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Energy:
A Geoscience Perspective
Allison M. Macfarlane, Guest Editor

Energy: The Issue of the 21st Century
Allison M. Macfarlane

Confronting the Climate–Energy Challenge
Daniel P. Schrag

Geological Carbon Dioxide Sequestration
S. Julio Friedmann

Nuclear Energy and Uranium Resources
Allison M. Macfarlane and Marvin Miller

Tapping Methane Hydrates for Unconventional Natural Gas
Carolyn Ruppel

About the Cover: A growing need for electricity in the developed and developing world will have a large impact on climate change, energy security, and energy supply in the 21st century. This photo was taken near Golden, Colorado, USA. Photo courtesy DOE/NREL.
The Mineralogical Society of America

The Mineralogical Society of America is composed of individual members interested in mineralogy, crystallography, petrology, and geochemistry. Founded in 1919, the Society promotes, through education and research, the understanding and application of mineralogy by industry, universities, government, and the public. Membership benefits include special subscription rates for American Mineralogist as well as other journals, 25% discount on reviews in Mineralogy & Geochemistry, titles and Monographs, reduced registration fees for MSA meetings and short courses, and participation in a society that supports the many facets of mineralogy. For additional information, contact the MSA business office.

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The Mineralogical Society of Great Britain and Ireland, also known as the MInSoc, is the international society for all those working in the field of mineral sciences. The Society aims to advance the knowledge of the science of mineralogy and as an application to other subjects, including crystallography, geochemistry, petrology, environmental science and economic geology. The Society further attracts researchers with scientific meetings and the publication of scientific journals, books and monographs. The Society publishes three journals, Mineralogical Magazine (print and online), Clay Minerals (print and online) and the e-journal MINARS Online (launched in January 2004).

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The Clay Minerals Society

The Clay Minerals Society (CMS) began as the Clay Minerals Committee of the US National Academy of Sciences - National Research Council in 1952. By 1962, the CMS was incorporated with the primary purpose of promoting research and disseminating information relating to all aspects of clay science and technology. The CMS holds an annual meeting, workshop, and field trips, and publishes Clays and Clay Minerals and the CMS Workshop Lectures series. Membership benefits include index registration for the annual meeting, discounts on the CMS Workshop Lectures, and Elements.

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The Geochemical Society

The Geochemical Society is an international non-profit organization for scientists involved in the study, practice, and teaching of geochemistry. Membership includes a subscription to Elements, access to the online quarterly Geochemical News, as well as an optional subscription to Geochemistry and Geochimisc Acta (24 issues per year). Members receive discounts on publica-tion of IGS Special Publication in MSA, Elsevier and Wiley/Jossey-Bass), and on conference registrations, including the V.M. Goldschmidt Conference, the fall meeting, and the annual GSA meeting. Geochemical Society
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The European Association for Geochemistry

The European Association for Geochemistry was founded in 1985 to promote geochemical research and study in Europe. It is now recognized as the pereminent geochemical organization in Europe encouraging interaction between geochemists and researchers in associated fields, and promoting research and teaching in the public and private sectors.

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The International Association of Applied Geochemists

The International Association of Applied Geochemists is an international organisa-tion founded in 1970 that specializes in the field of applied geochemistry. Its aims are to advance the science of geochemistry as it relates to exploration and the environment, further the common interests of exploration geochemists, facilitate the acquisition and distribution of scientific knowledge, promote the exchange of information, encourage research and development, advance the status of the discipline, and sponsor symposia, seminars and technical meetings.

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The Deutsche Mineralogische Gesellschaft

The Deutsche Mineralogische Gesellschaft (German Mineralogical Society) was founded in 1908 to “promote mineralogy and all its subdisciplines in teaching and research as well as the personal relationships among all members.” Its great tradition is reflected in the list of honorary fellows, which include G. v. Tschermak, P. Eskola, C.W. Correns, P. Ramdohr, and H. Strunz, to name a few. Today, the Society especially tries to support young researchers, e.g. to attend conferences and short courses. Membership benefits include the European Journal of Mineralogy, Mineralogische Rundschau, and Elements. Society NEWS EDITOR: Michael Burchard (burchard@min.uni-heidelberg.de)
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The The International Mineralogical Association

The International Mineralogical Association was founded in 1969, draws together professionals and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The Society’s ultimate goal is to promote research and development, encourage researchers, e.g. to attend conferences and short courses. Membership benefits include the international journal Geoscience, and the affiliate journal Geoanalytical Research.

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The International Association of Geoanalysts is a worldwide organization supporting the professional interests of those involved in the analysis of geological and environmental materials. Major activities include the management of proficiency testing programmes for bulk rock and microanalytical data, and certification of reference materials and the publication of the Association’s official journal Geostandards and Geoanalytical Research.

SOCIETY NEWS EDITOR: D. Burchard (burchard@min.uni-heidelberg.de)
International Association of Geoanalysts
H. Strunz, to name a few. Today, the

The The Mineralogical Society of Poland

The Mineralogical Society of Poland, founded in 1969, draws together professionals and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The Society’s ultimate goal is to promote research and development, encourage researchers, e.g. to attend conferences and short courses. Membership benefits include subscriptions to Mineralogia Polonica and Elements.

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

PARTICIPATING SOCIETIES

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Affiliated Societies

The International Mineralogical Association, the European Mineralogical Union, and the International Association for the Study of Clays are affiliated societies of Elements. The affiliated status is reserved for organizations that serve as an “umbrella” for other groups in the fields of mineralogy, geochemistry, and petrology, but that do not themselves have a membership base.
Richard Feynman’s ‘Minority Report to the Space Shuttle Challenger Inquiry’ has become a modern scientific legend. His brilliant, independent mind scythed through a mass of engineering detail, half-truth and wishful thinking and made the key observation that explained the destruction of the most complex machine ever made. He brought his conclusion home to public and politicians by a simple piece of showmanship involving a glass of iced water and a fragment of O-ring. NASA management estimated the probability of a shuttle failure at 1 in 100,000 or one failure if a shuttle lifted off every day for 300 years. Engineers close to the project estimated the risk of failure at 1 in 100. ‘What is the cause’, Feynman asked, ‘of management’s fantastic faith in the machinery?’ The report should be compulsory reading for all science students and can be found in several anthologies of Feynman’s wonderful, often funny but always profound essays.¹

Disquietingly, however, it requires more than a little effort to find his report through ‘official’ channels. It is not reproduced in the report of the Committee on Science and Technology, ‘Investigation of the Challenger Accident’, that went to the House of Representatives in October 1986, although there are several references to Feynman and some short extracts. It can be found in its entirety in the report of the Presidential Commission on the Space Shuttle Challenger (the ‘Rogers Report’), but you have to locate it in the contents list of Volume II, where it appears in Appendix F, ‘Personal observations on reliability’, with no attribution. One senses hidden establishment discomfiture here, where politicians and policy makers are confronted with the independence and detachment of an outstanding scientific mind, ranged against the technological and administrative might of NASA. Feynman’s report ends with a famous line – pin it up near your desk: ‘For a successful technology, reality must take precedence over public relations, for nature cannot be fooled’.²

The intersection of governmental policy and how we present science is particularly topical as I write, with the publication of the much trumpeted 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Press reports that I’ve seen include the assertion that it is the work of ‘2500 of the world’s leading scientists’. Like NASA, the IPCC seems to believe that sheer weight of numbers will impress politicians and the public alike. If you go to their website, under the headline ‘IPCC 4th Assessment Report – A comprehensive and rigorous picture of the global state of knowledge of climate change’, you are invited to click on a button and are rewarded by a little movie in which the following lines appear one by one:

- 2500+ scientific expert reviewers
- 800+ contributing authors
- 450+ lead authors from
  - 130+ countries
  - 6 years work
  - 4 volumes
  - 1 report

Now I don’t deny for one moment the importance of taking care of the environment, and I agree entirely that allowing levels of atmospheric CO₂ to increase much beyond present levels is a thoroughly bad thing. As Dan Schrag discusses in this issue, we could encounter tipping points in climate change that would have appalling consequences not for me but for my grandchildren, a prospect I truly find deeply worrisome. The political imperatives to get the burgeoning economies of India and China to adopt low- CO₂ ways of making power, and the United States and many other developed countries to make enormous cut-backs, are unquestionable and the most important social initiatives in the world today.

But we have to be very careful how we present the science. The IPCC approach implies that science reaches its powerful conclusions by a sort of international democratic consensus. Science is not democratic. Its life-blood is not certainty, it is doubt. Because we reach our conclusions through experiment and development of mathematical theories, both of which may be repeated and improved, scientific concepts that survive do so because they have withstood repeated attempts to disprove them. It takes only one Feynman, one simple, crucial, robust experiment, to change the fabric of science for ever. I think the IPCC has strayed, although with the best of intentions, into the realm of what Feynman called, in his commencement address at Caltech in 1974, ‘Cargo Cult Science’.³ Cargo cults developed on islands in the South Seas after the second world war. During the war great aeroplanes landed with lots of good things, and the islanders wanted this to continue. So they built runways, lit fires alongside them, erected a wooden hut for a man to sit in with wooden headphones and bamboo antennae, and waited for the planes to come. They had done

¹ Richard P. Feynman, _The Pleasure of Finding Things Out_.
³ Ian Parsons

Cont’d on page 156
ABOUT THE ENERGY ISSUE
So much could be written on the topic of energy, and several approaches could have been taken for an issue of Elements on this theme. We liked Guest Editor Allison Macfarlane’s proposal to focus on some emergent technologies and to put this century’s energy requirements in the context of climate change.

NEXT EDITORIAL MEETING
The editors are planning to meet at the Frontiers in Mineral Sciences conference in Cambridge. We will be firming up our line-up for the remainder of 2008 and the beginning of 2009. We continue to solicit proposals, but many of our thematic issues have resulted from potential guest editors contacting us and expressing interest in leading an issue. Please do not hesitate to contact any of us with an idea or a proposal.

ABOUT THE ZIRCON ISSUE
We received several positive comments about the zircon issue. You liked the international diversity of the contributors. It was hard to put down. It had an “Excellent set of articles, with outstanding photos and images.” Our favourite comment was sent by a colleague, who related that he missed his bus stop because he was so immersed in his reading.

EARTH CITIZEN
In the energy debate, let’s not forget the three Rs: reduce, reuse and recycle. And as Earth scientists, shouldn’t we lead by example? Having a smaller car and a smaller home, and using public transportation, for example, do not change one’s lifestyle much, but taken together such gestures, no matter how small, make a difference. We therefore plan to introduce a new feature called Earth Citizen in which we turn the writing over to you. We are seeking inspiring opinion pieces from scientists who not only study the Earth but also have made changes to their lifestyles as they have recognized the stress the human population puts on our planet. Give us facts and relate your experience. Perhaps you have helped your campus become greener for example. For our part, we will investigate how we can make Elements greener.

Ian Parsons, Susan Stipp, Bruce Watson, and Pierrette Tremblay

IN PRAISE OF THE OPTICAL MICROSCOPE
As Ian Parsons points out (Elements, 2007, volume 3, issue 1), cutting-edge instrumentation and techniques, like the atomic force microscope and the ion probe, are producing exciting new results that are leading to a more complete understanding of Earth processes. In order to devote more time to introducing such advanced techniques to undergraduates, he suggests they spend less time learning crystal optics. Of course, future advances in the geosciences will, of necessity, depend on these techniques. But it is also true that the majority of students leaving university with a bachelor’s degree in geology will never come near high-performance instruments like the atomic force microscope during their careers. In my own business of Cu-Ni deposit research in a government geological survey, my everyday, bread-and-butter tools are (still) the optical microscope (transmitted and reflected light) and whole-rock chemical analyses. If I need exact mineral compositions, the local university has a microprobe. These are the tools that help me evaluate, on a first-order basis, the characteristics and potential of Cu-Ni showings I study in the field. For the price of a polished thin section, you can’t beat the amount of basic information that you can obtain with an optical microscope. For example, an exploration geologist looking for Cu-Ni would be very interested to know the texture of pentlandite, the composition of plagioclase, and if olivine is absent or present in his or her rock samples. An optical microscope gives these answers routinely. But it took me a long time to really understand how to determine the composition of plagioclase with an optical microscope—a lot of practice and theoretical understanding was necessary. I wonder if it is in the best interest of a student to use an optical microscope like a “black box,” not really understanding what he or she is doing. Ian Parsons is not suggesting dropping crystal optics completely. But I think it would not be an advantage to make changes in the geology curriculum that would limit the average field geologist’s ability to get as much practical information as possible out of his or her field work.

Thomas Clark
Quebec City, Canada

FROM A NEW MEMBER
I am a member of AAG and have just received my first Elements magazine. What a superb publication! I love the thematic nature of the issues and the review nature of the articles to catch up on aspects outside my own speciality! Congratulations to all involved with this publication—I look forward to many more issues! And I have already started browsing at back issues online also. Excellent stuff!

Kingsley Burlinson
Darwin, Australia
We are pleased to present the members of the advisory board for 2007.

**Randall T. Cygan** received his PhD degree in geochemistry and mineralogy in 1983 from the Pennsylvania State University. In late 1983, he joined the Geochemistry Department of Sandia National Laboratories in Albuquerque, New Mexico, where he is now a Distinguished Member of the Technical Staff. He also spent two years as an assistant professor in the Geology Department at the University of Illinois. His research interests include kinetics, chemical diffusion, mineral dissolution, adsorption, shock metamorphism, and molecular simulation. He is a Centennial Fellow of the College of Earth and Mineral Science at Pennsylvania State University and a Fellow of the Mineralogical Society of America.

**Roberto Compagnoni** is a professor of petrology in the Department of Mineralogical and Petrological Sciences at the University of Turin. Since 2001 he is vice-head of the Interdepartmental Center “G. Scansetti” for Studies on Asbestos and other Toxic Particulates at the University of Turin. He was president (2004–2005) of the Italian Society of Mineralogy and Petrology. His research activity covers mainly the P–T path reconstruction and fluid–rock interaction of high-pressure and ultrahigh-pressure metamorphic rocks, the evolution of serpentinized ultramafics, the development of fibrous minerals, and the origin of jadeitites in the Western Alps.

**James I. (Tim) Drevier** is a native of Scotland. He received an undergraduate degree in chemistry from Cambridge University and a PhD in geochemistry from Princeton University. He is currently a Distinguished Emeritus Professor at the University of Wyoming. He has carried out research on the effects of acid deposition on surface water chemistry, the role of weathering processes in controlling the long-term average carbon dioxide concentration of the atmosphere, the effects of mining activities on surface water and groundwater quality, and the long-term controls on the composition of the oceans. He was president of the Geochemical Society from 2004 to 2005.

**Adrian Finch** is a reader in geography and geosciences at the University of St Andrews, Scotland, UK. He graduated from Durham University in 1987 in geology and went on to complete a PhD at the University of Edinburgh on the petrology and mineralogy of Greenland syenites. After a spell in industry, he became a research fellow in chemistry at Aberdeen University, working on novel superconductor materials. After lectureships at Luton and Hertfordshire universities, he took up a Royal Society of Edinburgh/BP personal fellowship at the University of St Andrews (2000). His research interests include the mineralogy of environmental proxies and mineral luminescence.

**John E. Gray** has been a research geologist with the U.S. Geological Survey since 1982. He received his PhD from the University of Colorado. His research has primarily focused on formation processes of gold and mercury mineral deposits in Colorado and Alaska and, more recently, on mercury contamination of the environment. He has studied transport, speciation, and translocation of mercury related to mining in Alaska, Nevada, Texas, the Philippines, Suriname, and Spain. He has also been involved in studies on the sources and historical deposition of mercury in lakes and reservoirs in the western U.S. He has been a councilor of the International Association of GeoChemistry since 2004.

**Janusz Janezczak** is a professor of mineralogy at the University of Silesia in Katowice, Poland. He currently serves as rector of that university. He is a past president of the Polish Mineralogical Society (1998–2002). He graduated and received his PhD from the University of Wroclaw. His research interests include the crystal chemistry of uraniumite as an analog for spent nuclear fuel, the mineralogy and geochemistry of natural fission reactors in Gabon and other analogs for radwaste repositories, environmental mineralogy including the phase composition of tropospheric dust particles, and the mineralogy of pegmatites. He was Fulbright Fellow at the University of New Mexico and a visiting professor at the University of Hiroshima.

**Hans Keppler** started collecting minerals and fossils at the age of 12. He studied mineralogy and chemistry in Karlsruhe (Germany). After his PhD, he spent two years as a postdoc at Caltech. He then moved back to Germany and joined the staff of Bayerisches Geoinstitut (Bayreuth). In 2000, he was appointed professor of mineralogy at the university in Tübingen, and in 2004 he returned as a professor to Bayerisches Geoinstitut. He has a broad range of research interests, with a focus on fluids and volatiles in the Earth’s interior and on in situ spectroscopic techniques at high P and T. In 2001, he received the Leibniz Prize, the highest award in German science.

**David R. Lentz** received his BSc (1983) and MSc (1986) degrees in geology from the University of New Brunswick (UNB) in Fredericton, New Brunswick (Canada). He then completed a PhD (1992) at the University of Ottawa on U–REE–Y-mineralized pegmatite-related skarn systems, before working with the Geological Survey of Canada for three years on VHMS deposits in New Brunswick. In 1994 Dave joined the New Brunswick Geological Survey as mineral deposits geologist. Since 2000, he has held the Economic Geology Chair at UNB (ORE Group), with a research focus on the petrogenesis of ore deposits.

**Maggie Loubsler** is with the University of Pretoria, South Africa, where she is responsible for the XRF facility and the training and support of postgraduate students. She presents an annual short course entitled Introduction to XRF Spectroscopy. Since 2005 she has been one of the presenters at the annual XRF School at the University of Western Ontario. Ms Loubsler has been a member of the IAG since 1998 and has been on the executive since 2006. She has been a member of the South African Chemical Institute since 1998 and the South African Spectroscopic Society since 1997, in the capacity of honorary secretary. She chairs the Geoanalysis 2009 organizing committee.

**Douglas K. McCarty** received his PhD in geology from Dartmouth College in 1993, his MS in 1990, and his BA in 1986 from the University of Montana. He has broad experience in geology, mineralogy,
clay science, diffraction, and computer modeling. He is an associate editor of *Clays and Clay Minerals* and heads Chevron’s Mineral Analysis Laboratory in Houston where he has worked for ten years. This laboratory founded the first biannual Reynolds Cup contest in 2002. The laboratory took second place in the second Reynolds Cup in 2004 and first place in the 2006 contest.

**Klaus Mezger** is a professor of geochemistry at the University of Münster. He received a Diplom in mineralogy from the University of Würzburg and a PhD in geochemistry from Stony Brook University. He was a postdoctoral fellow at the University of Michigan in Ann Arbor before working as a staff scientist at the Max Planck Institut for Chemistry in Mainz from 1991 to 1997. His research interests are mainly in the areas of geochronology, metamorphic petrology, early solar system processes, and the evolution of the crust–mantle system using radiogenic isotopes and high-precision trace element determinations. He does both analytical work and field-based research. In the past, he has served on several editorial boards including that of *Geochimica et Cosmochimica Acta*.

**James E. Mungall** received his MSc and PhD in igneous petrology at McGill University. After two years of experimental investigations of the transport properties of silicate melts at the Bayerisches Geoinstitut in Germany, Jim found himself back in Canada in the summer of 1996, looking for nickel deposits and communing with the affectionate mosquitoes of northern Quebec. In 1999, Jim found a place where he could combine a passion for field work with the possibility of doing experimental petrology and teaching at the University of Toronto, where he has remained ever since.

**Takashi Murakami** is a professor in the Department of Earth and Planetary Science, University of Tokyo. His current studies focus on atmospheric evolution in the Precambrian, mineral–atmosphere interactions, and uranium geochemistry and mineralogy. Murakami received BS (1975), MS (1977), and PhD (1980) degrees in mineralogy from the University of Tokyo. He worked for the Japan Atomic Energy Research Institute, the University of New Mexico, the Australian Nuclear Science and Technology Organisation, and Ehime University (Japan). He has served as an editor of the *Journal of Mineralogical and Petrological Sciences* and as a councilor and member of several committees of the Mineralogical Society of Japan.

**Eric H. Oelkers** is a CNRS Research Director and the Experimental Geochemistry and Biogeochemistry Responsible d’équipe in Toulouse, France. Eric currently serves as vice-president/president elect of the European Association for Geochemistry and as the coordinator of the MIR and MIN-GRO Europe-wide training and research networks. He has also served as a director of the Geochemical Society, co-editor in chief of *Chemical Geology*, and associate editor of *Geochimica et Cosmochimica Acta*. Eric has also co-edited four special journal issues, including the 2005 *Chemical Geology* issue “Geochemical Aspects of CO₂ Sequestration”. His research is focused on quantifying natural geochemical processes.

**Hugh O’Neill** is an experimental petrologist at the Research School of Earth Sciences, the Australian National University. His research interests center on the application of physical-chemical measurements to the understanding of the origin and evolution of the Earth and the terrestrial planets. He is especially concerned with studying the accretion and early differentiation of the Earth, how these processes influence Earth’s composition, and the subsequent mantle processes that lead to partial melting and production of basaltic magmas. He has spent much of his career measuring the thermodynamic properties of minerals and melts at high temperatures and pressures.

**Nancy L. Ross** is a professor of mineralogy and an associate dean at Virginia Tech. She received her BSc from Virginia Tech, MSc from the University of British Columbia, and PhD from Arizona State University. Her recent research includes studies of framework minerals at high pressure, neutron scattering studies of oxide nanoparticles, and electron density studies of sulfides. She has served as a member of council of the Mineralogical Society of America, as chair of the infrastructure development committee of COMPRES, and as a member of the board of reviewing editors of *Science*.

**David J. Vaughan** is professor of mineralogy and director of the Williamson Research Centre for Molecular Environmental Science at the University of Manchester. He has DPhil and DSc degrees from Oxford University and worked in Canada (at CANMET) and the USA (at MIT) before returning to Britain. His research centers on mineral chemistry, particularly of sulfides and oxides, mineral surface science, and ore and environmental mineralogy, areas in which he has also written or edited textbooks. He has been president of the (UK) Mineralogical Society and the European Mineralogical Union, was MSA Distinguished Lecturer in 2004, Schlumberger Medalist and RSC Geochemistry Award winner in 2006, and was elected a Fellow of the Geochemical Society/EAG in 2007.

**Olivier Vidal** is a CNRS researcher at the Laboratoire de Géodynamique (Université de Grenoble, France). He received a PhD in mineralogy from the Université Pierre et Marie Curie (Paris) in 1991 for work conducted mainly at the Mineralogisches Institut of the Ruhr Universität Bochum (Germany). He worked for eight years at the Laboratoire de Géologie of the École Normale Supérieure (Paris). His research focuses on experimental mineralogy and the use of thermodynamics in metamorphic petrology. During two postdoctoral positions at the French agency for nuclear energy (CEA) and the South West Research Institute in San Antonio (Texas), he worked on gaseous and mineral evolution in the vicinity of nuclear waste disposal sites.

**Everett Shock** grew up in southern California, earned his bachelor’s degree from UC Santa Cruz and his PhD from UC Berkeley, and worked in between for the USGS. He taught at Washington University for 15 years before moving to Arizona State University where he teaches geochemistry and environmental chemistry. Shock’s research interests include the transition from equilibrium to disequilibrium in hydrothermal systems and the implications for life, the intersection of geochemistry with genomics, the abiotic origins and transformations of organic compounds, the evolution of icy satellites and meteorite parent bodies, and the anthropogenic chemistry of urban systems.
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LOOKING GLASS WORLDS

Ordinary science proceeds in the following way: once we have our ground rules, assumptions, protocols, and data, we are ready to make incremental advances in our chosen field. But how do we decide whether our paradigm is better than another? We know how to compare hypotheses, but how do we compare paradigms that involve the whole infrastructure of our research program, including the language we use? Statistical and logical tests often are of no help. Formal logic tells us that failed predictions and counter examples are not enough to falsify a proposition. As failed predictions and conflicting evidence accumulate, one might make continual adjustments to the theory. But it seldom occurs to a practitioner to jettison everything and start afresh with a blank slate; there is too much baby in the bathwater.

When Alice in Wonderland went through the looking glass, she entered a world with different rules. Few of us have had the experience of discovering that the rules that had been guiding our research for the past years or decades were all wrong, that the predictions of our theories were wrong, that the assumptions were wrong, that our professors were wrong, that our textbooks were wrong. This has happened famously in astronomy, cosmology, physics, and chemistry. Scientists abandoned Ptolemy, Aristotle, alchemy, astrology, and static universes. In a more recent paradigm shift, Earth became a dynamic planet with drifting continents and young oceans, exposed to giant impacts that created the Moon and extinguished dinosaurs. Uniformitarianism and fixed continents bit the dust; catastrophes became acceptable. The new ideas are now all part of conventional wisdom, and few of us recall the mindsets that were in place when a different conventional wisdom prevailed.

