their crystallization (fenestration, hydrothermal processes) with an additional emphasis on their economic potential. A special session will be devoted to the alkali carbonates and carbonatites of the Gregory Rift in East Africa. Geologists, petrologists and geochemists will contribute with general or with case studies, be they based on experiments or field studies.

Eleven distinguished keynote speakers will review the state of the art knowledge on all aspects of the topic. A LITHOS Special Issue on the contributions from this workshop is planned to be published.

Please visit our website (http://www.ifg.uni-tuebingen.de/department/mines/petrology/peralk-carb-2011/index.html) or contact Michael Marks (michael.marks@uni-tuebingen.de). The total number of contributing participants will be restricted to 65. Please send an expression of interest with a preliminary title before 30th of November 2010. Participation will be confirmed until 15th December 2010.
Mainly intended to entertain you with some colorful photomicrographs, this page is also a way for me to thank Maria Teresa and Juan Carlos for a fantastic vacation. Think about the song by Chris Rea and relax: we travel to southern Spain and the stones on the shore at Carboneras. People shouldn’t be misled by the place name: yes, there’s a coal-fired power station right outside the village, but this is the only downside against a long list of assets that includes climate, culture, crystal-clear sea (photo 1), the amazing Cabo de Gata–Nijar National Park and, why not, food and drink. The geology of this area is equally exciting, and the rock types are so diverse that I decided to collect some beach pebbles for a photomicroscopic reportage.

Porphyritic andesite is by far the most common rock on the beach (2, 3) and forms most of the 200 km² Miocene volcanic field of Cabo de Gata. This rock was extruded in the Miocene, followed by garnet-cordierite-bearing dacites (4). The gravel also contains metamorphic rocks from the Alborán Domain: such as high-grade metapelites (5), quartzites (6), schists, and mylonites (7). The abundance of highly tectonized rocks is not surprising: along with the ductile imprint of subduction and exhumation on the crystalline basement, a widespread cataclasis occurs near the Carboneras fault (8), a lithospheric-scale, still-active structural element in the region. Thus, tectonic breccias add to those that occur primarily in the sedimentary strata of the neighbouring Neogene basins (9, 10). All the above rock types, and many others, are cemented together in beautiful beach conglomerates (11, 12), which formed all along the coast during the last rock-forming event in the Pliocene.

I had thin sections made from the pebbles and took photomicrographs: the images in this article are a glimpse into the marvelous, small world hidden in these rocks. The pebbles are the “artists”: I just help them showcase their best colours. And this is the power of polarized light, not of Photoshop!

**Bernardo Cesare**
University of Padova, Italy
www.microckscopica.org
From Lab to Field

**Elemental Analysis with XRF**

- S1 TURBO Handheld EDXRF for field surveys
- S2 PICOFOX TXRF Benchtop for ppb level effluent analysis
- S8 TIGER WDXRF for fast laboratory based analysis
- S2 RANGER EDXRF Benchtop for onsite analysis

[www.bruker-axs.com](http://www.bruker-axs.com)
Soil Water Remediation Models

Build them with GWB.

- 1D/2D reactive transport in partially to fully saturated media
- Trace soil-water reaction paths
- Mineral dissolution/precipitation kinetics
- Speciation, mineral saturation, gas fugacity
- Kd, Freundlich, Langmuir partition coefficients; full surface complexation models; cation exchange
- Activity and redox-pH diagrams

GWB Essentials – $999
GWB Standard – $3,499
GWB Professional – $7,999

The Geochemist’s Workbench®
Dynamic models of soil-water interaction.

RockWare®
Since 1983
303.278.3534 • 800.775.6745 • GWB.com