Young scientists are taught the scientific method and the rules of deductive logic, but are not taught how to deal with the trauma of having all the rules change in midstream, or even that they might.

What follows are two paradigms—looking glass images of each other.

The motivating question for your research program is “Why don’t volcanoes exist everywhere?” You know that plates drive themselves; they are deformable, breakable, and ephemeral, constantly reorganizing: new plate boundaries form and old ones close up, forming volcanic chains that tap a hot mantle of variable fertility. You view volcanic chains as abandoned or incipient plate boundaries and fracture zones—consequences of plate tectonics. Fertile blobs entrained in the shallow mantle will appear to be slowly moving with respect to quickly moving plates and stationary with respect to slowly moving plates. You know that there can be no absolute reference system, or absolute fixity, in a convecting, rotating, deforming planet.

A group of young theoreticians comes along and challenges the status quo. They ignore your assumptions and make new ones; they ask different questions and do different experiments and calculations. They have decided that the deep mantle is rigid and the upper mantle well stirred. They presume an absolute fixity of volcanic islands, absolute rigidity of plates, an absolute reference frame, and absolute temperature. The upper mantle is isothermal and homogeneous, so deep hot stationary tubes are invoked to bring core heat to the asthenosphere to form island chains. Unfamiliar concepts, such as “absolute motions,” “core heat,” “box models,” “reservoirs,” and “primordial mantle” are introduced. Volcanic islands are renamed “hotspots” and “plumes.” Volcanic chains are viewed as independent of plate tectonics and relabeled “hotspot tracks.”

You and your friends are asked to judge the papers of this emerging group of talented renegade investigators. The new ideas do not make sense to your peers. In the new theory the mantle is approximated as a solid with bizarre properties. It is fluid but rigid; it is homogenized by chaotic stirring; it is heated from below; it is not near the melting point; most of Earth’s radioactivity is in the undegassed lower mantle. Conflicting evidence is accommodated by changing the properties of the tubes, or by blaming approximations in the theory or lack of resolution in the data.

Needless to say, none of these ideas will pass peer review. This is the way science works.

But suppose these ideas had come first and had become entrenched in the literature. Suppose that they reflected conventional wisdom. The two paradigms, essentially opposite in every respect, would be treated differently in these Looking Glass Worlds. The defenders of an entrenched paradigm literally do not understand the language and concepts of the invading paradigm. There is an asymmetry in the way new ideas and conventional wisdom are treated—the standards are very much higher for the new ideas. There is also an asymmetry in understanding. The Old Guard is not familiar with the new language, while the invaders know the old ideas very well and have found them wanting. The inability to communicate and to compare paradigms is called incommensurability by the philosophers of science; this is probably more important than the concept of falsifiability, which is always in the eye of the beholder.

The older readers of this column will remember when our professors ridiculed continental drift, extraterrestrial theories of extinctions, catastrophic floods, and magma oceans; we believed in uniformitarianism, tectogenes, vertical tectonics, and the static-mantle geosynclinal theory. We laugh at the old ideas of fixed continents, but we readily bought into the idea of fixed islands and tubes to the core.

When do not question today’s conventional wisdom, we do so our peril—it too may look crazy to future generations.

Don L. Anderson
Caltech, Pasadena
CA, USA
OBITUARY FOR JOSEPH V. SMITH

Joseph Victor Smith died of pneumonia at the Beth Israel Medical Centre in Boston on 6 April 2007, at the age of 78. He was born on 30 July 1928 and raised on a hill farm in the Peak District of Derbyshire in the north of England. With the encouragement of his mother and uncle, both teachers at a school not noted for its academic successes, Joe won an open scholarship to Cambridge where he obtained a first-class honours degree in physics. After post-graduate work on the crystallography of calcium silico-carbonate minerals, he spent some time at the Geophysical Laboratory in Washington where he was influenced by W.S. Mackenzie (who, Joe said, gave him his lifelong interest in feldspars), Hat Yoder and Felix Chayes. After a brief return to Cambridge, Joe went to Penn State where he began work in earnest on feldspars and also became involved, via his consultancy with the Union Carbide Corporation, in zeolites – the molecular sieves that have proved so successful in improving the yield of gasoline from oil and producing phosphate-free detergents. He moved to the University of Chicago in 1960, becoming a full professor at the early age of 32.

One of his early achievements in Chicago was the building of one of the first operating electron microprobes. In those early days, there was considerable scepticism as to whether such probes would ever deliver meaningful results, but its routine use these days is a legacy of a few imaginative pioneers, one of whom was Joe. He was concerned not just with the numbers obtained but also with what they meant; for example, he noted the low Ca concentrations in mantle olivine, due to high pressures, compared with the higher amounts in its volcanic equivalent. In 1965, Joe started the Short Courses in Mineralogy, run in conjunction with the annual meetings of the Geological Society of America. These, and the accompanying Reviews in Mineralogy, published by the Mineralogical Society of America (the first 40 being edited by Paul Ribbe), continue to the present day with the added involvement of the Geochemical Society. In 1969 Joe became a Principal Investigator in the Apollo Programme, which led him to another interest: planetary geology and mineralogy. As if this were not enough, in the early 1970s he became involved in research on upper mantle mineralogy. His later interests included threats to mankind from meteorite collisions with the Earth and global conflict, but these went hand-in-hand with his fundamental interest in new technology and what it could do for mineralogy and crystallography. He became interested in the role of mineral surfaces in the origin of life, a subject on which he wrote an article for Elements (Volume 1, Issue 3). He was involved with Bob Clayton in setting up the ion probe at the Enrico Fermi Laboratory at the University of Chicago. Another major achievement was when he organised a multi-institutional, multi-disciplinary group of scientists and founded the Consortium for Advanced Radiation Sources to use the Advanced Photon Source at the Argonne National Laboratory. His research has resulted in over 400 publications in most of the major journals and includes his three encyclopaedic books on feldspars.

Among the many honours he received for this work were his election to the fellowship of the Royal Society of London and the National Academy of Sciences, and the award of the prestigious Roebling Medal of the Mineralogical Society of America and the Murchison Medal of the Geological Society of London.

So much for Smith the scientist. What of Smith the man? He was one of the most multi-faceted men I have met. Intensely curious, he was interested in literature, art and music; one of the pleasures of visiting Chicago in the autumn was the weekly trips downtown with Joe and Brenda to hear concerts of the Chicago Symphony Orchestra. He was also a prodigious reader, and not only of the scientific literature. He lived life intensely and, being an extremely dedicated and well-organised man, he was sometimes held by students to be a hard taskmaster. Those who knew him better recognised that this was only because he took it for granted that students and collaborators should be prepared to work as hard as he did himself. I can say personally that his rigorous working to deadlines was good for our collaboration. Even off duty, Joe’s unbridled energy meant that he could hardly relax completely and, in the early days when the Derbyshire farm was still in family hands, he returned to England each summer, not only to show his daughters the rural and architectural heritage of Britain, but also to help his father and his brother with the hay making. He was very loyal to family and friends. In later years, he and Brenda spent weekends at their lovely home on the shore of Lake Michigan in the Indiana Dunes Park, where they took great pleasure in entertaining friends from many parts of the world – but there were always jobs like installing a new rain-butt and fence-making to be done.

With his passing, the mineralogical community has lost one of its most productive and influential members. All the same, I like to imagine Joe is up there building another probe, just to find out what the Pearly Gates are really made from!

Barry Dawson
University of Edinburgh
EWING AND LAVEROV
Lomonosov Gold Medalists for 2006

The Lomonosov Gold Medal, named after learned Russian scientist Mikhail Lomonosov, is the highest award of the Russian Academy of Sciences. Each year, a Russian and a non-Russian receive the award for outstanding achievements in the natural sciences and humanities.

The Lomonosov Gold Medal for 2006 was awarded to Professor Nikolay Laverov, vice-president of the Russian Academy of Sciences, and Professor Rod Ewing of the University of Michigan. Both have played a significant role in fundamental research in the nuclear fuel cycle and nuclear waste management. Nikolay Laverov was recognized for his work on the back-end of the fuel cycle and his work related to uranium deposits and uranium mineralogy. Professor Ewing’s research has led to an understanding of radiation effects in solids and the discovery of radiation-resistant materials that can be used in the safe disposal of actinides, such as plutonium. Professor Ewing is the Donald R. Peacor Collegiate Professor in the Department of Geological Sciences and is also a professor in the Departments of Materials Science & Engineering and Nuclear Engineering & Radiological Sciences.

Previous recipients, of whom more than twenty are Nobel laureates, include Hans Bethe, John Kenneth Galbraith, James Watson, Linus Pauling, and Aleksandr Solzhenitsyn. The most recent award to a non-Russian in the geosciences was to Frank Press in 1997. Frank Press is a former president of the U.S. National Academy of Sciences.

The Lomonosov Gold Medal was presented to Professors Laverov and Ewing on March 27, 2007, in Moscow at the annual meeting of the Russian Academy of Sciences.

The Hudson Institute of Mineralogy, a not-for-profit organization chartered by the Board of Regents of the State University of New York, is seeking used analytical equipment, thin sections, and mineral specimens for its descriptive mineralogical laboratory and educational programs. We are dedicated to classical mineralogical research, preservation of mineral specimens, and educational outreach to primary and secondary school teachers and students. If your institution is upgrading its analytical equipment, we want your used, working devices. Further, if you are disposing of minerals, thin sections, or similar geological artifacts, let us put them to good use; aesthetics are unimportant, labels are! Please contact:

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S. Julio Friedmann
received his BS and MS degrees from MIT, followed by a PhD at the University of Southern California. After graduation, he worked for five years as a senior research scientist in Houston, first at Exxon and later at Exxon-Mobil. He next worked as a research scientist at the University of Maryland, where he was affiliated with the Joint Global Change Research Institute (JGCRI), and at the Colorado Energy Research Institute of the Colorado School of Mines. In his new appointment as head of the Carbon Management Program for Lawrence Livermore National Laboratory, he leads initiatives and research into carbon capture, carbon storage, and fossil fuel recovery and utilization. His research interests include carbon sequestration, underground coal gasification, hydrocarbon systems, deep-water depositional systems, basin and range tectonics and sedimentation, sequence stratigraphy, and landslide physics.

Allison M. Macfarlane
is an associate professor in the Department of Environmental Science and Policy at George Mason University in Fairfax, VA. She is also an affiliate of the Program in Science, Technology, and Society at MIT, where she continues his work on nuclear arms control and the linkage between nuclear power and nuclear proliferation. Dr. Miller is currently active as a consultant to the Nonproliferation Bureau of the State Department.

Carolyn Ruppel
recently joined the methane hydrates program at the U.S. Geological Survey as a research geophysicist after more than 12 years as a program manager at the U.S. National Science Foundation. She holds a PhD in solid Earth geophysics from MIT and has focused on numerical modeling, laboratory, and interdisciplinary shipboard studies of marine methane hydrate systems since the mid-1990s. Her current research interests include the petrophysics of hydrate-bearing sediments, the hydrogeology of marine and permafrost gas hydrate systems at pore to regional scale, the integration of physical, chemical, and biological data to understand methane seeps, and the hydrology of ecologically sensitive salt marshes subject to both natural and anthropogenic forcing.

Marvin Miller
received a PhD in applied physics from the Polytechnic Institute of New York in 1967. He was tenured as an associate professor of electrical engineering at Purdue University before joining the MIT Nuclear Engineering Department (NED) in 1976. He retired from NED in 1996 and is now a research affiliate with NED and the Program in Science, Technology, and Society at MIT, where he continues his work on nuclear arms control and the linkage between nuclear power and nuclear proliferation. Dr. Miller is currently active as a consultant to the Nonproliferation Bureau of the State Department.

Daniel P. Schrag
Professor of Earth and Planetary Sciences at Harvard University and the director of the Harvard University Center for the Environment. Schrag studies climate and climate change over the broadest range of Earth history. He has examined changes in ocean circulation over the last several decades, with particular attention to El Niño and the tropical Pacific. He has worked on theories for Pleistocene ice-age cycles. He has contributed to the development of the Snowball Earth hypothesis, which proposes that a series of global glaciations occurred between 750 and 880 million years ago and that they may have led to the evolution of multicellular animals. He is also working on technological approaches to mitigating the effects of human-induced climate change. Among various honors, Schrag was awarded a MacArthur Fellowship in 2000. Schrag arrived at Harvard in 1997 after teaching at Princeton and studying at Berkeley and Yale.

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Energy: The Issue of the 21st Century

Allison M. Macfarlane*

Energy usage makes modern life possible. Without it we would have no communications, transportation, food, health, and many other services and products that we rely on daily. Energy issues are moving to the forefront in the 21st century because of constraints imposed by increasing energy needs, climate change, energy security, and the apparent decline of fossil fuel resources. The main challenge is how to provide more energy for more people worldwide while at the same time reducing greenhouse gas and pollution emissions and providing secure and plentiful energy supplies. There is no silver bullet, so a variety of energy resources and technologies will be required.

KEYWORDS: energy, climate change

ENERGY AND CLIMATE: AN UNFOLDING CRISIS

The Intergovernmental Panel on Climate Change (IPCC) recently stated unequivocally that climate is warming and that burning of fossil fuels by humans is largely responsible (IPCC 2007a). Fossil fuel burning, responsible for emitting 6.4 GtC/yr (gigatonnes of carbon per year) in the 1990s, now emits 7.2 GtC/yr (for 2000-2005). The carbon dioxide concentration in the atmosphere is now 380 ppmv (parts per million by volume), up from 280 ppmv prior to the industrial revolution. Doubling the pre-industrial concentration of atmospheric carbon dioxide will likely lead to an increase in global average surface temperature of 2–4.5°C (IPCC 2007a). Such an increase might portend significant species extinction (up to 30%), increased stress on drinking water availability, increased coastal flooding, and potentially the melting of the Greenland and West Antarctic ice sheets, with a concomitant sea level rise of 4–6 m (IPCC 2007b). All of this results from our large appetite for fossil fuel-based energy.

Climate impacts are not the only energy-related issue facing us in the 21st century. Increased competition for finite energy resources due to growing economies and populations in the developing world and increasing need for more energy resources in developed countries may result in strained international relations or even war. Many countries are propelled by their need for energy independence to locate assured forms of energy supplies. For instance, this has been the policy of the United States for more than 50 years and has resulted in agreements with Saudi Arabia concerning their oil resources. Certainly, U.S., European, and now growing Chinese and Indian interest in the Persian Gulf region is largely due to the vast oil resources located there.

Over the next 25 years, fossil fuels are expected to continue to make up about 80% of total primary energy supply, according to business-as-usual forecasts of energy consumption (International Energy Agency 2006b). Nuclear power is expected to decline from 6.5% of total primary energy supply in 2004 to 4.7% in 2030. The usage of fossil fuels will shift somewhat from countries of the Organization for Economic Development (OECD) (50% in 2004 to 41% in 2030) to Asia (from 26% to 31%). China, in particular, will become more dependent on foreign oil as its economy expands. Currently, it stands third, behind the U.S. and Japan, among the top importers of crude oil.

Energy issues will continue to play a significant role in energy security and foreign policy issues. The current situation with Iran provides a good example. Iran claims that its desire for energy independence is forcing it to acquire nuclear power technology, which includes a uranium enrichment facility to make fuel for nuclear reactors (of which only one is under construction at the moment). Unfortunately, the enrichment facility can also be modified to enrich uranium to much higher levels than those needed for nuclear reactor fuel—levels that can be used to make nuclear weapons. Although such technology is allowed under the Nuclear Nonproliferation Treaty, the U.S. and a number of European countries are not happy with the situation and believe Iran is trying to develop a nuclear weapons capability. The situation became even more complicated when China and Russia balked in the face of calls for action against Iran at the UN Security Council. China had made a deal with Iran to obtain much-needed crude oil—and the Chinese did not want to risk losing this important resource, one of the few large oil reserves that were not already tied up by the U.S. or Europe.

Business-as-usual forecasts of carbon dioxide emissions suggest an increase from the 2003 level of 25 GtCO₂/yr (7 GtC/yr) to 44 GtCO₂/yr (12 GtC/yr) in 2030 (Energy Information Administration 2006b). The impacts from such increases will likely be devastating in human and environmental terms. Clearly, mitigation of carbon dioxide emissions must begin in the intervening years (see Schrag on page 171). In the next few pages, I review the existing global energy landscape and suggest some potential solutions to reducing CO₂ emissions while increasing energy security and availability.
HOW TO MEET FUTURE ENERGY DEMANDS

Clearly, the best way to meet future energy needs is not to put all one’s eggs in a single basket. Diversity of supply can satisfy increased energy needs, especially if efficiency and conservation are applied to existing and new technologies. A diverse supply base also ensures energy security and can begin to address restrictions imposed by declining crude oil production, if and when that comes about. The solution to climate change—reduced CO₂ emissions—will also come through reliance on a diversity of energy sources.

To stabilize carbon dioxide in the atmosphere at double the pre-industrial level, it will be necessary to maintain emissions at about 25 GtCO₂/yr (7 GtC/yr) (Pacala and Socolow 2004). Pacala and Socolow (2004) suggested a “wedge” model to satisfy future energy needs while decreasing carbon emissions. They suggested that attaining these goals required implementation of seven wedges representing energy-related resources and activities, each producing 92 GtCO₂ (25 GtC) emissions over the next 50 years, such that atmospheric carbon dioxide would be stabilized at 500 ppm (Pacala and Socolow 2004). Each wedge would take the form of an energy technology, such as nuclear power, or efficiency or conservation measures. We can apply the wedge model to our own discussion of future energy needs.

The future mix of energy resources will undoubtedly include fossil fuels, especially coal, oil, and natural gas, but unconventional fossil fuel consumption will also likely increase. Other energy supplies will include non-carbon-emitting sources, such as nuclear power, and renewable energy (e.g. hydroelectric, geothermal, wind, biomass, and solar). Reliance on some of each kind, and distribution across energy-use sectors, will help diversify supply.

Diversification of energy supply does not automatically signify deprivation. As Table 1 shows, a number of countries, including France, Germany, Japan, Norway, and Sweden, maintain a high standard of living while using comparatively less energy and emitting less carbon dioxide. Table 1 is instructive because it shows how fossil fuel dependent some countries are—and again, how this does not have to be the case to maintain a high standard of living, as measured by per capita gross domestic product.

Currently, the energy supply mix is not diverse, as shown in Figure 1. The world is heavily dependent on fossil fuels, and this applies to all end-use sectors, including residential, commercial, transportation, and industrial (Energy Information Administration 2006b). This picture is not likely to change much over the next twenty-five years, according to business-as-usual predictions of the Energy Information Administration (2006b). In fact, oil use will increase in all sectors, overall from 161 exajoules (EJ) in 2003 to 237 EJ in 2030, with the majority of the increase in the transportation and industrial sectors. Coal use will also increase in all sectors, from 106 EJ in 2003 to 208 EJ in 2030, with the main increases in industry and electricity generation. Natural gas consumption will increase about 55% over that period. Such a heavy dependence on fossil fuels results in high emissions of carbon dioxide and, for many countries, overdependence on foreign sources of these fuels, potentially affecting security of supply.

To address the diversity of supply issue, it is necessary to attack it from both the electricity generation angle, which will perhaps prove easier to accomplish, and the transportation angle. Both electricity generation and transportation are, and are expected to continue to be, major users of fossil fuels. Almost all motor vehicles are powered by oil, but in the electricity generation sector, nuclear power and hydropower already provide a significant proportion of capacity (32%) (Fig. 2). With recent research and development in renewable energy, these forms are poised to take up a larger percentage of this sector. The following section reviews the potential for change in the transportation and electricity generation sectors.

TRANSPORTATION

Transportation currently uses more than a quarter (27%) of all energy supplied (Energy Information Administration 2006b). Over the next twenty-five years, oil demand is forecast to increase in countries like India and China, which are rapidly industrializing their economies. For example, the U.S. is expected to increase oil consumption between 2003 and 2030 by 37%, whereas China is projected to experience a tripling of consumption and India a doubling over the same time period (Energy Information Administration 2006b). Change, if and when it happens, may be slow:

<table>
<thead>
<tr>
<th>Table 1</th>
<th>PER CAPITA GDP, ENERGY USE, AND CO₂ EMISSIONS</th>
</tr>
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<tbody>
<tr>
<td>Country</td>
<td>Per capita GDP ($2000/capita)</td>
</tr>
<tr>
<td>India</td>
<td>0.54</td>
</tr>
<tr>
<td>China</td>
<td>1.3</td>
</tr>
<tr>
<td>France</td>
<td>22.8</td>
</tr>
<tr>
<td>Germany</td>
<td>23.7</td>
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<tr>
<td>Canada</td>
<td>24.6</td>
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<tr>
<td>Sweden</td>
<td>29.3</td>
</tr>
<tr>
<td>United States</td>
<td>36.4</td>
</tr>
<tr>
<td>Japan</td>
<td>38.6</td>
</tr>
<tr>
<td>Norway</td>
<td>39.3</td>
</tr>
</tbody>
</table>

Data from International Energy Agency (2006b)
currently, on average U.S. cars achieve only 20.4 mpg (miles per gallon; 11.5 liters per 100 km), compared to 40 mpg (5.9 L/100 km) for European cars. Moreover, in the U.S. only two cars on the 2007 market achieve over 40 mpg (compared to five cars in 2005), while in Europe the opposite trend is seen: in 2007, 113 European cars got at least 40 mpg, compared to 86 in 2005 (Jones 2007).

Oil
As the data above show, the world is now entirely dependent on fossil fuels. This state of affairs will not change over the next 20 years at least. World crude oil reserves are estimated at 1293 billion barrels (Gbbls) of oil, while estimates of crude oil resources range up to 3000 Gbbls of oil (Energy Information Administration 2006b). The Middle East contains most of these resources (1265 Gbbls), whereas North America and Europe/Eurasia have equivalent amounts (487 Gbbls and 459 Gbbls, respectively), followed by Central and South America (319 Gbbls), Africa (300 Gbbls), and Asia (127 Gbbls) (Energy Information Administration 2006b). For perspective, in 2003, the world produced about 80 Mbbls/d (million barrels per day) (Energy Information Administration 2006b). Production by 2030 is projected to increase by almost 50% to 118 Mbbls/d (Energy Information Administration 2006b). Most of this increase will come from demand by the transportation and industrial sectors (Energy Information Administration 2006b).

Unconventional oil resources are already being tapped, given the current relatively high price of oil. Tar sands—clastic rocks or sands with significant bitumen concentrations—are chemically and physically similar to heavy oil, which is more viscous than the tar in the tar sands. Tar sand resources are estimated at over 3.2 Ttbbls (terab barrels, or trillions of barrels), and heavy oil resource estimates range from 1.4 to 2.7 Ttbbls (Rogner 1997). Tar sands are now becoming economically viable to extract, and in recognition of this, Canada has just added 174 Gbbls to its oil reserve estimates, becoming second only to Saudi Arabia in listed proven reserves. Oil shale represents potentially a large oil resource, with estimates of 3.3 to 18.4 Ttbbls globally (Rogner 1997). The oil shale resource in the U.S. is estimated to be 2.6 Ttbbls (Bunger et al. 2004).

Biofuels
Transport fuels can also be developed from crops, theoretically producing no net increase in atmospheric carbon dioxide emissions. Ethanol can wholly or partially replace gasoline in light-duty vehicles, though engines in most vehicles must be specially designed to use more than 10% ethanol. Sugar cane, corn, and cellulosic crops can be used to produce ethanol. Ethanol can be produced from sugar cane and corn using existing technology; production of ethanol from cellulosic crops awaits development of techniques to break down cellulose into sugars economically. Cellulosic ethanol would render large inexpensive feedstocks, such as crop residues, grasses, and forestry wastes, into useable fuel. Production of ethanol from corn requires the additional step of turning corn starches into sugars, and then fermenting them, resulting in higher costs for corn-produced ethanol. Currently, corn-based ethanol is more expensive than gasoline (not counting government subsidies) and produces equivalent CO₂ emissions (Farrell et al. 2006).

A promising alternative to ethanol is biodiesel, produced from plant oils including soybean and rapeseeds (even used restaurant oils). These plant oils are transesterified to produce methyl esters, called biodiesel, which can be used directly in diesel engines. Biodiesel can partially or fully replace diesel fuel in diesel engines, and can do so with potentially lower carbon dioxide emissions than ethanol.

Hydrogen
Another potential energy solution in the future is hydrogen to power fuel cells in vehicles and for electricity generation. Hydrogen is not a primary fuel source and therefore must be produced by breaking the chemical bonds of either a hydrocarbon (methane is currently used) or water. For large-scale hydrogen use to be practical, the cost of making hydrogen must come down significantly, and technical and political issues will have to be worked out to allow adequate numbers of hydrogen fueling stations and the installation of appropriate fuel tanks on vehicles. As a result, widespread use of hydrogen technology is unlikely for many decades.

ELECTRICITY
Global electricity generation is more diversified than transportation (Fig. 2) and therefore has the potential to more rapidly reduce carbon dioxide emissions over the coming years. Fossil fuels provide 65% of generated electricity, while 35% of electricity is generated by low-carbon-emissions technologies. The potential for the latter number to increase is counterbalanced by the abundance and wide distribution of coal. The solution to this dilemma may be carbon sequestration, a technology that removes the CO₂ emissions when the fuel is burned.
year, such a rate of growth is potentially devastating for the climate. Because coal is abundant and relatively cheap, growth in its use over the next 25 to 50 years is all but assured.

Given this grim scenario, there are some promising ways to reduce future carbon dioxide emissions from coal plants. The first is to increase the efficiency (and therefore reduce the CO₂ emissions) of coal plants. Right now, the majority of plants are subcritical pulverized coal plants, with efficiencies on the order of 34%. Shifting to supercritical or even ultrasupercritical pulverized coal plants, both of which use supercritical fluids, could increase efficiencies to 38% or even 43% (MIT 2007). Integrated gasification combined cycle (IGCC) coal plants could also increase efficiencies to more than 38%, though currently this is a higher-cost technology.

**Carbon Sequestration**

A more promising solution to increased coal use is technology that strips off CO₂ emissions and sequesters them underground for geologic time periods, a process called carbon sequestration. Carbon sequestration actually consists of three separate steps: CO₂ capture, transport, and underground sequestration. Carbon dioxide capture occurs at coal plants (or natural gas or biomass plants), and can be done either after combustion (for pulverized coal systems, in which it is separated from the flue gases) or prior to combustion (for IGCC systems). Existing plants can be retrofitted with this technology, though this can be expensive. A recent MIT coal study (2007) suggests that it is more cost effective to rebuild existing plants (replacing a subcritical unit with a super- or ultrasupercritical one) when adding this technology. If carbon-capture technology becomes the norm, then IGCC plants will be much more cost effective than pulverized coal plants (MIT 2007).

Carbon dioxide transport and sequestration are to some degree existing technologies. S. Julio Friedmann discusses the issues surrounding geological carbon sequestration on pages 179 to 184 of this issue.

**Natural Gas**

Natural gas reserves are also abundant and are estimated at 6113 trillion cubic feet, with an additional 4200 trillion cubic feet considered “undiscovered” (Energy Information Administration 2006b). Again, most of this resource is located in the Middle East (2565 trillion cubic feet of reserves), followed by Eurasia (1953 trillion cubic feet), Africa (486 trillion cubic feet), Asia (392 trillion cubic feet), North America (265 trillion cubic feet), Central and South America (251 trillion cubic feet), and Europe (201 trillion cubic feet) (Energy Information Administration 2006b). In 2003, world consumption of natural gas was 95 trillion cubic feet and is projected to increase to twice this amount by 2030 (Energy Information Administration 2006b).

Natural gas, like oil, has been the subject of a number of political conflicts in recent years. Pipelines are required to transport most natural gas resources to shipping routes. With the discovery of large reserves in the Caspian Sea region, this area has become a hot spot for gas-associated conflict. For example, the U.S. would like to build a pipeline that goes through Georgia, from the port of Baku in Azerbaijan—thus avoiding Russia—and then continues south through Turkey to the port of Ceyhan on the Mediterranean Sea. The Russians prefer the existing pipeline that goes through Russia, assuring them a portion of the profits, while Iran prefers a pipeline from Azerbaijan, directly south through Iran to the Persian Gulf (Klare 2001). Recently, Russia cut gas supplies to the Ukraine in a political dispute with that country, a move that directly affected Europe, which receives 90% of Russian gas through the Ukraine.

Another source of political debate in regards to natural gas is liquefied natural gas (LNG) terminals. It is estimated that by 2010, 10% of the U.S. natural gas supply will be from LNG (Cusick 2005). However, many communities refuse to welcome LNG terminals because of the risks posed by these facilities in the case of accidents or terrorist attack.

Unconventional gas may be even more abundant than conventional gas. Coal bed methane may be the best-known resource, occurring in coal seams (mainly anthracite or bituminous) and sandstones adjacent to coal beds. Coal bed methane resources are estimated at 3003 to 13,000 trillion cubic feet (Rogner 1997). Gas can also be trapped in shales (usually Devonian age), and an uncertain estimate of these global resources is 400 billion tonnes oil equivalent (Gtoe) (Rogner 1997). Gas can also be present in a number of rock types that provide low-permeability conditions. This kind of gas is known as tight gas, and resources are estimated to be about 190 Gtoe (Rogner 1997). Natural gas in aquifers offers a large resource of 8900 Gtoe (Rogner 1997). A potentially enormous resource exists in the form of methane hydrates, estimated at over 18,000 Gtoe (Rogner 1997). Carolyn Ruppel discusses the distribution and potential for exploitation of methane hydrates on pages 193 to 199 of this issue.

**Nuclear Power**

Although there has been much talk about a “nuclear renaissance” (e.g. Ewing 2006), it has yet to occur and it is not clear it will ever materialize. Though nuclear power is a well-established method to generate electricity (it accounts for 16% of world electricity generation; International Energy Agency 2006a) and emits few greenhouse gases (mostly via mining uranium ore and power plant construction), it suffers from a unique set of problems. One problem is the disposal of high-level nuclear waste. The nuclear industry has existed for over 50 years without implementing a solution for nuclear waste, though most experts agree that geologic repositories are the best answer. A second, more serious problem is the possible proliferation of nuclear weapons. The materials that create the nuclear reaction in power plants are the same as those that power nuclear bombs. The challenge is to keep the two applications separate. In a world with rapid nuclear power expansion, controlling the weapons materials may prove too great a challenge. More pragmatically though, the nuclear renaissance may not come to pass because of a more mundane issue, one that affects other types of electricity generation, including some renewables: high capital costs. In the U.S., capital costs will likely deter the industry from a large expansion, unless fossil fuel resources are highly taxed. The longevity of such a “nuclear renaissance” is unsure because of uncertainties over the size of the uranium resource. Allison Macfarlane and Marvin Miller consider this issue on pages 185 to 192.

**Renewable Energy Resources**

Renewable energy sources are promising for the future, though it will take many decades for them to emerge from providing less than 10–15% of global electricity supply in the absence of considerable efforts to promote them. In 2004, renewable energy resources, not including hydroelectricity, made up only 2.1% of global electricity generation (International Energy Agency 2006a). Some types of renewable energy, like wind power, have dropped in price significantly in recent years and are now competitive with fossil resources. The problem with some renewable resources,
such as wind and solar energy, is that they are intermittent and need to be supplemented by other secure forms of energy generation or by storage methods. Many renewable electricity generation technologies are relatively small scale and are certainly appropriate for rural regions. Below I consider a number of the more common renewable technologies.

Among renewable resources, **hydroelectricity** produces the largest proportion of electricity—16% of world generation in 2004 (International Energy Agency 2006a). Hydropower has the potential to grow by more than 60% by 2030 (International Energy Agency 2004). Most of this growth is expected in developing countries, since developed countries have tapped the majority of their large resources. The largest hydropower producers are, in order, China, Canada, Brazil, and the U.S., though Norway gets 99% of its electricity from hydropower (International Energy Agency 2006a). Though the power is relatively cheap, large hydropower developments suffer from environmental problems including loss of habitat and displacement of peoples from land inundation, sediment build-up, downstream sediment starvation, and aquatic effects like oxygen depletion and interruption of fish migration. Hydroelectricity no longer simply implies huge dam projects, such as the Three Gorges Project in China (with a capacity of 18 GW), but also includes micro-hydro projects (<100 kW) and run-of-the-river or diversion (instead of a single impoundment-type dam) projects, which are much more environmentally friendly.

**Geothermal energy** provides small amounts of electricity and heat, but could be expanded in many areas to provide cooling and heating through relatively simple heat pumps that use the upper 10 feet of the ground to provide a source of cool air (in the summer) and warm air (in the winter). In 2005, geothermal energy provided 9 GW of electrical capacity globally (BP 2006). This resource could expand beyond areas of high heat flow (the Pacific rim is one of the largest geothermal resources) if drilling techniques were capable of economically reaching the “hot dry rock” at up to 9 km depth, where temperatures exceed 100°C. These rocks would then need to be fractured, so that a working fluid (water, most likely) could be circulated down to the heat source and brought to the surface as steam to run turbines. If fully exploited this resource could expand geothermal energy’s reach to 11 billion EJ (Duchane and Brown 2002), triple that of fossil fuels. Issues remaining with this resource are drilling to adequate depths, finding or creating rock of sufficiently low permeability to prevent working fluids from flowing away, and most importantly, finding a reasonable heat extraction method (Tester et al. 2005).

**Solar electricity**, produced either via photovoltaic cells or more directly from thermal concentrating systems remains expensive, but small systems are beginning to expand their market share. Larger solar concentrating plants (10 MW or more) use mirrors to focus heat onto a working fluid (water, molten salt) to create steam and run a turbine. The best locations for solar thermal plants are areas that receive more than 6.7 W/m² of radiation. These areas are typically located in the lower latitudes. Solar thermal plants tend to operate when the sun shines; when it does not, stored energy must be used. Solar thermal energy technology is currently used relatively efficiently to heat buildings and provide hot water for residences.

Electricity production from solar photovoltaic technology is currently increasing rapidly. In 2003, world photovoltaic electricity production was 1.8 GW; in 2004, it was 2.6 GW (BP 2006). Solar photovoltaics provide electricity via the photovoltaic effect using materials such as amorphous silicon (Si), gallium arsenide (GaAs), cadmium telluride (CdTe), and copper indium diselenide (CuInSe₂). Theoretically, photovoltaic cells can reach efficiencies of 50%, though in practice, they achieve much lower efficiencies, in the range of 3–14% (Smil 2003). The potential for solar photovoltaic applications includes small units for residential/business use and larger units for more widely distributed power. Currently, Japan and Europe are the leading manufacturers and markets for photovoltaic cells, and their market share seems to be growing.

Electricity produced from **wind** is growing at a significant rate as well. Denmark now gets 20% of its electricity from wind power, for instance. Wind power provided 47.9 GW of electricity worldwide in 2004. By 2005, it had jumped to 59.2 GW (BP 2006). Most of this new wind power is concentrated in Germany and Spain, who together produce half of the world’s wind-based electricity (Sawin 2005). The electricity provided by wind is directly proportional to the size of the blade. As a result, a number of innovative designs are being implemented, including those that use vertically rotating axes (horizontal axes are more common). Wind power operates at wind speeds between 2.5 and 25 m/s, so electricity generation varies with seasonal climate variations. The size of the potential wind resource is high (some estimates put it between 6 and 35 TW (Smil 2003), but proposals for wind farms often meet public opposition because of noise, bird deaths, and aesthetics.

Another promising source of non-fossil energy is **biomass**, which can provide for both electricity and transport fuel needs. Traditional biomass fuels for heating and cooking made up 7% of global energy consumption in 2004 (International Energy Agency 2006a) and 68% of biomass primary energy demand (International Energy Agency 2004). Nontraditional biomass can be used for electricity production by co-firing biomass at a coal plant, by direct firing of biomass fuel, by biomass gasification in a combined cycle plant, and via landfill production of methane for power plants. Nontraditional biomass accounted for 2927 TWh of global electricity production in 2002 (International Energy Agency 2004). Although biomass produces carbon dioxide when burned, theoretically it is neutral with respect to atmospheric carbon dioxide emissions because the plants used for the fuel remove an equivalent amount of CO₂ from the atmosphere while they are growing. In reality, biomass tends to be a producer of carbon dioxide emissions when fertilization and transport of crops to the power plant are considered. A unique aspect of biomass is that if it is used in conjunction with a geologic carbon dioxide sequestration program, it can theoretically become a carbon sink, by extracting atmospheric CO₂ during crop growth followed by sequestration of this CO₂ in a geologic repository during burning.

**CONCLUSIONS**

No revolution in the way we use energy will come about without direct governmental action. Changes are already occurring in Europe where laws have been enacted to meet Kyoto Protocol standards. For example, Germany now has 11% of its electricity generated from renewable sources, half from wind power (E&E News PM 2005), and it plans to reach 20% from renewables by 2020 (Kammen 2006). The U.S., unfortunately, lags far behind, with only 2% of its electricity produced from renewable sources (not including hydroelectricity at 6.5%). The U.S. is currently the single largest emitter of greenhouse gases, though it will soon be overtaken by China. Neither country has a national program to reduce emissions of greenhouse gases. Clearly, a more robust global agreement on how to limit greenhouse gas emissions is necessary to mitigate some of the effects of climate change.
The solution to the energy and climate crisis is to be found in a mix of energy resources, bolstered by vibrant research and development (R&D) programs and global carbon dioxide emissions regulations. Renewable energy for electricity generation and biofuels for transport are essential for success, in addition to efficiency standards and conservation measures. Energy R&D offers great opportunities for development. In the U.S., for example, annual energy R&D funding (public and private) dropped from $12 billion in 1980 to $4 billion in 2005 (Kammen 2006). Kammen (2006) found that the stabilization of carbon dioxide in the atmosphere would require a five to ten fold increase in public sector funding for energy R&D ($3 billion in 2005). In addition, a carbon tax, a cap-and-trade system, or a hybrid regime needs to be in place to encourage the use of technologies that do not emit carbon dioxide. Only with dedicated investments and certain political action will we have a fighting chance against the coming tide.

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Confronting the Climate–Energy Challenge

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Combustion of coal, oil, and gas has raised the amount of carbon dioxide in the atmosphere to levels higher than they have been for millions of years. A brief review of the history of Earth’s climate puts the next hundred years in its natural context, suggesting that most predictions based on climate models may be underestimating the problem. Reducing risks of future climate change requires changes in existing energy systems. These changes will be in three areas: increasing energy efficiency, increasing the stock of non-fossil energy generation, and adopting technologies for capturing and storing carbon dioxide from fossil fuels.

KEYWORDS: climate change, paleoclimate, energy, carbon sequestration

INTRODUCTION

Energy is an essential element of modern society, with more than 80 percent coming from the combustion of fossil fuels. But the continued use of fossil fuel as the major source of world energy has ominous implications for the environment. Current consumption of fossil fuel releases more than 25 billion tonnes of carbon dioxide into the atmosphere each year. If current trends continue, atmospheric carbon dioxide (CO₂) will triple by the end of the century, bringing Earth’s atmosphere to a composition not seen for more than 40 million years. Given the long lifetime of energy infrastructure, it is difficult to design even the most aggressive mitigation strategy to keep CO₂ from doubling, especially with large deposits of inexpensive coal in those countries that consume the most energy.

Motivated by concerns about climate change, human health, economic prosperity, and national security, nations are beginning to choose new ways of obtaining energy that minimize harmful consequences. Nuclear, solar, wind, geothermal, and biomass energy, along with efforts to enhance energy efficiency, are all receiving greater attention from industries, governments, and individuals around the world. But fundamental questions remain about these technologies and their applications. Many are still expensive relative to fossil fuels and may also have harmful impacts when expanded to larger scales. More-efficient and less-expensive technologies may emerge but will require decades of basic research in science and engineering. A transition to new energy systems also raises a broad set of questions about national security and economic development.

In this paper, I discuss the components of a broad strategy to address the energy–climate challenge. First, I outline a core argument for why climate change is likely to generate broad demand for change in our energy systems and why that demand is likely to increase over the next few decades. Second, I discuss the various energy technologies that are likely to contribute to national and international strategies to address climate change by minimizing carbon dioxide emissions. Finally, I discuss whether the implementation of such strategies is likely to be sufficient to avoid catastrophic consequences and what additional options may exist.

THE GREAT CLIMATE EXPERIMENT

The life work of Charles David Keeling produced the famous Keeling curve (Fig. 1), a record of carbon dioxide measured in the atmosphere at Mauna Loa, Hawai‘i, far away from local sources of pollution. Keeling started monitoring in the late 1950s when atmospheric CO₂ was only 315 parts per million (ppm), and it was over 380 ppm when he died in 2005. This rise is due primarily to the burning of fossil fuels: coal, oil, and gas (Keeling and Garcia 2002). Deforestation and other changes in land use have also contributed. The rise in atmospheric CO₂ has not been as fast as the growth in CO₂ emissions. Approximately 60% of the CO₂ emitted to the air stays in the atmosphere, while 20% is taken up by the ocean and 20% by terrestrial ecosystems; this partitioning was demonstrated by measuring the subtle decline in atmospheric oxygen by Keeling’s son, Ralph (Keeling and Garcia 2002). This distribution has been remarkably constant over the last two decades. However, the capacity of the ocean and the terrestrial biosphere to partially compensate for our carbon emissions may change as future climate change slows down ocean circulation and as accumulation of organic carbon in soils with subsequent CO₂ emissions begins to balance the enhanced uptake in areas of reforestation.

The Keeling curve is a spectacular record of human impact on the atmosphere, although viewed by itself it understates the scale of our challenge. A more appropriate way to view Keeling’s measurements is in the context of a longer record of atmospheric CO₂ measured in ice cores from Antarctica. With the recent drilling of the EPICA core, measurements of ancient atmospheric composition obtained from bubbles in the ice have now been extended back 650,000 years before present (Siegenthaler et al. 2005). Over this time interval, CO₂ reached minimum levels of approximately 180 ppm during the glacial maxima, and peaked below
During the interglacials, atmospheric CO$_2$ concentrations never rose above 300 ppm (Fig. 2). Direct measurement of more ancient CO$_2$ levels is not possible unless more ancient ice is identified. However, through a variety of geochemical measurements, including carbon isotopes of organic molecules (Pagani et al. 1999) and boron isotopes that are used to reconstruct seawater pH (Pearson and Palmer 1999), atmospheric CO$_2$ concentration can be indirectly estimated over much longer timescales. These data suggest that atmospheric CO$_2$ has not been much higher than 300 ppm for 30 million years or longer. In this context, the scale of our global experiment becomes clear: we are perturbing the atmosphere beyond any state seen through the entire history of the human species. Therefore, we must look to the past to understand the likely implications.

**BEYOND NATURAL VARIABILITY**

The geologic record demonstrates not only that CO$_2$ is higher than it has been for millions of years, but also that the recent warming observed over the last 140 years of instrumental record is beyond the range of natural climate variability. Paleoclimate reconstructions of the last several millennia come from many sources, including tree rings, corals, lake sediments, ocean sediments, and speleothems. These records exhibit a substantial amount of regional climate variability over the last 1000 years, although the Northern Hemisphere average temperature based on reconstructions from multiple proxies remained relatively constant until the last 140 years (Crowley 2000). For example, there are still debates on whether the Little Ice Age, which had a dramatic effect on European farming in the 17$^{th}$ and 18$^{th}$ centuries, was associated with a change in global average temperature (Crowley 2000), but there is no doubt that the Little Ice Age was much greater in western Europe than in other regions. A goal of paleoclimatology has been to understand how local climate changes observed in the various archives relate to larger patterns of climate that can be attributed to specific external forcings (such as CO$_2$) or to specific dynamical processes (such as El Niño and the North Atlantic Oscillation).

There is one archive of information on past climate that has provided the most compelling evidence for an anthropogenic effect on Earth’s climate because the information comes from a part of the Earth system that is very stable: the equator. Tropospheric temperatures near the equator are remarkably constant over seasonal and interannual timescales, especially at higher altitudes where the effects of the boundary layer are small. Starting in the 1970s, L. Thompson and colleagues pioneered the use of solar-powered drilling equipment to obtain ice cores from tropical glaciers at high altitudes in Africa, the Himalayas, and the Andes, recovering records that in some locations extended back to the Last Glacial Maximum (LGM), 20,000 years ago. Through multiple visits to these remote locations, they have documented that tropical glaciers all over the world are receding faster and faster, and in many locations may disappear in the next few decades (Fig. 3) (Thompson et al. 2006). The ice cores, along with plant remains exposed as the glaciers recede, prove that the rate of melting observed today has not happened for thousands of years and cannot be explained by any cycle of natural variability.

**CLIMATE SENSITIVITY: A VIEW FROM THE PAST**

There is no serious debate that carbon dioxide will cause Earth’s surface to warm; what is uncertain is how much warming will occur. To observe the influence of CO$_2$ on climate, we need only consider our neighboring planet Venus, which has a surface temperature of 465° C because its atmosphere is nearly 100 times denser than Earth’s and is composed almost entirely of CO$_2$. If Earth were dry like

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**Figure 1** Atmospheric CO$_2$ concentrations (ppmv) derived from in situ air measurements at Mauna Loa Observatory, Hawai'i (Keeling et al. 2001)

**Figure 2** Atmospheric CO$_2$ concentrations inferred from inclusions in ice cores from Vostok (Petit et al. 1999; dark blue line), EPICA (Siegenthaler et al. 2005; light blue line) and obtained from instrumental measurements (Keeling et al. 2001; red line)
Venuses, predicting how human activities would affect the climate would be straightforward. Water on Earth affects the climate system in a number of different ways, which makes prediction more complicated. First, water vapor itself is the most important greenhouse gas, acting as an amplifier of other forcings, such as CO₂. Water can also change the planetary albedo—a measure of how much light from the sun is reflected back to space—through the formation of stratospheric clouds that formed in the Eocene during times of higher CO₂, which suggests that at least 2°C colder during the LGM (Lea et al. 2000). Atmospheric CO₂ has fluctuated over the late Pleistocene between 180 ppm and 280 ppm, which corresponds roughly to a 50% increase from glacial maximum to interglacial, or half a doubling. This means that a 2°C change from CO₂ implies a climate sensitivity of almost 4°C, which is at the high end of modern estimates.

The standard measure of how much amplification occurs in response to a rise in atmospheric CO₂ concentrations is climate sensitivity, defined as the change in global average temperature for a doubling of atmospheric CO₂. Most general circulation models used to predict future climate change use a climate sensitivity of between 1.5 and 4°C, based on calibration of these models to the observed temperature change over the last century. However, the last century may not be a good predictor of climate sensitivity in the future as CO₂ rises to levels far beyond the calibration range. This is where the geologic record of past climate change is especially useful. From both cold climates of the Pleistocene and warm climates of the Cretaceous and Eocene, the paleoclimate record can tell us something about how sensitive Earth may be to changes in atmospheric CO₂.

The timing of the periodic ice ages over the last two million years was set by changes in the distribution of incoming sunshine caused by variations in Earth’s orbit around the Sun. But orbital variations by themselves are not capable of driving global temperature changes of 5°C between glacial maxima and interglacials like the one we live in today. The orbital variations are amplified by changes in planetary albedo due to changes in land and sea ice and by changes in CO₂ as discussed above. The orbital variations are probably connected to climate through the growth of land ice, following the suggestions by Milankovitch (Imbrie 1982). Over these time intervals, temperature and CO₂ are coupled: the temperature change affects the CO₂, both directly through solubility in seawater and indirectly through circulation changes and perhaps aridity and enhanced dust deposition (Sigman and Boyle 2000), while the CO₂ affects the temperature through the greenhouse effect.

One way to estimate the relative contributions of ice albedo and CO₂ is by looking at the temperature change between glacial and interglacial worlds in the tropical waters of the western Pacific, far from the polar icesheets. The western equatorial Pacific is a warm and stable area of the world ocean; in this region, the sea surface temperature varies very little over seasonal and interannual timescales, and is not sensitive to changes in the polar regions or to changes in the deep circulation. Recent work has shown that the sea surface temperature in the western equatorial Pacific was approximately 3°C colder during the LGM (Lea et al. 2000). This cooling may be explained predominantly by radiative effects associated with changes in atmospheric CO₂, which suggests that at least 2°C of the 5°C total change from glacial to interglacial climates can be attributed to CO₂. As discussed above, atmospheric CO₂ has fluctuated over the late Pleistocene between 180 ppm and 280 ppm, which corresponds roughly to a 50% increase from glacial maximum to interglacial, or half a doubling. This means that a 2°C change from CO₂ implies a climate sensitivity of almost 4°C, which is at the high end of modern estimates.

Warm episodes of Earth history reveal even more cautionary lessons. The Eocene, which extended between 55 and 35 million years ago, was the last time when there is clear evidence for global warmth, and we suspect that CO₂ was well above modern levels (Pearson and Palmer 1999). The reconstructions of Eocene climate, including isotopic, chemical, and paleobiological data, reveal a general picture of a very warm world, with polar temperatures elevated by as much as 6 to 10°C, but tropical temperatures only slightly higher than modern, if at all (Zachos et al. 2001). In addition to the reduced meridional temperature gradient, there is evidence from the fossil locations of warm-climate plants such as palm trees that winters in the continental interiors were much milder than today (Wing and Greenwood 1993).

We do not know precisely how high atmospheric CO₂ was during the Eocene, so it is difficult to use the Eocene as a direct measure of climate sensitivity. However, the extreme warmth at high latitudes, and in particular the wintertime warmth in continental interiors, cannot be simulated by climate models by elevating greenhouse gas concentrations unless special cloud feedbacks are included that are not present in the models used to predict future climate change (Sloan and Pollard 1998). This suggests that there are feedbacks missing from our models that may cause us to underestimate future climate change, particularly at high latitudes. One interesting hypothesis is that the warm continental interiors were due to optically thick polar stratospheric clouds that formed in the Eocene during times of higher CO₂ (Sloan et al. 1992; Kirk-Davidoff et al. 2002). If correct, such a mechanism should become evident in the next century as CO₂ rises above 500 ppm. Whatever the
In general, Earth appears to be more sensitive to changes in atmospheric CO$_2$ than the models we use to predict the future because climate sensitivity in a strict sense appears to be higher in nature than in our models and because the models cannot provide probabilistic estimates for abrupt climate change. It would be a grave mistake to take these lessons from ancient climates as a reason to disregard predictions from climate models. These models are not perfect, but they do represent our best understanding of the climate system based on a century of observations, and they remain an essential tool for exploring future scenarios. At the same time, it is not surprising that the models are not perfect as our atmosphere is heading to a state unlike any seen for millions of years. In confronting climate change, it is important to realize that our predictions may be conservative.

**Towards a Solution**

Given the dramatic changes we are observing today and the dire view from Earth history, what can we do? The first challenge we must confront in working towards a solution to future climate change is that any “solution” will be incomplete. Some amount, perhaps even a substantial amount, of climate change is unavoidable. Reducing CO$_2$ emissions so that they are below the level of CO$_2$ uptake by the oceans and biosphere will not happen in a decade or two, but only through prolonged actions over 50 years and perhaps longer. Even if more immediate actions were possible, the current atmosphere with more than 380 ppm CO$_2$ may be too warm to allow the ice sheets on Greenland or West Antarctica to survive; exactly how much melting will occur if emissions were stabilized at current levels remains uncertain. In addition, the oceans will continue to warm for decades even if emissions were halted. Ecological changes due to climate change that has already occurred will continue to unfold for decades. Another problem is that the CO$_2$ resides in the atmosphere and surface ocean for centuries and is only slowly taken up by the deep ocean. If we were to reduce our emissions to zero immediately, it would take more than 200 years for terrestrial and oceanic uptake of carbon to restore the atmosphere to its pre-industrial condition. Thus, there is great momentum in the climate system, in the heat capacity of the oceans, in ice sheets, and in the residence time of carbon dioxide in the atmosphere, and this fact makes a certain amount of climate change inevitable. Future impacts will include sea level rise, changes in rainfall patterns, early melting of mountain snowpack and glaciers (which serve as a water supply for billions of people), changes in storms and tropical cyclones, and ecological changes that affect ecosystems crucial to human society. Adaptation efforts are essential to help people adjust to these changes.

Some people have argued, based on economics, that we dispense with mitigation and focus all our efforts on adaptation, trying to avoid the impacts of climate change or at least make them less costly (Lomborg 2004). The flaw in this argument is that adaptation becomes more and more difficult—ultimately impossible—if mitigation is not pursued. Consider the impact of sea level change, only one of many serious impacts of future climate change. One might propose that it is reasonable to do nothing about CO$_2$ emissions in response to future sea level rise and instead focus our efforts on building dykes and levees to protect low-lying areas and on moving cities to higher ground. This might be a fine strategy if sea level rise stopped after 2100. But after the first meter of sea level rise due to melting of the Greenland ice sheet, there will be the second, and the third—ultimately 7.2 meters if the Greenland ice sheet melts entirely (Fig. 4). And then there is the 6 meters of sea level equivalent stored in West Antarctica, and the 50 meters or
so in East Antarctica. The consequences of ignoring climate change and allowing atmospheric CO₂ to reach 1000 ppm or higher—quite possible if no mitigation steps are taken—are simply too great to allow adaptation in any meaningful sense.

Thus, dealing with climate change means both adaptation and mitigation. Adaptation requires significant attention and resources, but this discussion will focus on mitigation and more specifically, its scientific and technological challenges. Climate change mitigation requires an enormous shift in energy systems, which are themselves issues of national security and economic prosperity. This means that solving the climate–energy challenge is not just solving the problem of high CO₂ emissions; it also means creating low-carbon sources of energy that are secure and inexpensive. It is a challenge far too great to describe in detail in this paper. Instead, I will attempt in the final section to outline some of the scientific and technological approaches that are likely to be a part of any solution. It is important to remember, however, that scientific and technological considerations may be trumped by considerations of national security and economic well-being.

ENERGY SYSTEMS OF THE FUTURE

One source of confusion in discussions on how to reduce CO₂ emissions is that our energy system is really more than one system. We use energy for transportation, for electricity to power our lights and electronics, to heat or cool our homes, for manufacturing, and for agriculture. Our energy choices within each of these sectors come with different technological constraints that require different types of solutions if reductions in CO₂ emissions are to be achieved. For example, the internal combustion engine (along with the gas turbine in airplanes) currently dominates the transportation sector and is fueled almost exclusively by petroleum, responsible for approximately 40% of global CO₂ emissions (Table 1). The electricity industry has a much broader set of energy sources, including coal, natural gas, nuclear, hydroelectric, wind, solar, biomass, and geothermal, although coal, natural gas, and nuclear are currently dominant. Thus, the discussion of strategies for mitigating climate change must address not just sources of energy, but sources in relation to different societal needs.

Another consideration is differences in energy technologies among countries. Some countries, such as Saudi Arabia and Russia, are rich in hydrocarbon resources, and this guides their energy decisions. Other countries, such as Japan, have almost no domestic energy resources, and turn to technological solutions such as solar and nuclear power. The end use of energy also varies among countries. For example, both China and the U.S. have large coal reserves, but China consumes almost twice as much, in part due to its large manufacturing industry compared with the service economy of the U.S. (BP 2006). What this means is that there is no single strategy for how the world will address climate change but rather a portfolio of strategies. Rapidly developing countries will have different solutions from those of developed countries. Even countries with similar levels of economic development will employ different solutions because of geography, political and cultural attitudes, and political systems. This does not mean that individual solutions must be created for all countries. CO₂ emissions are not distributed evenly; a handful of countries contribute most of the emissions and will be responsible for bringing about most of the reductions. If the U.S., China, India, the European Union, Russia, Japan, Australia, Canada, and perhaps Indonesia and Brazil each take significant steps to reduce emissions, it is likely that such efforts will be successful in reducing the impacts of climate change on the rest of the world.

Another constraint is the timescale over which it is possible to build new energy systems. Eliminating carbon emissions from electricity generation by using nuclear power, for example, would require building two large nuclear plants each week for the next 100 years. This rate of change is simply not possible given current constraints on steel production, construction capacity, and the education of operators, and because of many other practical considerations. Taken together with the diverse uses of energy and the different needs of different nations, this means that there is no silver bullet solution for the climate–energy challenge. A myriad of approaches is required. One can group these approaches into three broad categories, each of which will contribute an essential part to any serious climate mitigation effort.

Reduction of Energy Demand

The first category involves reducing CO₂ emissions by reducing energy consumption. This does not necessarily require reducing economic activity, i.e. consuming less; rather it means restructuring society, either by investing in low-energy adaptations such as efficient public transportation systems, or by adopting energy-efficient technologies in buildings, in automobiles, and throughout the economy. Huge discrepancies in energy efficiency exist today among developed countries. In general, countries with higher historical energy prices, such as most of western Europe, are more efficient than countries with inexpensive energy, including petroleum. However, the differences can also be explained by historical investments in cities and suburbs and in highways and public transportation systems, as well
as by a variety of other factors. But whatever the cause of the current differences among countries, there is great potential across the developed and the developing world to dramatically lower energy use through smarter and better energy systems.

Much of the efficiency gains can be accomplished with existing technologies, such as compact-fluorescent lighting or more efficient building designs; these are often referred to as the “low hanging fruit” as they are often economically advantageous because they are simple and inexpensive. In addition, there are technological improvements in end use that would contribute greatly to any emissions reduction effort by making large jumps in energy efficiency. For example, if better batteries for electric automobiles can be developed that are economical and reliable, and if the technology is broadly adopted, it will allow for the replacement of the low-efficiency internal combustion engine with the high-efficiency electric motor. Moreover, electric cars would break the monopoly that petroleum currently has as the source of energy for transportation, thus addressing security concerns involving the geopolitics of oil and allowing transportation fuel to come from carbon-free sources discussed below. Whether better batteries are technically possible remains a question.

**Non-Fossil Energy Systems**

The second category of solutions to the climate–energy challenge involves expansion of non-fossil energy systems, including wind, solar, biomass, geothermal, and nuclear power. Again, there is no silver bullet. Wind is currently the most economical of these energy systems for electricity generation. However, wind requires huge excess capacity because of problems with intermittency, and so it cannot become a source for baseload power unless storage technologies improve. Solar-generated electricity has similar problems with energy storage and is also expensive compared with wind or nuclear power. Nuclear power can be used for baseload power, unlike wind or solar, but issues of safety, storage and handling of nuclear waste, and security concerns about nuclear weapons proliferation will have to be addressed before widespread expansion is likely, at least in the U.S. and western Europe (aside from France). This category is one with great hopes for technological “breakthroughs”—such as fusion, inexpensive solar, and inexpensive fuel cells—that may revolutionize our energy systems. Thus, basic research and development must be a part of any climate mitigation strategy. However, no responsible strategy should rely exclusively on breakthrough technologies as they may not exist for decades, if ever.

Outside of the electric realm, biomass converted to biofuel may play a major role in reducing CO$_2$ emissions in the transportation sector, at least until powerful, inexpensive, and reliable battery technologies or some alternative transportation technologies are developed. For example, Brazil currently obtains most of its transportation fuel from fermentation of sugar cane into ethanol, and similar programs are being implemented around the world. A more efficient technology may be the conversion of biomass into synthetic diesel fuel via the Fischer-Tropsch process, which was used by the Germans in World War II to transform coal into liquid fuel. This process has the advantage of creating a more diverse range of fuel products, including jet fuel for air transport, and of being more efficient through use of all types of biomass, not just sugar (or cellulose for a cellulosic conversion process). Moreover, the Fischer-Tropsch process, which involves gasification of the biomass followed by conversion to liquid fuel via a cobalt or iron catalyst, requires removal of CO$_2$ to avoid poisoning the catalyst, making adaptation easy for the capture and storage of CO$_2$, as discussed below.

**Carbon Sequestration**

The third category of solutions involves CO$_2$ capture from emissions sources and storage in geologic repositories, a process often referred to as carbon sequestration. This is an essential component of any climate mitigation portfolio because of the abundance of inexpensive coal in the largest economies of the world. Even with huge improvements in efficiency and increases in nuclear, solar, wind, and biomass power, the world is likely to depend heavily on coal, especially the five countries who hold 75% of world reserves: U.S., Russia, China, India, and Australia (Table 1). However, as a technological strategy, carbon capture and storage (CCS) need not apply only to coal; any point source of CO$_2$ can be sequestered, including biomass gasification, which could result in negative emissions.

The scientific questions about CCS deal with the reliability of storage of vast quantities of CO$_2$ in underground repositories—and the quantities are indeed vast. Reservoir capacity required over the next century is conservatively estimated at one trillion tonnes CO$_2$ and it may exceed twice this quantity. This amount far exceeds the capacity of old oil and gas fields, which will be among the first targets for sequestration projects because of additional revenues earned from enhanced oil recovery. However, there is more than enough capacity in deep saline aquifers to store centuries of emissions (Anderson and Newell 2004), and also in deep-sea sediments, which may provide leak-proof storage in coastal sites (House et al. 2006). In general, the storage issues do not involve large technological innovations, but rather improved understanding of the behavior of CO$_2$ at high pressure in natural geologic formations that contain fractures and faults. Geologic storage does not have to last forever—only long enough to allow the natural carbon cycle to reduce the atmospheric CO$_2$ to near pre-industrial levels. This means that storage for 2000 years is long enough if deep-ocean mixing is not impeded significantly by stratification. It seems likely that many geological settings will provide adequate storage, but the data to demonstrate this over millennia do not yet exist. A more expansive program aimed at monitoring underground CO$_2$ injections in a wide variety of geologic settings is essential if CCS is to be adopted before the middle of the century (Schrag 2007).

The technological advances in CCS involve improving the efficiency of the capture of CO$_2$ from a coal-fired power plant. Capture can take place either by postcombustion adsorption, or through design of a power plant (either oxy-combustion or gasification) that produces a pure stream of CO$_2$ as an effluent. Either way, the capture of CO$_2$ is expensive, both financially and energetically. It has been suggested that capture and storage combined would use roughly 30% of the energy from the coal combustion in the first place (IPCC 2005) and may raise the cost of generating electricity from coal by 50% (Anderson and Newell 2004), with two thirds of this increase coming from capture. Even though these estimates are uncertain, given that carbon sequestration is not yet practiced at any coal plant, it is clear that technological innovation in the capture of CO$_2$ from a mixed gas stream is important.

Carbon sequestration also includes enhanced biological uptake such as through reforestation or fertilization of marine phytoplankton. These approaches could be considered a separate category as planting trees is quite different from injecting vast quantities of CO$_2$ underground. If pur-
It is very difficult to know which scenario is correct. Because of the potential for catastrophe, it seems prudent to ask what societies might do if the rate of climate change were to accelerate over the next few decades and if the consequences were to be much worse than anticipated. One approach that has long been discussed is the engineering of our climate system by adjusting the incoming solar radiation by means of reflectors in space or in the upper atmosphere (Keith 2000); indeed, there may be some ways to accomplish a reduction in solar radiation at very low cost relative to other strategies of mitigation (Schelling 1996). Recently, such ideas have gained more prominence (Crutzen 2006), not as a substitute for serious emissions reductions, but in the sober realization that efforts to reduce emissions may not be sufficient to avoid dangerous consequences. The power to engineer the climate comes with an awesome responsibility. How could we engineer such a system to be failsafe? Which countries would control it? And what would happen if something went wrong, if we discovered some unforeseen consequences that required shutting the effort down once human societies and natural ecosystems depended on it?

These scientific, political, and ethical questions will be debated over the next few years and decades. However, it is likely that they will not be hypothetical for long; even with the most urgent efforts over the next decade to take action and begin mitigation efforts with vigor, we must accept that the most urgent efforts over the next decade to take action and begin mitigation efforts with vigor, we must accept that the world will warm another 2 or 3°C, that ice sheets will decay more quickly than expected, and that the impacts of a warmer world on humans and on natural ecosystems will be worse than we now predict.

References


Carbon content was calculated assuming 25.4 tonnes carbon per terajoule (Tj) coal; 19.9 tonnes carbon per Tj petroleum; 14.4 tonnes carbon per Tj natural gas (CO2 content 3.6 times as much). Differences between anthracite, bituminous, lignite, and sub-bituminous coal were not included. (Data from BP 2006)

sued aggressively, such strategies might offset CO2 emissions by as much as 7 Gt per year by the end of the century, out of total emissions of more than 80 Gt per year as forecasted in most business-as-usual scenarios. These approaches might be an important piece of a solution, but they will not replace the need for improved energy efficiency, non-fossil energy sources, and carbon sequestration.

Will It Be Enough?

The nature of the climate experiment means that no one truly knows what a safe level of CO2 really is, apart from the impossible goal of the pre-industrial level of 280 ppm. It is possible that nations will implement many of the approaches outlined above over the next few decades, which would stabilize atmospheric CO2 below 600 ppm; it is difficult to imagine that a much lower stabilization level will be realized given the current state of the world energy systems. It is possible that this effort will be enough, that the world will warm another 2 or 3°C, that ice sheets will slowly melt, and that most of the severe consequences will be gradual, allowing adaptation by humans and natural ecosystems. On the other hand, it is also possible that even with concerted effort and cooperation among the large nations of the world, the climate system will respond too quickly for humans to adapt, that the Greenland and West Antarctic ice sheets will decay more quickly than expected, and that the impacts of a warmer world on humans and on natural ecosystems will be worse than we now predict.

Table 1: Carbon content in gigatonnes (Gt) of fossil fuel proven reserves and annual production (2005)

<table>
<thead>
<tr>
<th>COAL</th>
<th>PETROLEUM</th>
<th>NATURAL GAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RESERVES</td>
<td>PRODUCTION</td>
<td>RESERVES</td>
</tr>
<tr>
<td>U.S.</td>
<td>184.0</td>
<td>0.64</td>
</tr>
<tr>
<td>Russia</td>
<td>117.1</td>
<td>0.15</td>
</tr>
<tr>
<td>China</td>
<td>85.4</td>
<td>1.24</td>
</tr>
<tr>
<td>India</td>
<td>69.0</td>
<td>0.22</td>
</tr>
<tr>
<td>Australia</td>
<td>58.6</td>
<td>0.23</td>
</tr>
<tr>
<td>Middle East</td>
<td>0.3</td>
<td>0.00</td>
</tr>
<tr>
<td>Total World</td>
<td>678.2</td>
<td>3.23</td>
</tr>
</tbody>
</table>

Carbon content was calculated assuming 25.4 tonnes carbon per terajoule (Tj) coal; 19.9 tonnes carbon per Tj petroleum; 14.4 tonnes carbon per Tj natural gas (CO2 content 3.6 times as much). Differences between anthracite, bituminous, lignite, and sub-bituminous coal were not included. (Data from BP 2006)


Geological Carbon Dioxide Sequestration

S. Julio Friedmann*

A key means of reducing greenhouse gas emissions from fossil fuels is to separate and concentrate CO₂ from large point sources and inject it underground. The injection process, so-called “geological carbon sequestration”, uses off-the-shelf technology from the hydrocarbon industry and can be deployed at a useful scale. Widespread deployment will require a greater understanding of processes that trap CO₂ underground, improved means of monitoring the injection stream, and a small number of large-scale experiments in settings with the most important representative geology. If successful, geological sequestration could greatly reduce greenhouse gas emissions while we continue to benefit from fossil fuels until true alternatives emerge.

**KEYWORDS:** carbon sequestration, carbon management, carbon storage, carbon dioxide, greenhouse gas abatement

**INTRODUCTION**

In the global energy system, fossil fuels currently account for 85% of all energy supply and more than 98% of transportation fuel. Given the expectations of enormous energy demand growth (a doubling or tripling in 50 years) and the low cost and high availability of fossil fuels, it is widely believed that fossil fuel consumption will continue at a large scale through the next century. However, combustion of these fuels releases enormous volumes of greenhouse gases, chiefly CO₂. Every year, 25 gigatonnes (Gt) of man-made CO₂ enter the atmosphere, nearly all of it from fossil fuel combustion. Concerns about the risks of greenhouse gas emissions and attendant climate change impacts are increasing, and it appears that these risks are substantial. This has prompted renewed focus on reducing emissions through improved efficiency, renewable energy supplies, and nuclear fission. Even if future demand growth was met by carbon-free sources of energy, there would be no reduction in emissions because fossil fuel use will continue, especially in developing nations with rapid economic growth.

In this context, carbon dioxide sequestration has emerged as a key technology pathway to reducing greenhouse gas (GHG) emissions (IPCC 2005). Sequestration is the long-term isolation of carbon dioxide from the atmosphere through physical, chemical, biological, or engineered processes. Geological carbon sequestration (GCS) appears to be among the most promising large-scale approaches to major emission reduction in the next 20–50 years (MIT 2007) for several reasons:

1. The potential storage capacities are enormous. Formal estimates of global storage potential vary substantially but are likely to be between 3000 and 10,000 gigatonnes of CO₂. This can be compared with the annual global anthropogenic flux of 25 gigatons.

2. GCS uses existing technology. Carbon dioxide has been separated from large point sources for nearly 100 years and has been injected underground for over 30 years.

3. GCS is actionable. In the U.S., Canada, and many other industrial countries, large CO₂ sources, like power plants and refineries, lie near prospective storage sites. These plants could be retrofitted today and injection begun.

However, in order to achieve substantial GHG reductions, geological storage needs to be deployed at a large scale. For example, a 1 GtC/yr (3.6 GtCO₂/yr) abatement requires GCS from 600 large pulverized-coal plants (~1000 MW each) or 3600 injection projects at the scale of Statoil’s Sleipner project (Pacala and Socolow 2004), during which one million tonnes of CO₂ have been injected every year for ten years (Arts et al. 2004).

**STORAGE MECHANISMS**

A number of geological reservoirs appear to have the potential to store many hundreds to thousands of gigatonnes of CO₂ (IPCC 2005). The most promising reservoirs are porous and permeable rock bodies, generally at depths of 800 m or greater. Given conventional geotherms, the pressure–temperature constraints would make CO₂ a supercritical phase at these depths (Bachu 2000). In this state, CO₂ acts like a liquid, with a density less than that of brine, a fairly low solubility in water, and a viscosity less than that of oil (Fig. 1). The high densities are critical to successful storage such that a large volume of CO₂ can be injected into a limited pore volume.

Three classes of target reservoirs are capable of sequestering large volumes of CO₂:

- **Saline formations.** These contain brine in their pore volumes, commonly with a salinity greater than 10,000 ppm.

- **Depleted oil and gas fields.** A combination of water and hydrocarbons fills their pore volumes, and in some cases, economic gains can be achieved through enhanced oil or gas recovery. Injection of substantial quantities of both natural and anthropogenic CO₂ already occurs in the U.S.

- **Deep coal seams.** Often called unmineable coal seams, these are composed of organic minerals and contain brines and gases in their pore and fracture volumes.

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Because of their large storage potential and broad distribution, it is likely that most geological sequestration will occur in saline formations. However, initial projects will probably occur in depleted oil and gas fields, accompanying enhanced oil recovery, due to the great abundance and quality of subsurface data and the potential for economic return. Although there remains some economic potential for enhanced coal bed methane recovery, initial economic assessments do not appear promising, and substantial technical hurdles remain in the way of obtaining the desired benefits (IPCC 2005).

For these three reservoir classes, CO₂ storage mechanisms are reasonably well defined and understood. CO₂ sequestration targets will require physical barriers to CO₂ migration towards the surface. These barriers will commonly take the form of impermeable layers (e.g. shales, evaporites) overlying the reservoir, although they may also be dynamic in the form of regional hydrodynamic flow. Physical trapping allows for very high CO₂ pore volumes, in excess of 80%, and acts immediately to limit CO₂ vertical flow. At the pore scale, capillary forces will immobilize a substantial fraction of a CO₂ bubble, commonly measured to be between 5 and 25% of the CO₂-bearing pore volume. The fraction is determined by the interfacial tension angle, the wettability angle of the pore surfaces, and the effective diameter of the pore throat (e.g. Gladnikh and Bryant 2003). This process acts immediately to trap CO₂ as a residual phase in the pores and continues to act during and after plume flow. Once in the pores, over a period of tens to hundreds of years, the CO₂ will dissolve in other pore fluids, including hydrocarbon species (oil and gas) and brines. The CO₂ is fixed indefinitely in the pores, unless other processes intervene. Over longer time scales (hundreds to thousands of years), the dissolved CO₂ may react with minerals in the rock volume, precipitating the CO₂ as new carbonate minerals. In the case of organic mineral frameworks such as coals, the CO₂ will physically adsorb onto the rock surface, sometimes displacing other gases (e.g. methane, nitrogen).

Although substantial work remains to characterize and quantify these mechanisms (see below), they are understood well enough today to develop reliable preliminary estimates of the percentage of CO₂ that can be stored over some period of time. These estimates are based in part on decades of studies in analogous systems, including hydrocarbon systems, natural gas storage operations, hazardous waste injection, and CO₂-enhanced oil recovery. In the case of enhanced oil recovery, CO₂ has been injected underground for over 30 years, with no demonstrated examples of substantial leakage. In addition, numerous CO₂ accumulations occur naturally around the world, including the CO₂ domes of the central Rocky Mountains (Stevens et al. 2001), high-CO₂ gas fields (Brennan et al. 2004), and the carbogaseous (charged with carbon dioxide) provinces of Europe (e.g. Czemichoski-Lauriol et al. 2003). In these regions, large volumes of CO₂ have been stored safely for tens of millions of years.

This information provides the basis for qualitative risk estimation. Specifically, it is very likely that more than 99.9% of injected CO₂ will be retained for 100 years, and likely more than 99% for 1000 years (IPCC 2005). In other words, the crust is generally well configured to store CO₂.

**POTENTIAL RISKS**

Since supercritical CO₂ is buoyant at the relevant crustal pressures and temperatures, it will seek the Earth’s surface in most settings. A large CO₂ accumulation would exert forces on the reservoir, cap rock, faults, and wells. CO₂ must also be injected at pressures above reservoir pressures, creating a pressure transient during and after injection. In addition, dissolved CO₂ forms carbonic acid, which can alter rock and well-bore properties and composition. Therefore, despite confidence in the storage mechanisms discussed above, the possibility of leakage from storage sites remains.

These risks were recently highlighted by geochemical analysis and laboratory experiments carried out at a pilot injection in South Liberty, Texas (Hovorka et al. 2006). Kharaka et al. (2006) observed rapid dissolution of some minerals, chiefly carbonate, oxide, and hydroxide minerals. Although this population represented a small fraction of the rock volume (~2%), the rapid kinetics of dissolution liberated iron, manganese, calcium, and organic carbon molecules into the brine. This raised questions about the possible environmental effects of GCS and about the long-term fate of injected CO₂.

In order to evaluate the possibility of catastrophic leakage, Pruess et al. (2006) attempted to determine the conditions for positive feedbacks that might lead to runaway CO₂ release. Importantly, they found none. Rather, CO₂ interac-
tion with the crust generally produces negative feedbacks; for example, acidic dissolution of carbonate minerals increases pH and reduces reactivity of brines. In some cases, it appears that storage mechanisms are self-reinforcing. The geochemical modeling of Johnson et al. (2004) suggests that CO$_2$ reactions with some minerals (e.g. chlorite) reduce the porosity and permeability of shale, making it a better physical seal. This behavior was observed by Watson et al. (2005) in shales overlying natural CO$_2$ accumulations. These studies suggest that while Kharaka et al. (2006) may have discovered a new element of risk, that element does not appear to represent a major concern to CO$_2$ storage.

The geomechanical response to CO$_2$ injection may still cause concerns. In a parallel set of studies, Johnson et al. (2005) simulated large pressure excursions from CO$_2$ injection. They concluded that under certain conditions, such excursions lead to fracture dilation, with some seepage of CO$_2$ into overlying units. In the case of most cap rocks, which have both fractures and reactive minerals (e.g. chlorite), this creates a competing rates problem between dilation of fracture and precipitation of reactive minerals in fracture voids. In this system, fracture closure or dilation is sensitive to CO$_2$ diffusion distance and reaction rate. In addition, the pressure transient from injection could lead to fault-slip-induced fluid migration (e.g. Wiprut and Zoback 2002). While it is generally possible to predict the conditions under which this might occur (e.g. Chiaramonte et al. 2006), effective storage will require proper system calibration and injection management.

Additional work will reduce the uncertainties associated with long-term sequestration. Nonetheless, it should be noted that today’s knowledge gaps do not cast doubt on the fundamental likelihood that GCS can be deployed both widely and successfully. Rather, they suggest a science program that can quickly constrain uncertainties and point to the aspects of risk that require mitigation or technical development.

**MONITORING AND VERIFICATION**

Once injection begins, a program for monitoring and verification of CO$_2$ distribution is required in order to:

- Understand key features, effects, and processes needed for risk assessment
- Manage the injection process
- Delineate and identify leakage risk and surface escape
- Provide early warnings of failure near the reservoir
- Verify storage for accounting and crediting

For these reasons, monitoring and verification is a chief focus of many research efforts, including programs by the U.S. Department of Energy (US DOE 2006) and the European Union (CO2 ReMoVe), and the International Energy Agency’s Greenhouse R&D Programme.

Early research and demonstration projects will require more involved monitoring systems than future commercial projects because they will be attempting to establish the scientific basis for geological sequestration. Today there are three well-established large-scale injection projects with ambitious scientific programs that include monitoring: Sleipner in the Norwegian North Sea (Arts et al. 2004), Weyburn in Saskatchewan (Wilson and Monea 2004), and In Salah in Algeria (Rüdilford et al. 2005).

These projects are being carried out in substantively different geological settings, and in each project, roughly 1 million tonnes CO$_2$ are injected per year (Fig. 2). At Sleipner, CO$_2$ enters a 100 m thick, very porous and permeable, fairly homogeneous, brine-bearing, deep-water sandstone 800 m below the North Sea’s floor (Arts et al. 2004). At Weyburn, CO$_2$ is injected into a 10 m thick, highly heterogeneous, fractured, oil-bearing carbonate shelf succession ~1300 m below southern Saskatchewan (Wilson and Monea 2004). At In Salah, CO$_2$ enters a 10 m thick, low-porosity and low-permeability, fractured, heterogeneous, brine-bearing fluvial–tidal network ~2100 m below central Algeria. This range in geological setting, pore structure, crustal velocity, and depth provides insight into the utility of various monitoring approaches in the field (MIT 2007).

Perhaps surprisingly, in the context of these and other research efforts, there has been little discussion about what are the most important parameters to measure and in what context (research/pilot versus commercial). Rather, the literature has focused on the current ensemble of tools and their costs. In part due to the success at Sleipner, 4-D seismic (space plus time-lapse) surveys have emerged as the standard for comparison, with 4-D surveys deployed at Weyburn and likely to be deployed at In Salah. This technology excels at delineating the boundaries of a free-phase CO$_2$ plume and can detect low saturation of conjoined free-phase bubbles that might be an indicator of leakage. Results from these 4-D seismic surveys establish the basis for long-term effectiveness of geological sequestration.

However, time-lapse seismic surveys do not measure all the relevant parameters, and the technique has limits in some geological settings. Key parameters for research and validation of CO$_2$ behavior and fate involve both direct detection of CO$_2$ and detection through proxy data sets. Temperature, pressure, pH, resistivity, EM potential, crustal deformation, and changes to stress azimuth and magnitude all provide insight into the distribution, saturation, and mechanical response to CO$_2$ injection (MIT 2007). Interpretation of these data requires greater empirical and experimental control, including petrophysical studies of CO$_2$–rock–brine–hydrocarbon systems.
LARGE-VOLUME EXPERIMENTS

As mentioned previously, achievement of substantial CO$_2$ emissions reductions through GCS will require hundreds to thousands of large-volume injection facilities distributed around the world. Each existing large project and some small projects (e.g. the Frio Brine Pilot; Hovorka et al. 2006) have provided some demonstration of effectiveness, monitoring technologies, and operational economics. Importantly, each existing large project also has revealed an important aspect of the geology that was not previously known or in some cases incorrectly characterized. For example, at Sleipner, the importance of small flow heterogeneities was not anticipated but was clearly seen (Arts et al. 2004). At Weyburn, CO$_2$ migrated in unexpected ways along secondary fractures (Wilson and Monea 2004).

Such features would not have been revealed through a small-scale (<100,000 tonnes CO$_2$/yr) experiment because geological thresholds in the Earth’s crust are sensitive to the magnitude and rate of excursions (e.g. pressure build-up, changes in pH). Unless those thresholds are reached, no effect occurs. For example, an attempt to induce earthquakes in the Rangely field of northwestern Colorado required massive injection of fluids to overcome the fracture yield criteria of the system (Raleigh et al. 1976). Because the Earth’s crust is a complex, heterogeneous, non-linear system, field-based demonstrations are required to understand the likely range of crustal responses, including those that might allow CO$_2$ to escape from reservoirs. In addition, many important effects (e.g. cement or casing corrosion, induced seismicity, mechanical failure of wells and cap rocks) can only be understood in the context of large demonstrations and large experiments. Despite a substantial scientific effort at Weyburn and Sleipner, many parameters that could have been measured to circumscribe the most compelling scientific questions have not yet been collected. These include distribution of CO$_2$ saturation, stress changes, and well-bore leakage detection.

Substantial GHG abatement requires a geographically diverse portfolio of large injections. Importantly, the three largest demonstrations are in geologically distinct settings, which helps to demonstrate that GCS may have broad application. However, key potential sites have not yet been tested at scale (e.g. Cenozoic basins of eastern China, Himalayan foreland, U.S. Gulf Coast). In each active demonstration project to date, current measurement, monitoring, and verification technologies are not formally integrated and may not be sufficient to document either injection volumes or leakage risk and activity within the necessary full range of important geological or surface geographic conditions.

SCIENTIFIC GAPS

The current set of large-scale experiments, studies of natural and man-made analogs, and integrated laboratory and numerical experiments provide confidence that we will soon be able to deploy GCS at scale. That is not to say that the scientific work is complete. There remain questions about the long-term fate of CO$_2$, the cost of operation, and storage effectiveness. While there are many topics of interest, a few of high importance and scientific value are discussed below.

$\text{CO}_2$ Dissolution and Precipitation Kinetics

The rate at which CO$_2$ dissolves in brines of varying composition, temperature, pressure, and mixing degree greatly affects the long-term trapping mechanisms (i.e. the formation of carbonic acid, bicarbonate, and new minerals). These issues in turn affect other important concerns, such as the configuration and infrastructure of storage reservoir engineering (e.g. Keith et al. 2005) or the long-term fate of CO$_2$ (Ennis-King and Paterson 2003). Although there has been some work on the controls of dissolution rate (e.g. interfacial effects; Yang et al. 2005) more could be done.

Similarly, knowledge of CO$_2$-brine-mineral dissolution and precipitation kinetics is limited. Recent years have seen many experimental studies on individual minerals or classes of minerals (e.g. Carroll and Knauss 2005 and references therein). Still, much remains to be learned about rock systems, including true multiphase chemistry, mineral–CO$_2$ equations of state, and minerals that may represent only a small volume of the rock but have rapid dissolution kinetics (e.g. metal oxides or hydroxides).

As a subtopic, most GCS work on mineral reaction kinetics has focused on pure CO$_2$-rock-brine systems. Very little work has been done on gas streams with small concentrations of other gases, in particular SO$_2$, NO$_x$, and H$_2$S. These co-contaminant gases have the potential to dramatically alter the chemical response of a gas–brine–rock system, even if very small amounts of these gases are present (Knauss et al. 2005). Because the capture and separation of trace gases with CO$_2$ may save capital and operating expenses, investigation of reactions in such systems may prove useful in the near future to determine if mixed-gas systems present additional concerns or risks.

Groundwater

The majority of sequestered CO$_2$ will be stored in saline formations at depth. CO$_2$ stored in these formations should have little or no effect on groundwater. However, if CO$_2$ were to reach the surface along some fast pathway, then CO$_2$ might enter fresh groundwater systems. It is highly unlikely that the rate or volume of CO$_2$ would present a problem. However, the results of Kharaka et al. (2006) have raised the possibility that rapid local reactions could release unwanted elements and compounds into groundwater. Again, for most reservoirs this may have no effect. However, some reservoirs have elevated levels of natural arsenic. In such a system, even a small release of CO$_2$ might result in an increase in local arsenic concentrations that could bring a municipal water supply out of compliance with U.S. Environmental Protection Agency regulations. Similarly, widespread deployment of GCS could potentially displace enough water to create saline groundwater intrusions in contiguous formations.

Wells

Wells almost certainly present the greatest risk to leakage because they are drilled to bring large volumes of fluid quickly to the Earth’s surface. In addition, they remove the aspects of the rock volume that prevent buoyant migration. Well casings and cements are susceptible to corrosion from carbonic acid. When wells are adequately plugged and completed, they are likely to trap CO$_2$ at depth effectively. However, large numbers of orphaned or abandoned wells may not be adequately plugged, completed, or cemented (Ide et al. 2006), and such wells represent potential leak points for CO$_2$.

One analog site is particularly well suited for study. Crystal Geyser, Utah (Shipton et al. 2005), is a well that penetrated a natural CO$_2$ accumulation in 1936, was poorly completed, and has erupted CO$_2$ ever since (Fig. 3). Eruptions are episodic and vary in size. Measurements of individual and sequential eruptions suggest that large events bring tens of tonnes of CO$_2$ to the surface, with an average daily flux of 40–50 tonnes (Gouveia et al. 2005). During the eruptions, atmospheric concentrations of CO$_2$ were not recorded at or above dangerous levels. While this style of eruption does not appear to present a substantial risk (Bogen et al. 2006), more study is needed to understand how representative of well leakage this site may be.
Little is known about the probability of escape from a given well, the likelihood of such a well existing within a potential site, or the risk such a well presents in terms of potential leakage volume or consequence. Current approaches involve statistical characterization of many wells and semi-quantitative analysis (Celia et al. 2006), or modeling and simulation of features and processes in well-bore environments (Gerard et al. 2006). Work in understanding the key features of wells (e.g. fracture geometry and character), the chemical response of well components to CO$_2$ systems, and the evolution of natural and engineered interfaces could provide both better estimates of well-bore integrity risk and potential mitigation and remediation strategies (IPCC 2005).

**Mitigation, Mineralization, and Alternative Schema**

In general, it is believed that the risks posed by GCS are extremely small and readily managed (IPCC 2005). However, there is room for scientific and engineering to investigate related technologies and engineering schemes to further reduce or altogether eliminate such risks.

The primary risk of CO$_2$ leakage stems from the forces buoyant CO$_2$ exerts on the storage environment. However, once CO$_2$ dissolves into the surrounding fluid, this fluid becomes more dense than one without CO$_2$, greatly reducing or eliminating such risks. Keith et al. (2005) proposed a method to rapidly mix brine and CO$_2$ by inducing reservoir circulation. In one simple configuration, the majority of CO$_2$ would dissolve into the formation brine within 50 years. It is likely that other drilling configurations could work even more rapidly, and the injected brine could be spiked with metal oxides to increase the rate of mineral precipitation in the reservoir, further reducing leakage risk.

Finally, if the risks become truly problematic, one could directly react CO$_2$ with metal oxide–bearing minerals (IPCC 2005). In most cases, such reactions are exothermic, but the kinetics are very slow. Engineering approaches to this problem (e.g. Lackner 2002) remain expensive, with costs of $50–100/tonne CO$_2$ (substantially higher than conventional storage costs). However, improved understanding of mineral reaction kinetics, interfacial reactions, and novel materials could provide insight into ways to reduce these costs. Ultimately, if metal or biological processes could catalyze direct mineralization reactions, they might provide an alternative to conventional storage.

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**CONCLUSION**

Geological carbon dioxide storage appears to be a safe, effective means of achieving a substantial reduction of atmospheric carbon dioxide emissions while maintaining the benefits of fossil fuel use. The present knowledge base suggests that billions of tonnes can be stored safely each year through injection into conventional reservoirs such as saline formations or depleted oil and gas fields. However, accelerated deployment of this technology could greatly benefit from additional basic geoscience research. Many GCS uncertainties involve current understanding of structural geology, stratigraphic heterogeneity, and CO$_2$–brine mineral kinetics.

In this context, the greatest priority in managing the CO$_2$ from continued fossil fuel use should be the initiation of commercial-scale experiments that include a substantial science program. Questions that regulators, financiers, operators, and public stakeholders might have about performance, safety, effectiveness, and risk require investigations at commercial scale. Thus, the geoscience community has a unique opportunity to be part of the solution by presenting to the world a major technology pathway to reducing the impacts of global climate change.

**FIGURE 3** An eruption from Crystal Geyser, Utah. Eruptions commonly reach 5–10 m height. Note: the individuals at the site do not appear at risk. Courtesy of Z. Shipton. Inset: Children playing at Crystal Geyser. Note the original casing sticking out of the active well.


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Nuclear Energy and Uranium Resources

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The amount of electricity generated by nuclear power plants may increase in the next few decades, as this form of energy is one of the few that are proven, reliable, and relatively carbon dioxide free. A question often asked about nuclear power is how long its main resource, uranium, will last. In the face of a large expansion of nuclear power to deal with climate change considerations, we revisit the question of the adequacy of the uranium resource and show that there is adequate supply for at least the next century and probably more.

KEYWORDS: nuclear energy, uranium resources, uranium deposits

INTRODUCTION

Nuclear energy may be on the verge of a renaissance largely as a result of the need for carbon-free energy sources. Pressures imposed by predictions of impending catastrophic climate change and the need for more energy may result in a great increase in the amount of electricity produced by nuclear power in the next 100 years. If reserves of fossil fuels start diminishing in the early to middle part of the 21st century, as some have predicted, then there will be an even more urgent need to replace these resources. As a viable method of generating electricity, nuclear power therefore requires a closer look.

Nuclear energy is a well-established source of electricity (Ewing 2006). According to the International Energy Agency, 17% of the world’s electricity was generated by nuclear energy in 2002. In 2005 global nuclear electric generating capacity was 369 gigawatts electric (GWe), from 440 reactors (OECD Nuclear Energy Agency 2005) distributed among 30 countries. In 2003 these reactors generated 2523 TWh (Terawatt-hour) of electricity (Energy Information Administration 2005). Most of the world’s nuclear power plants are in the North (Fig. 1), including the United States (103 operating plants), France (59), and Japan (54).

A number of scenarios have been proposed to examine the potential impacts of increased nuclear energy use on carbon emissions. For example, Pacala and Socolow (2004) have identified substituting nuclear electricity for coal as one of seven strategies (which they term “wedges”), each of which would reduce carbon dioxide emissions by 92 Gt CO₂ over 50 years so as to stabilize these emissions at their current level of 25.6 Gt CO₂/yr. (Wedges include carbon dioxide capture and storage and energy efficiency and conservation, among other options.) Implementing the nuclear wedge would require the addition of 700 GWe of new nuclear capacity over the 50-year period.

A recent MIT study on the future of nuclear energy (Ansolabehere et al. 2003) suggested 1000–1500 MWe would be needed by 2050 to make a significant reduction in carbon dioxide emissions. The MIT study estimated that 1000 MWe of nuclear power would displace 15–25% of the predicted growth of carbon dioxide emissions.

CONSTRANTS ON FUTURE NUCLEAR ENERGY USE

Cost

First and foremost among potential roadblocks to nuclear power expansion is economics. Though nuclear power offers relatively low operational, maintenance, and fuel costs ($0.018/kWh versus $0.023–0.05/kWh for fossil fuels in 2001; Energy Information Administration 2006b), its initial capital costs are very high. Average estimates are about $2000/kWe to build a new nuclear plant, whereas a comparable combined cycle gas turbine plant can be built for just $500/kWe and in far fewer years (Ansolabehere et al. 2003). In addition to the simple math of costs, the risk of investing in nuclear power involves obtaining a license, dealing with political opposition to plant siting, and concerns about water sources and discharges. Nonetheless, in the presence of high carbon taxes, nuclear power could become competitive with other sources of electricity (Ansolabehere et al. 2003).

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Another stumbling block to the expansion of nuclear power is the problem of nuclear waste, which so far remains unresolved. No country has yet found a permanent solution to the disposal of high-level nuclear waste, though most agree that the solution will involve a geologic repository. Finland and the United States have selected repository sites and are completing work on them, though no waste will be stored until at least 2018. The problems faced by these sites are both political and technical, though potentially they can be overcome if repositories are sited properly.

How big a problem is nuclear waste? About 25–30 tonnes of spent fuel are created per year per GWe (World Nuclear Association 2006). Thus, each year about 12,000 tonnes of spent fuel are produced based on the world’s current nuclear energy capacity (World Nuclear Association 2006). This spent fuel is now stored at reactor sites or in centralized facilities, awaiting final disposal. A major expansion in nuclear power to 1500 GWe would create between 30,000 and 45,000 tonnes of spent fuel per year. To put this number in perspective, the nuclear waste site designated by the U.S. government, Yucca Mountain, Nevada, is set to hold 70,000 tonnes of waste. Globally, with an increase in nuclear energy generation to 1500 GWe/yr, the equivalent of a repository the size of the Yucca Mountain site would have to be opened every two years for an open fuel cycle.

Nuclear Waste

Though other energy sources may have their own problems with cost and waste, a problem unique to nuclear power concerns the proliferation of nuclear weapons as a result of expansion of energy production. Most nuclear plants today are light water reactors that operate on the once-through fuel cycle, where uranium enriched to levels on the order of 3–5% $^{235}$U is used as fresh fuel and the plutonium generated by irradiating $^{238}$U in a reactor is not separated from the unused uranium or the intensely radioactive fission products. Neither this low-enriched fresh fuel nor the unseparated plutonium can be used directly in nuclear weapons, but the need for enriched uranium provides a rationale for the construction of enrichment plants that can be converted, if desired, to produce weapons-grade uranium ($^{235}$U ≥ 90%). The degree of difficulty for enrichment depends on the nature of the enrichment process, but it is relatively straightforward in the centrifuge process now commonly used. The centrifuge issue is at the heart of the current concern about Iran’s insistence on building its own enrichment plant.

As uranium presents a security risk on the “front end” of the nuclear fuel cycle, plutonium poses a risk on the “back end.” Over the lifetime of fuel in a reactor (about 18 months for light water reactors), about 1% of the fuel by weight is transmuted to plutonium. For the amounts of spent fuel discussed above, the quantity of plutonium in spent fuel becomes significant, considering that it takes about 8 kg of plutonium (or considerably less for a sophisticated weapons designer) to make a nuclear weapon. Although this plutonium is not extracted from spent fuel in the once-through cycle, it can be extracted via a process called “reprocessing” using a “closed” fuel cycle. A number of countries use this process to reuse plutonium in mixed oxide reactor fuel. It might be possible for a nation to conceal the construction and operation of a clandestine reprocessing plant until a significant amount of plutonium has been produced.

An even greater proliferation risk is associated with closed fuel cycles, in which plutonium is extracted from spent fuel in a reprocessing plant and reused as reactor fuel. The risk stems from the fact that significant amounts of plutonium could be covertly diverted from reprocessing plants without being detected by standard International Atomic Energy Agency (IAEA) safeguard procedures (or overtly diverted following a takeover of the plant by the host state) and incorporated quickly into weapons. Such reprocessing plants now...
operate in France, the UK, Russia, India, and Japan. While all these states, with the exception of Japan, already possess nuclear weapons, the concern is that such plants will proliferate to non-weapons states if closed fuel cycles come to be viewed as necessary for the expansion of nuclear power.

Expansion of nuclear power to 1500 GWe on the once-through cycle would require a concomitant increase in the need for uranium enrichment capacity. As previously noted, even if such plants are justified because they produce low-enriched uranium for reactor fuel, they could be converted to the production of weapons-grade uranium, and the weapons potential of even a small plant is considerable. For example, a plant that could produce the low-enriched uranium required annually to supply a single large light water reactor could be converted to produce enough weapons-grade uranium for about 30 bombs per year.

Since an expansion of nuclear power on this scale would be distributed among many countries, a consensus has developed in the nonproliferation community that unrestricted national deployment of enrichment plants would pose a serious proliferation risk even if such plants were safeguarded by the IAEA. One suggested solution is to offer states that are willing to forgo indigenous enrichment plants supplies of enriched uranium for their reactors from states that already have commercial enrichment facilities, with the possible participation of the IAEA to provide additional assurance of a reliable fuel supply. However, the political acceptability of the division of the world into “fuel cycle” states and “reactor-only” states, on top of its current division into weapons states and non-weapons states sanctioned by the Nuclear Nonproliferation Treaty, is doubtful. A less-discriminatory approach would be to operate all enrichment plants on a multinational basis (International Atomic Energy Agency 2005a). As a complement to new institutional approaches to minimizing proliferation risk, such as multilateral ownership and operation of enrichment plants, fuel cycles that have a higher degree of inherent proliferation resistance—including the denatured thorium cycle—should also be investigated (see box 1).

Public Acceptance and Safety

For nuclear power to succeed, it must also overcome the stigma resulting from the Three Mile Island and Chernobyl accidents and be perceived as a safe source of electricity. For instance, in a poll of the public in 18 countries, over half (62%) supported the use of existing plants, but 59% did not favor building new ones (International Atomic Energy Agency 2005b). In the U.S., one of the countries that most favor nuclear power, only 40% approved of building more nuclear power plants and 40% disapproved (International Atomic Energy Agency 2005b). Though memories of those accidents are fading, the perception of hazards posed by radiation has not. Indeed, these concerns have been exacerbated since the September 11, 2001 attacks by the realization that terrorist attacks could trigger major releases of radioactivity from reactors and other nuclear facilities.

Some of this negative attitude may abate with the construction of newer, safer nuclear reactors. Some new designs—in particular, the High Temperature Gas Reactor—are termed “inherently safe” by the nuclear industry due to the fact that the radioactive afterheat from the build-up of fission products does not cause the fuel to melt as it could in a shut-down light water reactor. However, if water or air contacts the fuel (every effort is made to avoid this), there could be a graphite fire, potentially releasing radiation.

Security and Terrorism

More hazardous than a reactor meltdown would be the results of a successful attack on a densely packed spent fuel cooling pool at a reactor. After nuclear fuel is used in a reactor, it is emplaced in a deep (30–40 ft) pool of water to cool and to allow radioactivity to decay. In the United States, many of these pools are nearly full and are arranged in a densely packed array to maximize storage space. If a terrorist attack resulted in a loss of water in the pool, release of massive amounts of radiation could occur, with worse land contamination than that produced by the Chernobyl accident (Alvarez et al. 2003). Fairly straightforward measures can be used to avert such disaster, including keeping pools at low density by transferring older spent fuel to dry cask storage on site (Alvarez et al. 2003), but these measures have not been implemented at reactor sites in the United States.

Uranium Resources

Both proponents and opponents of nuclear power identify the supply of uranium as a constraint on nuclear power growth. Concerns about the size of the uranium resource first motivated the nuclear industry in the 1960s to envision the use of fast breeder reactors, which would actually create more fuel than they use. Because of economics, technical factors, and most importantly, the discovery of large uranium deposits, fast breeder reactors never caught on. The uranium resource issue has received little attention over the past few decades and is therefore perhaps the least understood potential constraint on nuclear power. In the next section, we examine this issue more closely.

Availability of Uranium Resources

Nuclear energy may provide a secure source of electricity, but it can do so only if its fuel, uranium, is available in good supply over a long period of time. The question of the cost of uranium and its impact on the cost of nuclear electricity is particularly important. Is there enough uranium to support an economically viable large-scale expansion in...
The Use of Thorium as a Nuclear Fuel

Thorium-based nuclear fuel cycles have been extensively studied over the last 40 years, and considerable experience has been gained in using thorium fuel in power reactors around the world. Although no thorium-fueled power reactors operate today, there has been a recent revival of interest in such reactors because of their higher degree of resistance to weapons proliferation, smaller production of long-lived actinides in the spent fuel, and decreased demand for uranium resources compared with conventional light water reactors.

Thorium is approximately four times as plentiful in the Earth’s crust as uranium, and there are substantial deposits in several countries, notably Australia and India (USGS 2007). The major difference with thorium is that while natural uranium consists of a fissile isotope $^{235}\text{U}$ and a fertile isotope $^{238}\text{U}$, with relative abundances of $-0.7\%$ and $99.3\%$ respectively, thorium consists almost entirely of the fertile isotope $^{232}\text{Th}$ without any fissile component. However, absorption of a neutron in $^{232}\text{Th}$ produces the fissile uranium isotope $^{233}\text{U}$ just as neutron absorption in $^{238}\text{U}$ produces the fissile plutonium isotope $^{239}\text{Pu}$. Thus, thorium can be partially or wholly substituted for natural uranium in nuclear reactors. In fact, $^{233}\text{U}$ is superior to both $^{235}\text{U}$ and $^{239}\text{Pu}$ as a nuclear fuel in thermal reactors such as the common light water reactor because it produces the most neutrons per neutron absorption at thermal energies (slow neutrons).

The neutron behavior of $^{233}\text{U}$ implies that if thorium is wholly substituted for natural uranium in reactors, with minimal losses, it may be possible to “breed” on the thorium cycle and produce as much (or more) $^{233}\text{U}$ by neutron absorption in thorium as is consumed in reactor operation. Since $^{233}\text{U}$ doesn’t occur in nature, startup of such a reactor requires enriched uranium (typically 20% $^{235}\text{U}$). However, after startup no further enriched uranium is required.

In some fuel cycles, thorium is only partially substituted for natural uranium. The requirement for mined uranium for both startup and subsequent operation is significantly smaller than in thermal reactors such as the light water reactor, fueled solely with low-enriched uranium, typically 4–5% $^{235}\text{U}$. Moreover, much less thorium is required, typically by a factor of 10. The main advantage of such mixed or “denatured” fuel cycles compared to pure thorium cycles is that the amount of $^{233}\text{U}$ in the natural uranium is enough to reduce the fraction of breed $^{233}\text{U}$ in the $(^{233}\text{U} + ^{238}\text{U})$ mixture to less than 20%. Thus, isotopic enrichment would be required to obtain uranium-grade $^{233}\text{U}$ (uranium with a $^{233}\text{U}$ content ≥90% from uranium in the spent fuel). This process would be much more difficult than chemically separating $^{233}\text{U}$ from spent fuel in the pure thorium cycle or plutonium from spent fuel in the standard uranium fuel cycle. Moreover, less plutonium is produced in the mixed thorium cycle because of the partial replacement of $^{238}\text{U}$ by thorium, and the relative amount of $^{239}\text{Pu}$ in the plutonium isotopic mix is smaller, which makes bomb making more difficult. As a result, the mixed thorium cycle would have a greater degree of “weapons proliferation resistance” than the standard uranium cycle.

Besides a greater degree of weapons proliferation resistance, the use of thorium in nuclear reactors would lead to a substantial reduction in the production of the long-lived isotopes of elements such as neptunium, americium, and curium, as well as plutonium, thus reducing the radiotoxicity of the spent fuel. However, it seems unlikely that these benefits and the potential for “stretching” uranium resources will lead to the adoption of the mixed thorium cycle in existing light water reactors or other thermal reactors as long as abundant uranium is available. The real potential of the thorium cycle is if it can be used to achieve “break-even” breeding that would produce enough $^{233}\text{U}$ to refuel the reactor but no excess, while operating with denatured fuel. This would make the thorium cycle a viable alternative to the fast breeder reactors when and if uranium becomes scarce.

nuclear power over the next two hundred years? To answer this question, we need to estimate the demand for uranium and the potential supply over that time period.

Estimating demand far into the future entails large uncertainties, so we will focus our discussion on the next twenty-five to fifty years and make simpler predictions further out than that. In the short term, the next 20 years or so, uranium demand will be based on the capacity of the existing nuclear installations as well as on the reactor capacity factor (the percentage of electricity actually produced, compared to the generating capacity of the plant), the burnup of used nuclear fuel, and the length of time fuel is in a reactor (OECD Nuclear Energy Agency 2004). In the longer term, demand will depend on how many new reactors are built and on the introduction of new reactor designs.

Estimating the supply of uranium for the next few hundred years should prove a little easier to do. Uranium can be obtained from two sources: geologic deposits of uranium and secondary supplies. The latter includes stockpiles in the nuclear industry—highly enriched uranium from the nuclear weapons complexes of Russia and the U.S. that has been blended with depleted uranium to make low-enriched uranium suitable for use as reactor fuel—and mill tailings from uranium enrichment (Preston and Baruya 2006).

How Much Uranium is Needed?

In 2004, mining produced 40,263 tonnes of uranium, while existing reactors required 67,320 tonnes (OECD Nuclear Energy Agency 2005). The price of uranium oxide ($\text{U}_3\text{O}_8$) has risen steadily since 2001, when the weighted average price was about $22.33/\text{kg}$ (Energy Information Administration 2006c). The cost of uranium was $27.74/\text{kg}$ in 2004 and $31.59/\text{kg}$ in 2005.

Predictions of future, near-term demand are based on plans for reactor construction. In 2005, 27 reactors were under construction, almost exclusively in Asia and eastern Europe. India has 9 reactors under construction, while Russia has 4; other countries building reactors include Argentina, China, Finland, Iran, Japan, Korea, Romania, and Ukraine (OECD Nuclear Energy Agency 2005). Projections beyond the next few years are given in Table 1, which compares estimates from two different sources. Both sources predict an increase in nuclear energy generating capacity over the next 25 years. The associated increase in uranium demand represents a potential increase of 37% over today’s demand (see Table 2).

A number of factors affect longer-term predictions of uranium demand. These include the number of operating reactors and the types of reactors. The number of future reactors will in part be affected by the demand for, and price of, electricity, which in turn will be affected by constraints imposed by climate change mitigation measures, such as carbon taxes. If these come to pass, nuclear energy could prove more economically competitive than it is now and it could expand substantially. Developments such as the creation of a hydrogen economy for transportation could affect the need for more nuclear power, especially if the nuclear option becomes an economically competitive way to produce hydrogen. If this were the case, there could be a large increase in nuclear power. For example, the production of enough hydrogen for current U.S. transportation needs alone would require 7100 TWh of electricity, which equates to 145,000 tonnes of uranium per year (OECD Nuclear Energy Agency 2005).

The type of reactors built in the future will also impact uranium demand. If there is a move to more reprocessing of spent nuclear fuel, the use of plutonium separated from it in mixed oxide fuel (MOX fuel) will not likely affect uranium
demand. MOX fuel can be used in light water reactor designs, the dominant type of reactor in the world. Use of uranium recovered from reprocessing for reactor fuel (France has used it in two of its reactors) may decrease demand somewhat. If fast reactors replaced existing thermal reactors [the light water designs use thermal (slow) neutrons], uranium supplies could be extended by a factor of 30 (OECD Nuclear Energy Agency 2005).

A “simplistic,” illustrative estimation of uranium demand until 2100 starts with the OECD estimates given in Table 2 and predicts 100,000 tonnes in 2030. Thereafter, adding 1000 tonnes/yr results in 170,000 tonnes used in 2100, for a total of 11.6 million tonnes used between 2005 and 2100. A recent MIT study (Ansolabehere et al. 2003) provided an estimate of the amount of uranium required for a scenario in which the world installed 1500 GWe capacity by 2051 and employed a once-through fuel cycle. In this case, 9.45 million tonnes of uranium would be used during the first 50 years of the 21st century. If capacity stayed constant at 1500 GWe through the rest of the 21st century, by 2100, nuclear power would consume an additional 15 million tonnes uranium, for a total of 24.5 million tonnes for the whole century, a little more than is currently estimated to exist (see Table 3). Given the cost, waste, and proliferation implications of the 1500 GWe scenario, it is less likely to occur than the “simplistic” one discussed earlier.

How Much Uranium is There?

Uranium is present in small concentrations in much of the Earth’s crust and in seawater. It is present in relatively high concentrations in a number of locations around the world. The OECD Nuclear Energy Agency, in collaboration with the International Atomic Energy Agency, publishes a biennial report on uranium resources, colloquially known as the “Red Book,” in which uranium resources are classified as Identified Resources and Undiscovered Resources (OECD Nuclear Energy Agency 2005). Identified Resources are those from which uranium is currently produced or has been produced in the past. They include known uranium deposits whose size and ore grade are known with a high degree of assurance, such that the volume mineable in given cost ranges is well known (Reasonably Assured Resources). Identified Resources also include uranium deposits inferred to exist on the basis of strong geological evidence (Inferred Resources; OECD Nuclear Energy Agency 2005).

Less well known are Undiscovered Resources, which include those based on indirect geologic data from known deposits (Prognosticated Resources) and those based on geologically likely factors about which little is known (Speculative Resources); therefore, the size of these deposits is not well constrained (OECD Nuclear Energy Agency 2005). There are also other unconventional resources, such as phosphate deposits, which will be discussed later in this article.

Table 3 lists the current Red Book estimates of uranium resources around the world. Identified Resources comprise more than 11,293,000 tonnes of uranium. Another 11 million-plus tonnes of Undiscovered Resources are predicted to exist, bringing the current estimate of the resource base to more than 23 million tonnes. This is about twice the amount required under the simplistic scenario of 11.6 million tonnes uranium for our needs up to 2100. Certainly, there is plenty of uranium to see us out this century and likely enough for another century. Unconventional resources not counted by the Red Book may add significantly to these figures. To understand unconventional resources better, we need to consider the geologic setting of uranium.

In assessing the availability of uranium, it is important to keep in mind that, as is the case with other ores, there is no economic incentive for mining companies to prove out resources or convert them to reserves many years before they can be sold. Thus, predictions of the future availability of uranium based on current cost, price, and geological data, as collected in the Red Book, for example, are likely to be extremely conservative. In particular, given the limited geographical coverage of uranium exploration worldwide, there is considerable potential for discovery of new resources of economic interest.

Uranium Geology and Geochemistry

Uranium as an element is more abundant than tin, but less common than lead, zinc, copper, and nickel. Thorium is about four times as abundant as uranium in the Earth’s crust (see Box 1). Uranium occurs in two oxidation states, $^{4+}$ (uranous ion) and $^{6+}$ (uranil ion). The uranous ion is stable.

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**Table 1** Predictions of world nuclear generating capacity, in GWe

<table>
<thead>
<tr>
<th>Source</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIAa</td>
<td>380</td>
<td>403</td>
<td>422</td>
<td>433</td>
<td>438</td>
<td></td>
</tr>
<tr>
<td>OECDb</td>
<td>373</td>
<td>390</td>
<td>427</td>
<td>455</td>
<td>491</td>
<td>N/A</td>
</tr>
</tbody>
</table>

a Energy Information Administration (2006d).
b OECD (2005) Note that these projections were derived from an average of high and low estimates. N/A, not available

**Table 2** Predictions of uranium demand, in tonnes uranium

<table>
<thead>
<tr>
<th>Source</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>OECDa</td>
<td>66,800</td>
<td>72,000</td>
<td>79,000</td>
<td>80,900</td>
<td>91,500</td>
</tr>
</tbody>
</table>

a OECD (2005) Note that these projections were derived from an average of high and low estimates.

**Table 3** Current estimates of uranium resources by category

<table>
<thead>
<tr>
<th>Resource Category (in US$/kg U)</th>
<th>Uranium (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Identified Resources</strong></td>
<td></td>
</tr>
<tr>
<td>Reasonably Assured Resources</td>
<td></td>
</tr>
<tr>
<td>&lt; $130</td>
<td>3,297,000</td>
</tr>
<tr>
<td>&lt;$80</td>
<td>2,643,000</td>
</tr>
<tr>
<td>&lt;$40</td>
<td>1,947,000</td>
</tr>
<tr>
<td><strong>Inferred Resources</strong></td>
<td></td>
</tr>
<tr>
<td>&lt;$130</td>
<td>1,446,000</td>
</tr>
<tr>
<td>&lt;$80</td>
<td>1,161,000</td>
</tr>
<tr>
<td>&lt;$40</td>
<td>&gt; 799,000</td>
</tr>
<tr>
<td><strong>Total Identified Resources</strong></td>
<td></td>
</tr>
<tr>
<td>&gt; 11,293,000</td>
<td></td>
</tr>
<tr>
<td><strong>Undiscovered Resources</strong></td>
<td></td>
</tr>
<tr>
<td>Prognosticated Resources</td>
<td></td>
</tr>
<tr>
<td>&lt;$130</td>
<td>2,518,800</td>
</tr>
<tr>
<td>&lt;$80</td>
<td>1,700,100</td>
</tr>
<tr>
<td><strong>Speculative Resources</strong></td>
<td></td>
</tr>
<tr>
<td>&lt;$130</td>
<td>4,557,300</td>
</tr>
<tr>
<td><strong>Cost unassigned</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2,978,600</td>
</tr>
<tr>
<td><strong>Total Undiscovered Resources</strong></td>
<td></td>
</tr>
<tr>
<td>11,754,800</td>
<td></td>
</tr>
<tr>
<td><strong>Total, all resources</strong></td>
<td></td>
</tr>
<tr>
<td>&gt; 23,047,800</td>
<td></td>
</tr>
</tbody>
</table>

Source: OECD (2005)
only in reducing or anoxic environments, while the uranyl ion is stable under oxidizing conditions. As a result, minerals containing U\(^{4+}\) occur in igneous, sedimentary, or metamorphic rocks, where crystallization occurred under reducing conditions. U\(^{4+}\) forms ore minerals such as uraninite and pitchblende, while U\(^{6+}\) forms (UO\(_2\))\(^{2+}\) complexes. Uranium complexes are not stable at high temperatures (Dahlkamp 1993). Uranium is found in a wide variety of geologic settings, reflecting its two oxidation states (Kesler 1994) and its long history of evolution and reworking in crustal rocks. Because of uranium’s large ionic radius and its valence, it tends to be incorporated into late-forming silicate minerals. Thus, uranium is preferentially concentrated in the continental portion of the Earth’s crust, leaving oceanic crust relatively depleted in uranium. Uranium is incorporated into subduction zone magmas, which then rise through the overlying crust; some of this uranium is partitioned into hydrothermal fluids.

In Archean times, from 3800 to 2500 million years ago, the Earth’s crust was much more mobile than it is today, due to the Earth’s higher radiogenic heat content. Uranium ores first appeared in middle to late Archean times. Between 3200 and 2600 million years ago, an increase in the growth of continental crust was accompanied by the deposition of the first uraniferous quartz-pebble conglomerates (Plant et al. 1999). About 2500 million years ago, tectonic activity, perhaps related to the assembly of a supercontinent, resulted in the emplacement of large amounts of uraniferous granite (with concentrations up to 600 ppm U; Crowley et al. 2005). Between 2000 and 1600 million years ago, further continental growth resulted in emplacement of more high-uranium granites. Tectonic activity continued throughout the Proterozoic and Phanerozoic, but the original sources of a number of younger uranium deposits were Archean or early to middle Proterozoic preconcentrations of uranium.

**Uranium Deposits**

Most uranium deposits exist because of the interaction of uraniferous fluids with the surrounding rocks; deposits are therefore classified according to the type of host rock. Table 4 lists key deposits in order of economic importance. The oldest known deposits occur in quartz-pebble conglomerates shed from Archean-age mountains located in what is now southern Africa and Canada. Because these rocks may also contain significant concentrations of gold, uranium is often a by-product of gold mining.

<table>
<thead>
<tr>
<th>Red Book rating, economic significance (2005)</th>
<th>Red Book Classification</th>
<th>Geologic Association</th>
<th>Detailed Geologic Description</th>
<th>Examples of Deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unconformity deposits</td>
<td>Igneous/metamorphic to sedimentary</td>
<td>Continental – post-orogenic basins</td>
<td>Rabbit Lake, Cigar Lake, Athabasca basin, Saskatchewan, Canada; McArthur basin, Northern Territory, Australia</td>
</tr>
<tr>
<td>2</td>
<td>Sandstone</td>
<td>Sedimentary</td>
<td>Continental – post-orogenic basins</td>
<td>Colorado Plateau, U.S.; Moynkum, Inkay, Kazakhstan; Westmoreland, Australia; Akouta, Niger; Hamr-Straz, Czech Republic</td>
</tr>
<tr>
<td>3</td>
<td>Hematite breccia complexes</td>
<td>Igneous</td>
<td>Acid igneous rocks</td>
<td>Olympic Dam, Australia</td>
</tr>
<tr>
<td>4</td>
<td>Quartz-pebble conglomerates</td>
<td>Sedimentary</td>
<td>Continental – post-orogenic basins</td>
<td>Witwatersrand basin, South Africa; Blind River/Elliot Lake, Canada</td>
</tr>
<tr>
<td>5</td>
<td>Vein deposits</td>
<td>Sedimentary</td>
<td>Continental – post-orogenic basins</td>
<td>Schwitzwalder, U.S.; Dhaa district, Congo</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Igneous</td>
<td>Associated with hydrothermal fluids</td>
<td>Limousin, Massif Central, France; Iberian Meseta, Spain, Portugal; Pribram, Czech Republic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Metamorphic</td>
<td>Associated with hydrothermal fluids</td>
<td>Schwitzwalder, U.S.; Dhaa district, Congo</td>
</tr>
<tr>
<td>6</td>
<td>Intrusive deposits</td>
<td>Igneous</td>
<td>Alkaline complexes</td>
<td>Rössing, Namibia; Ilmaaussa, Greenland; Palabora, South Africa</td>
</tr>
<tr>
<td>7</td>
<td>Volcanic and caldera-related deposits</td>
<td>Igneous</td>
<td>Felsic volcanics</td>
<td>Streltsovsk caldera, Russia; Dornot deposit, Mongolia; Nopal deposit, Mexico</td>
</tr>
<tr>
<td>8</td>
<td>Metasomatite</td>
<td>Igneous</td>
<td></td>
<td>Pervomayskoye, Ukraine; Lagoa Real, Brazil; Valhalla, Australia</td>
</tr>
<tr>
<td>9</td>
<td>Surficial deposits</td>
<td>Sedimentary</td>
<td>Yeelirrie, Australia; Langer Heinrich, Namibia</td>
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</tr>
<tr>
<td>10</td>
<td>Collapse breccia pipe</td>
<td>Sedimentary</td>
<td>Continental</td>
<td>Arizona Strip, Grand Canyon, U.S.</td>
</tr>
<tr>
<td>11</td>
<td>Phosphorite deposits</td>
<td>Sedimentary</td>
<td>Marine deposits</td>
<td>Uncle Sam, U.S.; Gantour, Morocco; Al-Abiad, Jordan</td>
</tr>
<tr>
<td>12</td>
<td>Other types</td>
<td>Metamorphic</td>
<td>Metamorphic</td>
<td>Forstau, Austria; Mary Kathleen, Australia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedimentary</td>
<td>Limestone</td>
<td>Grants, U.S.</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Uranium-rich coal</td>
<td>Serres basin, Greece; North &amp; South Dakota, U.S.</td>
</tr>
<tr>
<td>13</td>
<td>Rocks with high U content</td>
<td>Igneous</td>
<td>Pegmatite</td>
<td>Greenbushes, Australia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedimentary</td>
<td>Granite</td>
<td>Australia; Nepal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Black shale</td>
<td>Chatanooga Shale, U.S.; Chanziping, China; Gera-Ronneburg, Germany</td>
</tr>
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</table>

*Sources: Dahlkamp (1993); OECD Nuclear Energy Agency (2005); Plant et al. (1999)*
Unconformity deposits formed during the Proterozoic and contain the highest-grade uranium ores on Earth. Average ore grades range from 0.12% to 22.28% uranium (Jefferson et al. in press). The unconformities developed between Archean–early Proterozoic metasedimentary rocks and mid-Proterozoic sandstones. Unconformity-type uranium mineralization was formed between 1300 and 1600 Ma, about 50–250 Ma after the overlying basin sediments were deposited (Kaffensperger and Garven 1995).

Sandstone-type deposits occur in arkosic (feldspar-rich) beds younger than 440 Ma. Tabular sandstone-type deposits form subparallel to bedding, parallel to the paleodrainage direction, and tend to be underlain by evaporites and overlain by mudstones (Young 1984; Sanford 1994). These deposits form the largest uranium resource in the U.S. Roll front deposits form in intracratonic basins and result from a sharp change in redox conditions. They are crescent shaped in cross-section and are overlain by volcanic ash deposits (Spirakis 1996).

Other sedimentary deposits of uranium include vein deposits in Proterozoic sediments that were later metamorphosed. These range in grade from 0.085% to >0.85% U (Plant et al. 1999). Collapse breccia pipe deposits in Arizona in the United States occur in a sequence of limestone, sandstone, and shale and contain 0.25–0.85% U (Plant et al. 1999). Surficial deposits occur in three main environments: (1) with calcite in arid environments (0.025–0.75% U); (2) in peat bogs in cool, wet conditions (85 ppm–1.00% U); and (3) in karst caverns in limestone (0.5–0.8% U) (James Otton personal communication; Dahlkamp 1993; Plant et al. 1999). Apatite deposits associated with uranium occur with phosphorite deposits (<20–6500 ppm U). Other minor deposits occur in limestone, lignite (0.01% U), and black shale formed from marine muds (50–400 ppm U) (Dahlkamp 1993; Plant et al. 1999).

Igneous deposits include breccia complexes that formed in the middle Proterozoic during anorogenic magmatism. These deposits contain 0.05–0.068% U (Dahlkamp 1993; Plant et al. 1999). Uranium can be associated with veins in granites (0.025–0.035% U) and can be distributed in intrusive igneous rocks with high concentrations of sodium and potassium (alkaline igneous rocks) (40–300 ppm U). Uranium is found in extrusive (volcanic) rocks as well. These tend to be felsic (light-colored) volcanic rocks, such as rhyolite and trachyte, associated with continental extensional settings (0.04–4% U). Uranium also occurs in rocks altered by hot fluids associated with emplacement of magmatic bodies. These deposits, known as metasomatites, occur in settings where the fluids were dominated by sodium (<0.17% U) or where the fluids were dominated by iron (hematite) and the feldspar minerals in the rocks were altered to clay minerals (1–2.5% U) (Dahlkamp 1993; Plant et al. 1999). Some pegmatites have relatively high concentrations of uranium, in the range of 0.04–0.13% (Dahlkamp 1993). Many granites are mildly enriched in uranium, such as leucogranites in the Nepalese and Indian Himalayas, where uranium concentrations range from 1.88 to 28.60 ppm (MacFarlane 1992). Uranium in metamorphic rocks is of minor economic importance, with concentrations in the range of 8.5–850 ppm (Dahlkamp 1993; Plant et al. 1999).

Finally, uranium is not limited to rocks—it is also found in seawater at concentrations of 0.5–3.3 ppb (Dahlkamp 1993). Seawater resources have the potential to greatly expand the total uranium resource (see Box 2).

Nineteen countries produced uranium in 2004. Of these, seven countries (Canada, 29%; Australia, 22%; Kazakhstan, 9%; Russia, 8%; Niger, 8%; Namibia, 8%; and Uzbekistan, 8%) produce about 55% of the world’s supply, while the top 10 countries (Canada, 29%; Australia, 22%; Kazakhstan, 9%; France, 7%; Russia, 8%; Niger, 8%; Namibia, 8%; South Africa, 5%; and Uzbekistan, 8%) produce about 69% of the world’s supply (NEA 2005). Nineteen countries produced uranium in 2004. Of these, seven countries (Canada, 29%; Australia, 22%; Kazakhstan, 9%; Russia, 8%; Niger, 8%; Namibia, 8%; and Uzbekistan, 8%) produce about 69% of the world’s supply (NEA 2005). Since the early 1970s the main research effort on seawater extraction has been in Japan. Over a three-year period, Japanese researchers extracted about 1 kg of uranium by using a highly selective, inexpensive amidoxime adsorbent. This material is full of voids so that seawater can pass through it with little loss of head. The process can be driven by ocean currents of modest magnitude (1 m/s) without the use of an external power source (Seko et al. 2003). Estimates of the recovery costs using this process range from $400 to $1200 per kilogram.

Although the major attraction of recovering uranium from seawater is the large size of the total resource, all schemes proposed to date have focused on exploitation of coastal waters close to the equator to depths no greater than 100 m. This is due to the fact that the amount of uranium recoverable by the adsorbent decreases sharply with decreasing temperature. It is likely to be uneconomic to extract uranium in waters where the average temperature is less than 15°C, i.e. outside a latitude band between ~35°N and 45°N and deeper than 100 m. Since the top layer of the ocean, the so-called “mixed layer,” mixes with the deeper ocean at an average rate of 2 m/yr, the uranium in the top 100 m is replenished over a period of 50 years.

Since the average depth of the ocean is 4000 m, the top 100 m contains 2.5% of the total uranium, or 10^10 tons. Restricting recovery to the above latitude band reduces this by half. Extracting 1% of this over a 50-year period gives ~5 x 10^6 tons. This amount is 5% of the uranium required, about 10^7 tons, to fuel an oft-quoted recent projection of the growth of nuclear power, from 350 GW to 1500 GW in 50 years (Ansolabehere et al. 2003).

Thus seawater uranium might be an important alternative for providing “nuclear energy security” for countries like Japan that have no indigenous uranium resources. Improved technology, especially adsorbents with better performances at lower temperatures, could increase the economically extractable resource significantly. However, improved technology can be expected to increase the availability of terrestrial uranium resources as well.

#### Box 2  Uranium from Seawater

Uranium may become economically recoverable from seawater in the future. While the total resource is very large, about 4.5 billion tonnes of the uranyl tricarbonate \( \text{[UO}_2\text{CO}_3]^4^- \), its very low concentration, 3 mg U/m\(^3\), presents an impediment to economic recovery. Huge amounts of seawater must be processed to recover quanti- ties of uranium that are significant on a commercial scale. For example, at a realistic uranium extraction efficiency of 1%, an ocean stream equivalent to ~700 times the annual flow of the Mississippi River would have to be processed to recover about 10,000 tonnes of uranium to provide the annual fuel for approximately 50 GW of reactor capacity. This indicates the need for a highly selective, durable, and inexpensive medium to extract the uranium and a means of moving large amounts of seawater through it without using too much energy.

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5%) accounted for almost 90% of world production. The majority of uranium exploration in 2004 focused on unconformity-type, sandstone-type, and hematite breccia complex deposits. Most of this exploration occurred in Australia, Canada, India, Kazakhstan, Russia, the United States, and Uzbekistan (OECD Nuclear Energy Agency 2005). In general, though, over the past decade and a half, very little new uranium exploration has been done (Schneider and Sailor 2005). More exploration is likely in the future due to the recent increase in the price of uranium.

CONCLUSIONS

Economic uranium deposits are found in a wide variety of geologic settings. Because the price of uranium has been relatively low for the past few decades, exploration for undiscovered resources has been limited. In addition, a number of countries do not list uncertain resources or those in high-cost categories, so the numbers in Table 3 underestimate the total resource (van der Zwaan in press). As a result, current estimates of total global uranium resources are uncertain and conservative. Nuclear power will certainly continue to form an important component of the global energy supply and especially the non-carbon-dioxide–emitting electricity supply for the next 20–30 years. As existing reactors reach the end of their lifetimes, will they be replaced by more nuclear facilities? Nuclear power has the potential to expand and hence reduce anthropogenic carbon dioxide emissions. The degree to which it will be used in the future depends on a variety of complicated factors, including economics, waste disposal, proliferation, safety, and security. The one factor expansion of nuclear power will not depend on for at least the next 100 years is uranium resources—of those we are assured.

REFERENCES


Tapping Methane Hydrates for Unconventional Natural Gas

Carolyn Ruppel

Methane hydrate is an icelike form of concentrated methane and water found in the sediments of permafrost regions and marine continental margins at depths far shallower than conventional oil and gas. Despite their relative accessibility and widespread occurrence, methane hydrates have never been tapped to meet increasing global energy demands. With rising natural gas prices, production from these unconventional gas deposits is becoming economically viable, particularly in permafrost areas already being exploited for conventional oil and gas. This article provides an overview of gas hydrate occurrence, resource assessment, exploration, production technologies, renewability, and future challenges.

KEYWORDS: methane hydrate, energy, natural gas

INTRODUCTION

When various low molecular weight gases (e.g. methane, ethane, carbon dioxide, hydrogen sulfide) combine with water at the pressures and temperatures common in the sediments of continental margins and permafrost regions, the resulting compound is gas hydrate, an icelike substance consisting of water cages surrounding guest gas molecules in a clathrate structure. Structure I clathrates (Fig. 1), the most widespread type, have cubic symmetry (space group Pm3n; lattice parameter ~12 Å) with 46 water molecules and 8 potential gas guest sites. The gas sites are two smaller (average radius \( r = 3.95 \) Å) pentagonal dodecahedral cavities and six larger cavities (\( r = 4.33 \) Å) with 12 pentagonal and 2 hexagonal faces (Sloan 2003). If gas molecules fill all the cages, as they rarely do in nature, Structure I clathrates can concentrate methane by ~160 times compared to gas at standard pressure and temperature. Methane hydrate deposits and the often-proximal gas-charged sediments thus constitute a potentially large, but currently untapped, hydrocarbon reserve within porous sediments.

Methane hydrate is a conventional hydrocarbon resource (natural gas) that is found in an unconventional form (frozen), at shallower (tens to hundreds of meters), more readily accessible depths than conventional oil and gas, and in locations both within and outside some of the permafrost and marine areas that supply conventional fuels (Fig. 2). The methane contained in gas hydrate deposits can originate through the same, deep-seated thermal cracking (thermogenic) processes that produce oil and conventional natural gas from sedimentary organic carbon. More often, though, the carbon isotope signature (\( \delta^{13}C \)) of the hydrated methane indicates a biogenic source, namely microbial degradation of sedimentary organic matter. Even within a major petroleum basin like the Gulf of Mexico, the volumetrically most extensive gas hydrate deposits (i.e. those located in pore space in regional strata, not concentrated in discrete faults and seeps) may be dominated by biogenic (\( \delta^{13}C \) values between ~110‰ and ~50‰), not thermogenic (\( \delta^{13}C \) values between ~50‰ and ~20‰), methane.

Prior to the last decade, gas hydrates were studied primarily to enhance safety and productivity in the petroleum industry. Without thermodynamic or kinetic inhibitors or measures to closely control pressure and temperature (see Sloan 1998), conventional wells and pipelines can clog with artificial gas hydrates that damage equipment, halt production, and endanger workers. If natural gas is not carefully dried, even some consumer gas lines can be subject to gas hydrate formation. Within the past few years, naturally occurring gas hydrates have also become an important focus for the private sector. As conventional offshore hydrocarbon exploration has shifted to progressively deeper waters (greater than 300 to 500 m), there has been increased awareness of potential hydrate-associated geohazards (e.g. Howland and Gudmestad 2001), such as uncontrolled degassing from shallow sediments, seafloor collapse, and sediment fluidization.

Since the mid-1990s, the academic research community has undertaken numerous studies of geochemical, geophysical, and microbiological processes in marine gas hydrate reservoirs (Tréhu et al. 2006). Although locating economically important gas hydrate deposits is not a priority for this community, the Integrated Ocean Drilling Program (IODP) and its predecessor, the Ocean Drilling Program (ODP), have directly sampled gas hydrates (Fig. 2) during clathrate-focused expeditions on the Cascadia active margin (Tréhu et al. 2003; Expedition 311 Scientists 2005) and on the Blake Ridge and Carolina Rise passive margin (Paull et al. 1996).

National governments and some industry interests have also invested substantially to investigate natural gas hydrates (Fig. 2). Since 1998, permafrost gas hydrates, which will undoubtedly be the first exploited commercially, have been explored at the edge of Canada’s Mackenzie Delta during drilling and prototype production testing in the Mallik well (e.g. Dallimore and Collett 2005). Japan, motivated by a lack of domestic hydrocarbon reserves and the government’s strong commitment to gas hydrates research, cosponsored the Mallik drilling and also undertook ocean drilling in the Nankai Trough gas hydrate province beginning in 1999. Recently major gas hydrate drilling campaigns have also been conducted in offshore India and China. In the U.S., the
Natural Gas in the 21st Century

Methane hydrates and associated free gas deposits have relevance as an unconventional energy resource only insofar as natural gas is a viable fuel to power the world’s economies. Natural gas is typically made up of methane, ethane, butane, and propane, but the focus here is on methane, which constitutes 70% to over 90% of most conventional natural gas. Although methane has ~80% of the heat content [4.62 million BTU or 4840 megajoules (MJ) per barrel] of crude oil ($8.55 million BTU or 6120 MJ per barrel], natural gas remains impractical for applications that rely on a liquid fuel stable at ambient pressure and temperature. Nonetheless, the U.S. Energy Information Administration projects an increase of more than 90% in annual, absolute global consumption of natural gas between 2003 and 2030, corresponding to a ~2% increase (from 24% to 26%) in natural gas use relative to other energy sources.

The world’s largest-known reserves of conventional natural gas lie in Iran, Qatar, and western Siberia. Compared to liquid fuels that need intense refining, raw natural gas has a much shorter path from extraction to reaching a usable form, as it requires only separation of the different gases. The critical challenge is transportation of the gas, which requires either specialized pipelines or extreme cooling to form liquid natural gas (LNG). At present, less than 10% of global natural gas production is transported as LNG, and a significant increase in LNG capacity will be necessary to accommodate rising global natural gas consumption in areas that cannot be served by direct pipelines. Due in part to transportation issues, the small amounts of natural gas produced from methane hydrates in the initial commercial projects might be used to power infrastructure on site instead of being transported to markets.

Natural gas is regarded as a relatively clean hydrocarbon-based fuel because methane combustion yields fewer pollutants than either oil or typical coal, with markedly lower emissions of CO$_2$, nitrogen oxides, SO$_2$, and particulates. Methane is ~20 times more potent than CO$_2$ as a greenhouse gas and is typically oxidized in the atmosphere in less than 10 years. Natural outgassing of methane hydrates is estimated to account for ~1–2% of present-day atmospheric methane. Conventional fossil fuel production and use accounts for 15% to 18%, and rice production, wetlands, ruminants, and landfills for up to ~75%. Methane emissions will certainly increase if methane hydrate reservoirs are exploited for natural gas, but a more critical concern is possible catastrophic release of methane to the atmosphere or ocean from shallow gas hydrate deposits as a result of extraction activities or even climate change. For marine gas hydrates, some released methane would probably be oxidized in the sediments and water column; some might dissolve in the ocean and alter pH, carbonate solubility, and oxygen levels in the vicinity of the emission; and a fraction might reach the atmosphere either immediately or over time. For permafrost gas hydrates, the potential for direct outgassing of methane to the atmosphere is considerably greater.

THE IN SITU METHANE HYDRATE RESOURCE

An understanding of the conditions under which methane hydrates form and remain stable in natural systems is necessary for assessing the extent of the resource. On present-day Earth, the suitable pressure and temperature conditions occur at depths shallower than ~1 to 2 km in permafrost regions and in the uppermost tens to several hundreds of meters of marine sediments on continental margins lying at water depths greater than ~300 m (Fig. 3). Gas hydrates have also been discovered beneath large lakes and inland seas (e.g. Lake Baikal, Black Sea).
Temperature, which is largely governed by the background, conductive geothermal gradient and superposed perturbations associated with fluid advection, primarily controls the thickness of the gas hydrate stability zone. Typical geothermal gradients in the shallow sediments of permafrost and marine settings range from 15°C km\(^{-1}\) to 50°C km\(^{-1}\), while the temperature of the phase transformation from methane hydrate to gas increases by only a few degrees per kilometer for pressures greater than ~6 MPa (equivalent to ~600 m water depth). Hydrostatic, not lithostatic, pressure is often used to determine the phase transformation for methane hydrate: Saturated, near-seafloor or near-surface sediments have high porosity (usually 50–75%), meaning that they are mostly water by volume and have water-supported grains. Increasingly, though, studies of gas hydrate reservoir dynamics include more sophisticated pressure formulations (e.g. Flemings et al. 2003).

The pressure and temperature controls on gas hydrate stability lead to predictable vertical zonation of reservoirs (Fig. 3). In marine settings conducive to gas hydrate formation, methane hydrate is stable in the sediments closest to the seafloor but often does not form in this portion of the stability zone due to the consumption of methane in oxidation reactions. Below this zone, gas hydrates may occur as disseminated deposits in fine-grained sediments, as vein or fracture fill deposits, as nodules, or as cementing material in higher permeability sediments (e.g. sand, volcanic ash). Beneath the base of the gas hydrate stability zone, sediment pores may be charged with free gas. In places, a negative impedance seismic reflector—the bottom-simulating reflector or BSR—marks the phase boundary between higher-velocity, gas hydrate-bearing sediments above and lower-velocity sediments charged with free gas below (e.g. Hyndman and Davis 1992; Minshull et al. 1994). The BSR cuts across stratigraphic layers and can be dramatically deflected by thermal perturbations associated with fluid flow or salt diapirs.

In many locations in the world’s oceans, gas hydrate is stable (but relatively rare) not only in the sediments, but also in the deeper part of the water column and at the seafloor. Gas hydrate (density of 910 kg m\(^{-3}\)) that detaches from seafloor outcrops or that forms around methane bubbles is buoyant relative to ocean water (nominal density of 1024 kg m\(^{-3}\)) and eventually dissociates (outside its stability field) or dissolves in ocean waters undersaturated in methane as it ascends. In a global inventory, seafloor gas hydrates (e.g. in the northern Gulf of Mexico) are not volumetrically important. Such deposits occur primarily at sites of enhanced advective flux (e.g. seeps), where the gas hydrates are sustained from below even as they dissolve in the overlying water; they also occur where physical barriers (e.g. petroleum or biofilm coatings on gas hydrate mounds) prevent wholesale dissolution of exposed seafloor hydrates in ocean water.

Compared to marine methane hydrate reservoirs, permafrost reservoirs have more complex zonation (Fig. 3b). Typically, free gas is the stable methane phase nearest the surface, with a zone of coexisting water ice and methane hydrate in the underlying sediments. Because some of the geophysically detectable properties of water ice are similar to those of methane hydrate (e.g. shear wave velocity, electrical properties), assessment of gas hydrate concentration and distribution is particularly difficult within this zone. At greater depth, the system resembles marine reservoirs, although BSRs are typically lacking. Another key difference between gas hydrate reservoirs in marine and permafrost regions is the direct impact of terrestrial hydrologic processes (e.g. unsaturated flow, aquifer recharge) in the latter setting.

Within its stability field, methane hydrate only forms if the constituent water and methane are available. While some gas hydrate may contain biogenic methane produced in situ within the stability zone, rates of microbial methane generation and/or the concentrations of methanogenic microbes are probably too low for this to be the most important mechanism. More likely, fossil biogenic methane that has been transported into the stability zone by hydrologic processes (e.g. Hyndman and Davis 1992; Minshull et al. 1994; Nimblert and Ruppel 2003) constitutes a significant portion of the gas trapped in global gas hydrate deposits. In this scenario, much of the gas hydrate forms...
from ascending fluids that contain aqueous phase methane (Hyndman and Davis 1992). The solubility of methane gas in water actually increases with temperature (and therefore depth) in the presence of gas hydrate (e.g. Buffett and Zatsepina 2000), so ascending fluids encounter decreasing methane solubility, which may result in exsolved methane combining with water to form gas hydrate. Such a formation mechanism is consistent with observations of sediments younger than the included pore waters (e.g. Fehn et al. 2000) or methane in some provinces. Another gas hydrate formation mechanism—formation around gas bubbles (Minshull et al. 1994)—is energetically favorable and relatively rapid and may produce massive deposits near the base of the gas hydrate stability zone, in permeable conduits that have enhanced fluid flow (e.g. faults that tap free gas zones) and near the seafloor.

The composition of fluids (pore waters and gases) and host sediment characteristics affect the formation and stability of gas hydrates in natural systems. Increasing pore water salinity inhibits gas hydrate stability. A 3.3% by weight increase in salinity (difference between freshwater and typical seawater) produces a ~1.1° C reduction in the phase transformation temperature for pure methane hydrate for pressures up to ~10 MPa. Pore water salinity changes can be caused by dissolution of salt diapirs, deep-seated brine formation, or the exclusion of salts from the gas hydrate lattice upon hydrate formation (e.g. Torres et al. 2004). The pressure-temperature conditions for methane hydrate phase transformation can also be affected by the presence of gases like ethane and carbon dioxide, whose molecules are small enough to fit in the guest sites in Structure I clathrates, or by fine-grained sediments, which generate increased capillary pressures (Clennell et al. 1999).

**FIGURE 3** Temperature-pressure conditions and methane hydrate stability in (A) marine and (B) permafrost settings. The columns at the right depict the vertical distribution of free gas, methane hydrate, and other phases within the sediments and water column in marine settings and within sediments in permafrost settings. MODIFIED FROM KVENVOLDEN AND LORENSON (2001)

**RESOURCE ASSESSMENT**

In the past 25 years, numerous estimates have been made of the amount of methane contained in global gas hydrate deposits (the resource) and the amount that can be economically extracted (the reserve). Published estimates of total methane in marine gas hydrates range from ~3100 Tm$^3$ to ~7,650,000 Tm$^3$, while the range for the smaller permafrost reservoirs is 14 Tm$^3$ to 34,000 Tm$^3$ (see Collett 2002). Global estimates for methane contained in both permafrost and oceanic reservoirs have now converged on ~15,000 Tm$^3$ (10 terratonnes) but range from 0.5 to 24 terratonnes (Kvenvolden and Lorenson 2001). For the U.S. Exclusive Economic Zone offshore and North Slope permafrost region combined, Collett (1995) estimated ~9000 Tm$^3$ of methane in gas hydrates, an estimate now lowered to ~5700 Tm$^3$ based on observations during drilling (Collett pers. comm.). Even this latter figure, which represents more than one-third of the nominal global estimate given by Kvenvolden and Lorenson (2001), is ~150 times the 95%-confidence-level estimate of the U.S. conventional natural gas reserve (Collett 2002) and ~900 times the current annual natural gas consumption in the U.S.

The lack of consensus about methane hydrate resource estimates frustrates policy makers, the energy sector, and scientists, but major improvements in the assessments will require intense data collection and far more complete understanding of gas hydrate reservoir dynamics. Part of the disparity among resource estimates can be attributed to markedly different assumptions about gas hydrate concentrations. In some assessments, gas hydrate concentrations are assumed to be several tens of percent of pore space. Yet field-based studies have rarely found in situ gas hydrate concentrations in excess of a few percent to perhaps 10% of pore space outside of highly permeable lithologies or conduits (e.g. faults and fractures) or localized features characterized by rapid flux (e.g. cold seeps, mud volcano flanks).

Further complicating resource assessments is the poor state of knowledge about gas hydrate distribution. Researchers routinely overestimate the resource by assuming that methane hydrate is distributed throughout the entire stability zone. In fact, the distribution of gas hydrate in natural systems is fundamentally inseparable from the hydrodynamics.
Commercial-scale production of methane from gas hydrate or the proximal free gas deposits will require safe, efficient, cost-effective, and environmentally sound extraction technologies. Some experience garnered from producing natural gas in conventional reservoirs can be readily applied to gas hydrate reservoirs. For example, extracting free gas from beneath capping, gas hydrate-bearing sediments is similar to production of natural gas from beneath much deeper structural traps in conventional reservoirs.

Direct mining of solid methane hydrate will probably remain economically and logistically impractical due to the relatively low concentrations of gas hydrate per unit volume of sediment in most places and the difficulty of maintaining gas hydrate within its stability field. Instead, exploitation of the solid hydrate will involve controlled dissociation (Fig. 4) of the gas hydrate through perturbations to pressure, temperature, and/or chemical conditions in the reservoir (Holder et al. 1984; Sloan 1998; Collett 2002). Dissociation increases pressure in the reservoir, meaning that the free gas released from the gas hydrate should in some cases flow freely to the wellhead (Max et al. 2006). In contrast, energy must often be expended to drive natural gas to the wellhead for extraction in conventional reservoirs. Owing to the relatively shallow nature of gas hydrate deposits, premature blowouts, borehole collapse, and thermal accidents can be rapidly fatal and difficult to correct.

Gas hydrate dissolution (~55 kJ mol\(^{-1}\) at 273 K for pure methane hydrate) means that ice formation could also pose a production challenge. Injection of heated fluids (liquids or steam), possibly enhanced by hydrofracturing of the formation, is the simplest technique for driving dissociation of methane hydrate to liberate gas for extraction (Fig. 4a). While conducive heating of the sediments is limited by the low thermal diffusivity of saturated sediments ( nominally 3 to 7 \(\times\) \(10^{-7}\) m\(^2\) s\(^{-1}\)), forced injection of hot fluids or steam could expose larger amounts of gas hydrate to destabilizing temperatures. Because dissociation is largely a surface phenomenon (Max et al. 2006), more energy must be expended to extract methane from the interior of deposits than from those close to the injection well. The thermal stimulation method has several disadvantages. Heating and pumping large quantities of fluids in places with cold ambient temperatures (permafrost or deep sea) would be expensive. There would also be the potential for permeable zones other than the target area to capture significant fluid flow and heat from the injection event and, conversely, it might be difficult to penetrate massive, low-permeability gas hydrate deposits (if they exist) with the fluids. Last, there would be the possibility of unintended gas hydrate dissociation and mechanical weakening of the sediments adjacent to the thermal stimulation borehole.

For more than two decades it has been known that depressurization (Fig. 4b) requires less energy input, yields more gas, and has lower overall production costs than thermal stimulation alone (e.g. Holder et al. 1984). Initially, the free gas that often underlies gas hydrate deposits would be extracted, thereby lowering the pressure in the overlying sediments and leading to dissociation, gas expansion, and then a drop in formation temperature. In an ideal reservoir, such depressurization should cause relatively uniform dissociation progressing upward from the base of the gas hydrate stability zone. Dissociation would continue until the reservoir pressure drops to the equilibrium pressure.
corresponding to the now-reduced formation temperature (Sloan 1998). Continued production would require heating of the reservoir to prevent gas hydrate from forming again and to drive new dissociation.

Methods developed to prevent the formation of gas hydrate plugs in hydrocarbon pipelines may also be applied to produce methane from gas hydrates (e.g. Sloan 1998). Injection of inhibitors like methanol, glycol, or brine could drive dissociation (Fig. 4c) but carries unknown environmental risks. Brines, which also occur naturally, might be the obvious choice to enhance production where depressurization combined with limited thermal injection is the primary production technique.

A more exotic mechanism for production of methane from gas hydrates is substitution of CO$_2$ for methane in the gas hydrate molecule. Natural gas hydrate reservoirs could thus be used for simultaneous energy extraction and sequestration of waste CO$_2$ generated by burning fossil fuels. The thermodynamics and kinetics are favorable for the exchange of methane for CO$_2$, but the process occurs rapidly only near the surface of the gas hydrate masses, leaving the deeper crystals untouched. Thermal perturbations and the processing of CO$_2$ to form emulsions of very fine droplets prior to injection (McGrail et al. 2004) might allow more methane to be released from natural deposits.

Since the 1980s, there have been claims of natural gas production from gas hydrate in the Messoyakha field in Russia, but subsequent analyses indicate that gas hydrates may not have contributed to recovered gas at the site (Collett and Ginsburg 1998). The first verifiable production of natural gas from gas hydrate probably occurred during depressurization and thermal injection tests conducted at the Mallik permafrost well in 2002 (Dallimore and Collett 2005). This test was promising not for the amount of gas produced, but rather for information it provided about extraction techniques, production rates, well control, and the capacity of models to predict the rate and pattern of gas extraction.

RENEWABILITY

Compared to conventional oil, which develops at depths of kilometers over millions of years, the largely biogenic methane contained within most natural gas hydrates accumulates at far shallower depths, from lower concentrations of buried organic matter, and possibly more rapidly. These factors might make gas hydrate seem potentially more renewable than conventional hydrocarbon resources, although certainly not renewable in the sense that biofuels are. Because gas hydrate formation from aqueous-phase methane is so slow even at high rates of advection (e.g. Nimblett and Ruppel 2003), artificial stimulation to enhance the flow of existing free gas into the hydrate stability zone is probably the best prospect for catalyzing regeneration of methane hydrate. Still, this simply enhances the formation of new methane hydrate without actually replenishing the methane itself. Biogenic methane production is limited by the availability of organic carbon, the population of methanogens, and the rates of methanogenesis and related biochemical processes. Without artificial manipulation of the microbial consortium or the environmental factors that affect the rates of microbial methanogenesis, it is difficult to envision a means for actually renewing the biogenic methane supply on short timescales.

THE FUTURE

Coal and conventional oil and gas have largely powered the industrialized world for decades. Petroleum production may peak by the middle of the 21st century, while coal use is increasingly criticized for its contribution to air pollution and greenhouse gas accumulation. Methane hydrates could provide a cleaner hydrocarbon fuel accessible at shallower depths than conventional oil and gas, but major advances in exploration, extraction, and distribution techniques will be necessary to achieve routine production of natural gas from these deposits. The recent U.S. government proposal to temporarily suspend natural gas royalties for production of gas from gas hydrates in Alaska or on the U.S. outer continental shelf may stimulate commercial interest in unconventional gas from gas hydrates. Nonetheless, the National Petroleum Council recently predicted that methane hydrate is unlikely to contribute significantly to natural gas production before ~2025. According to Kumar, as summarized by Doyle et al. (2004), milestones in the projected development and production timeline include production of natural gas from the free gas near methane hydrate deposits within 5
REFERENCES


Collett TS, Fehn U, Snyder G, Egeberg PK (2000) Gas hydrates deposits starting more than a decade from now, and deep-water production in perhaps 20 years. Enhanced recovery owing to technology developments in the next 10 years, extraction from permafrost gas hydrate deposits starting more than a decade from now, and deep-water production in perhaps 20 years. Elements 3 (2): 129-137


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Mineralogical Society of America

PRESIDENT’S LETTER

Mineral Madness Month

In our world of proliferating professional meetings, it is difficult to choose which we will attend. MSA’s vision is to participate in several meetings, in part to reflect the diversity of our membership. One such “meeting” is the Tucson Gem and Mineral Show—the largest gathering of mineralogists, gemologists, and collectors in the world. The most difficult aspect of this “meeting” is deciding how long to stay.

For those of you who haven’t had the pleasure of visiting this show, it occurs over a four-week period beginning in late January. Thousands of mineral, gem, rock, and fossil dealers and collectors from around the world descend on Tucson, Arizona. Hotel rooms are transformed into mineral galleries, parking lots into showcases, and restaurants into bargaining rooms. Mineral madness month culminates with the official Tucson Gem and Mineral Society (TGMS) Show held in the convention center in mid-February. Dealers move their wares from hotels onto the convention floor and are joined by nearly 100 museums, educational institutions, and private collectors who bring awe-inspiring specimens to dazzle spectators. Our colleagues arrive from around the world. For some, it is eye candy at its finest and for others, an exquisite field area. Every type of mineral is available, as is every price range—including a $2 million quartz and tourmaline specimen!

This year MSA had the pleasure of presenting our Distinguished Public Service Medal at the TGMS banquet (described in the April issue, Elements 3: 88). Over 300 people attended the awards ceremony, including many of our members. Marie Huizing, our medalist and 30-year managing editor of Rocks & Minerals, is well known and dearly admired by this community. When I presented the medal to her, there was a standing ovation and much noise I had to yell into the microphone. The applause lasted for minutes. It was an awesome sight to see this level of enthusiasm for our medal and our winner, and to look out over a sea of clapping hands and standing colleagues. After her acceptance speech as she was stepping down from the stage, she received an even longer standing ovation! MSA gained much visibility and appreciation from the mineral-collecting community. And we netted a few new members, including the premier mineral photographer and dealers from Australia! This venue helped raise awareness about our society to an important group of (mostly) non-members.

Our next event will be the presentation of the 2007 Dana Medal to Dr. Frank Spear at the “Frontiers in Mineral Sciences” meeting in Cambridge, England, in late June. I look forward to seeing many of you there, and as enthusiastic as at TGMS.

Barb Dutrow
2007 MSA President
An up-to-date review with emphasis on crystal structure and classification, electrical and magnetic properties, spectroscopic studies, chemical bonding, high- and low-temperature phase relations, thermochemistry, and stable isotope systematics of metal sulfides. Where appropriate for comparison, there are brief discussions of the selenide or telluride analogs of the metal sulfides and sulfosalt minerals. There are major sections on sulfide mineral surface chemistry and reactivity, formation and transformation of metal-sulfur clusters and nanoparticles, modeling of hydrothermal precipitation, and sulfides in biosystems. Volume 61, 2006, David J. Vaughan, (ed) i-xiii and 714 pp. ISBN 093995073-1.

US$40

For more description and table of contents of this book, and online ordering visit www.minsocam.org or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly VA 20151-1125 • USA
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EAG ANNOUNCES ITS AWARDS

The EAG is proud to announce its 2007 medalists. The Urey Medal is given annually by the Society for outstanding contributions to the advancement of geochemistry during a career. The Houtermans Medal is awarded annually to a scientist under 35 years of age for exceptional contributions to geochemistry.

Urey Medal to Elderfield

The 2007 Urey Medal has been awarded to Harry Elderfield of the University of Cambridge. Harry is a pioneer in ocean chemistry and paleochemistry who has had a far-reaching impact on geochemistry. He has contributed significantly to marine chemistry, most notably with respect to the fate of metals in hydrothermal processes, the formation of manganese nodules, and the biogeochemical cycles of elements like iodine and strontium. He has authored almost 200 scientific papers and edited three books.

Harry Elderfield has also unselfishly served the international community, notably as an editor of Geochemistry, Geophysics, Geosystems (G3) and Earth and Planetary Science Letters. Harry’s current interests include the definition of chemical proxies from biogenic carbonates and their use in understanding the ancient ocean. In particular, he has pioneered the development of foraminiferal magnesium thermometry, which is rapidly becoming accepted as a means for estimating past ocean temperatures.

Houtermans Medal to Parman

The 2007 Houtermans Medal has been awarded to Steve Parman of Durham University, UK. Steve is a leading expert on the behavior of volatiles in the Earth’s interior. His work on water in early-Earth magmas, highlighted in a 2004 Earth and Planetary Science Letters Frontiers article (219: 173–187) is providing new insights into Earth’s thermal evolution. Likewise, his recent research on noble gas solubility in the mantle published in Nature in 2005 (437: 1140–1143) is challenging the existing models of mantle structure and evolution.

SULPHUR IN GLASSES AND MELTS – WORKSHOP REPORT

An international workshop, organized by Harald Behrens and entitled “Sulphur in Glasses and Melts”, was held at the University of Hannover, Germany, on March 1–2, 2007. The workshop brought together more than fifty European and North American scientists and engineers engaged in Earth and glass sciences. The involvement of experts from both fields of research was crucial because the dissolution of sulphur in silicate melts and processes involving fluids is of major research interest in both natural and industrial processes. For example, the degassing of magmas during volcanic eruption injects large quantities of sulphur species into the atmosphere, which may have a dramatic impact on climate and the environment. Likewise, bubbling induced by decomposition of sulphate is widely used for fine tuning melting glasses for use in glass manufacturing. The presentations dealt with the following topics: diffusion and degassing in melts; spectroscopic techniques for determining the oxidation state and local environments of sulphur in glasses; evolution of sulphur concentrations in igneous systems via measurement of melt inclusions; partitioning of sulphur between melts and fluids; saturation of sulphur and equilibrium with sulphur-bearing minerals; and thermodynamic models for sulphur solubility.

Gearing up for the 2007 Goldschmidt Meeting

The 17th annual meeting will take place August 19–24, 2007 at the University of Cologne in Germany and will be held in association with the annual meeting of the German Mineralogical Society. We look forward to seeing you all in Cologne. Check next page for the latest news.

EUROPEAN UNION RESEARCH INFRASTRUCTURE – TRANSNATIONAL ACCESS (RITA) PROGRAMME

The Structure and Properties of Materials at High Pressure

The Bayerisches Geoinstitut is funded by the European Union Research Infrastructures – Transnational Access programme for a four-year period that started in January 2005. This support follows nine years of funding, between 1994 and 2003, through the HCM/TMR Large-Scale Facility and Access to Research Infrastructures programmes.

The Research Infrastructures – Transnational Access programme funds visiting scientists (“users”), from institutions in EU states and associated states (with the exception of Germany), who wish to use the experimental, analytical or computational facilities of the Bayerisches Geoinstitut. Visiting scientists are accepted generally for periods between one week and three months. The funding covers travel expenses, accommodation and living expenses incurred during the stay in Bayreuth (usually for one user per user group) and all experimental costs. The staff members of the Bayerisches Geoinstitut provide full support for the users in terms of training and assisting with experiments. A wide range of research projects related to Earth sciences, solid-state physics and chemistry and materials science are possible. Users have access to a wide variety of experimental, analytical and computational facilities. A total of 324 experiment days of access are provided per year.

Further details can be found at www.rita.bgi.uni-bayreuth.de/
THE EUROPEAN ASSOCIATION FOR GEOCHEMISTRY AND THE GEOCHEMICAL SOCIETY ANNOUNCE THE 2007 GEOCHEMISTRY FELLOWS

In 1996, the European Association for Geochemistry and the Geochemical Society established the honorary title of Geochemistry Fellow, to be bestowed upon outstanding scientists who have, over some years, made a major contribution to the field of geochemistry. These fifteen Geochemical Fellows will be honored at the 2007 Goldschmidt Conference in Cologne, Germany.

1. Dr. Jill Banfield, University of California–Berkeley
2. Dr. Don Canfield, The University of Southern Denmark
3. Dr. Marc Chaussidon, Centre de Recherches Petrographiques et Geochimiques
4. Dr. Jitendra Nath Goswami, Physical Research Laboratory
5. Dr. T. Mark Harrison, University California–Los Angeles
6. Dr. Frank C. Hawthorne, University of Manitoba
7. Dr. Michael F. Hochella Jr., Virginia Tech
8. Dr. Boaz Luz, The Hebrew University of Jerusalem
9. Dr. Catherine McCammon, Bayerische GeoInstitut
10. Dr. Judith A. McKenzie, Swiss Federal Institute of Technology
11. Prof. Hugh St Clair O’Neill, The Australian National University
12. Dr. Robert O. Pepin, University of Minnesota
13. Dr. Mark Thiemens, University of California–San Diego
14. Dr. David Vaughan, The University of Manchester
15. Dr. Arthur F. White, U.S. Geological Survey
FROM THE PRESIDENT

As I write this in April, the snow has receded in central Pennsylvania and is now only intermittently making a return as we welcome spring. With spring comes anticipation of our upcoming annual meeting—the Goldschmidt Conference (www.goldschmidt2007.org), in Cologne, Germany, organized by Prof. Herbert Palme and his team. It looks like it will be a great meeting, filled with wonderful science.

Spring is also the moment when we express our appreciation to the Geochemical Society (GS) committee members who rotate off their positions. It continues to amaze me that in this time of increasingly busy schedules, scientists from around the world run the GS as volunteers, giving their time to keep our Society functioning for the benefit of the worldwide geochemical community. We truly appreciate these volunteers. I will also use this space to introduce you to the functions of our various committees, in the hope that you would like to participate in one of them. We are always looking for new members for committees, and committee membership is renewed each year through nominations coordinated by the vice president, Marty Goldhaber (mgold@usgs.gov). Our business manager, Seth Davis (gsoffice@geochemsoc.org), also maintains a list of GS members who express interest in serving on a committee—please write Seth if you are interested. The GS Board is currently considering changes to some of our nomination procedures, which we will explain in a future message in Elements.

The following committee members are rotating off the Nominations Committee on June 30, and their efforts are greatly appreciated: Martin Palmer, Chair (National Oceanographic Centre, Southampton) and J.K. Bohlke (USGS). The Nominations Committee puts forward nominations for our officer positions and always seeks a balance that reflects the diversity of our members.

We also salute the retiring members of the Program Committee: Tracy Rushmer, Chair (University of Vermont) and Albert Galy (University of Cambridge). This important committee discusses how to promote geochemistry at national and international meetings. The committee implements many of our program initiatives outside of the Goldschmidt Conference. Of particular interest this year, the committee has discussed the reduced attendance by geochemists at the Geological Society of America meeting and the impact of this decrease on our Ingerson Lecture. We have decided to maintain the Ingerson Lecture at GSA, but we hope that better advertising and improved coordination of the lecture with the GS–MSA reception will increase its attendance. If you are running a geochemical symposium at GSA in the future, you might consider trying to coordinate it with the Ingerson Lecture if appropriate.

The retiring members of the Clarke Award Committee include Randy Cygan, Chair (Sandia National Laboratory) and Alan Matthews (Hebrew University of Jerusalem), both of whom have contributed greatly to the Society. Cygan’s committee made some important suggestions about how the GS should run the award process, and we will be acting on some of those suggestions. We welcome suggestions about our awards from all members, and we have received some very good ones this year. We will try to implement your ideas where appropriate.

We salute the following members of the GS/EAG Fellows Committee who helped us pick an excellent slate of Fellows this year (see the 2007 Fellows on the previous page): Doug Rumble, Chair (Carnegie Geophysical Laboratory) and Bruce Watson (Rensselaer Polytechnic Institute).

The Patterson Award is the highest award that the GS bestows in environmental geochemistry. The committee that has been choosing the awardees over the last several years was chaired by Brian Popp (University of Hawai’i). We appreciate Brian’s efforts as well as the efforts of Don Sparks (University of Delaware)—both Brian and Don are rotating off this year.

Finally, the highest award that the GS bestows is the Goldschmidt Award, and the Goldschmidt Committee similarly did a fine job this year. We appreciate the hard work of Sam Mukasa, Chair (University of Michigan) and David Hilton (University of California–San Diego).

I would also like to invite you to submit more nominations for all GS awards. This year we had an extraordinarily high number of nominations for Fellowships, and the chosen Fellows are thus of the highest quality. We need such influxes of nominations for all the awards, and we encourage members and nonmembers alike to nominate deserving candidates. Again, the GS is a volunteer organization, and we need members to contribute to all these committees. We welcome your suggestions and nominations. See you in Cologne.

Susan L. Brantley
President, Geochemical Society
Professor of Geosciences and Director of Earth and Environmental Systems Institute, Pennsylvania State University
Please bookmark this link in your browser for easy reference because other Science Direct web pages will not allow access. Note that full-text articles are available from 1995 to the present.

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Through an arrangement with AGU, GS is pleased to be able to offer G-cubed access to subscribing members. Every subscribing member should receive an AGU membership number (even if their subscription is through GS). If you do not know yours, please request it from the GS business office.

New Look for www.geochemsoc.org
The Geochemical Society has contracted a web development company to greatly improve the content and usability of our site. The new site is projected to be up and running before the 2007 Goldschmidt Conference.

If you have suggestions or questions please let me know.

See you in Cologne

Seth Davis
gsoffice@geochemsoc.org

17th ANNUAL GOLDSCHMIDT CONFERENCE, COLOGNE, GERMANY
AUGUST 19–24, 2007
EUROPEAN ASSOCIATION FOR GEOCHEMISTRY AND THE GEOCHEMICAL SOCIETY
INCORPORATING THE ANNUAL MEETING OF THE GERMAN MINERALOGICAL SOCIETY

The conference will begin Sunday late afternoon with registration and an icebreaker in the Mensa building. Sessions will start at 8:30 am each day with plenary lectures. Mornings and early afternoons will be devoted to symposia in some 14 lecture halls, with late afternoons being reserved for poster sessions. Wednesday afternoon will be free for visiting the city. In the evening the conference dinner will be served in the Gürtzenich, the traditional ballroom and reception hall of the City Council.

A series of plenary lectures will highlight various phases in the evolution of planet Earth: from accretion, through internal differentiation and crust formation and the shape and structure of the present surface to the earliest stages in the evolution of life.

- Monday: A. Morbidelli
  “Terrestrial Planet Formation: Our Solar System and Extrasolar Worlds”

- Tuesday: Paul Asimow
  “Magmatism and the Evolution of the Earth’s Interior”

- Wednesday: John Valley
  “Evidence of the Earliest Crust on Earth”

- Thursday: James Kirchner
  “The Chemistry of Earth’s Dynamic Surface”

- Friday: Jochen Brocks
  “Molecular Fossils and Early Life on Earth”

In addition to these lectures, over 70 keynote presentations will be made. Speakers confirmed for keynote presentations include Frank Richter, Nicolas Dauphas, David Hilton, Samuel Bowring, Rick Carlson, John Gurney, Willy Benz, Alex Halliday, John Patchett, J.-P. Lorand, Rich Walker, Don DePaolo, Chris Hawkesworth, John Blundy, Max Schmidt, James A. Van Orman, Stefan Shouten, Ruth E. Blake, Erik Hauti, Terry Seward, Terry Bidleman, Jürgen Popp, John Stone, Howard Spero, Alex Sobolev, and John Clemens.

The 2007 Goldschmidt looks set to be among the biggest geochemistry conferences ever. Do plan to come and be a part of it. Further information can be found on the conference website

www.goldschmidt2007.org

GEOCHEMICAL SOCIETY AWARDS AT THE 2007 GOLDSCHMIDT CONFERENCE

2007 V.M. Goldschmidt Award
1. Dr. Günter W. Lugmair, UC–San Diego
   Citationist: Dr. Jerry G. Wasserburg, CalTech

2007 F.W. Clarke Award
2. Dr. Ethan Baxter, Boston University
   Citationist: Donald DePaolo, UC–Berkeley

2006 C.C. Patterson Award
3. Dr. Fred T. Mackenzie, University of Hawai’i
   Citationist: John W. Morse, Texas A&M University

2007 C.C. Patterson Award
4. Dr. Gordon E. Brown Jr., Stanford University
   Citationist: Prof. George R. Helz, University of Maryland

2007 Distinguished Service Award
5. Dr. Michael F. Hochella Jr., Virginia Tech

2007 Gast Lecturer
6. Dr. Katherine H. Freeman, The Pennsylvania State University
   Lecture Title: “Molecular and Isotopic Proxies – From Microbes to Mountains”

ORGANIC GEOCHEMISTRY DIVISION AWARDS AT IMOG 2007

2006 A.E. Treibs Award
7. Dr. Bernd Simonneit, Oregon State University

2007 A.E. Treibs Award
8. Dr. Walter Michaelis, University of Hamburg

The Organic Geochemistry Division of the Geochemical Society will also be presenting the 2007 Best Paper Award (to be determined) at the 23rd International Meeting on Organic Geochemistry (IMOG) in Torquay, Devon, UK, on September 9–14, 2007 (www.imog2007.org).
FROM THE PRESIDENT

Welcome to Frontiers 2007

This month the MinSoc is very pleased to be hosting the Frontiers in Mineral Sciences meeting in Cambridge, UK (26–28 June). This meeting will be the first joint meeting of the mineralogical societies of the USA, Canada, France and Great Britain & Ireland. The initial concept for the meeting was developed when Michael Carpenter and David Price were the presidents of MSA and MinSoc, respectively, and it quickly grew to embrace MAC and SFMC. The meeting will cover all aspects of mineralogy and associated studies in petrology and geochemistry, and it has been a great pleasure to see the interest this unique venture has generated – the meeting rapidly became fully subscribed, with over 350 participants.

In addition to the scientific interest, MinSoc feels assured the occasion will be pleasant in all respects since it is taking place in Cambridge in summer. Participants will have the opportunity to savour pleasures such as walking round the Cambridge colleges and punting on the river Cam. The conference dinner and medal presentations will take place in the Fellows’ Garden in Magdalene College. MinSoc is pleased to acknowledge Michael Carpenter as initiator and principal Cambridge organiser of the conference. We look forward to seeing all participants at the end of June.

Ben Harte
President, Mineralogical Society of Great Britain and Ireland

Peter Kelemen – Hallimond Lecturer 2007

Peter Kelemen of Columbia University will be giving the Hallimond Lecture at the Frontiers meeting on Tuesday 26 June. His talk, entitled “Feedback Mechanisms in Reactive Fluid Transport: Field Examples and Simple Models”, is based on his extensive work in the field of reactive fluid transport. His studies are concerned with the genesis and evolution of the Earth’s crust in ocean basins, arcs and continents. He brings the perspective that reactions between melt and rock during transport through the upper mantle are as important as melting, mixing and crystal fractionation processes in producing different crustal bulk compositions in different tectonic settings.

BURSARY AWARDS FOR 2007

The Council is pleased to announce its bursary awards for 2007.

Student Bursaries have been awarded to Sally Morgan (University of Leeds), Hong Phuc Vu (University of Leeds) and Victoria Vry (Imperial College).

Details on the Society’s bursary programme can be found on the website www.minersoc.org/pages/awards/awards.html.

MINERALOGICAL MAGAZINE — MANUSCRIPT E-SUBMISSION AND TRACKING GOES LIVE

In mid-March, online submission and tracking of manuscripts to Mineralogical Magazine went live. In order to submit your paper to the journal, please go to www.minersoc.org/pages/e_journals/minmag.html and click on the “Submit” button. The new system will enable more rapid turnaround of manuscripts and will allow authors to check progress.

CONTENTS OF THE JUNE 2007 ISSUE OF CLAY MINERALS

- Clay mineral genesis and chemical evolution in the Miocene sediments of Somosaguas, Madrid basin, Spain
- O Feshakari, E Garcia-Romero, J Clevas-Gonzalez and N Lopez-Martinez
- Brazil Capim Basin kaolin mining, processing and applications
HH Murray, C Alves and CH Bastos
- Identification and characterisation of iron-rich smectites in Cambança region of West Turkey
Y Seri and K Yurdakoc
- Land erosion and associated evolution of clay mineral assemblages from soils to artificial lakes in two distinct climatic regimes in Portugal and Brazil
R Fonseca, EJAS Barbega and K Tazari
- Surface modification of bentonites. V. Sol-gel transitions of calcium montmorillonite in the presence of end-capped poly(ethylene oxides)
G Lagaly and S Ziesner
- Thermally induced mineral and chemical transformations in marls around a basaltic dyke (Perthus Pass, southern Massif Central) – possible long-term implications as natural analogue of nuclear waste disposal
C Henry, J-Y Boisson, A Bouchet and A Meunier
- Evaluation of selected kaolin clays as a raw material for the Turkish cement and concrete industry
A Aras, M Albayrak, M Arikian and K Sobelev
- R 2≥1 type illite-smectite formation at near-surface temperatures
A Sandler and H Saar
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It is now possible, and in fact we encourage you, to submit your papers online to Clays and Clay Minerals. Use the links from the journal page of the Society’s website (www.clays.org) or go directly to http://ccm.allentrack2.net, register, and then follow the instructions on how to upload your files. We hope that this will help to reduce our submission-to-publication times and that it will make the process more transparent to authors and editors alike.

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The entire archive of Clays and Clay Minerals has been reproduced in electronic format, and access is available online, again via the journal page of the Society’s website. Click on “Archive.” The archive is also available on two DVDs, and these are available for purchase from the Clay Minerals Society office. They cost $600 for institutional libraries, $100 for individuals, and $75 for members of the Society.

Call for News Items

The Clay Minerals Society news section of Elements contains information of interest to the clay science community. Please consider contributing your ideas, highlights of your work, photos, and other items of interest to your peers. Non-commercial information is free of charge; however, commercial advertising space is available at a cost (contact the managing editor, Pierrette Tremblay). Send your contributions to the incoming news editor, Steve Hillier (s.hillier@macaulay.ac.uk).

Many thanks to Kevin Murphy for his volunteer contribution to The Clay Minerals Society as acting CMS News Editor for Elements in 2006–2007. We appreciate his time and care.

Forthcoming Papers in Clays and Clay Minerals

Some papers accepted for publication in the June 2007 issue of Clays and Clay Minerals:

- Steven M. Kuznicki, Christopher C.H. Lin, Junjie Bian, and Alejandro Anson
  Chemical Upgrading of Bowie, Arizona, Sedimentary Sodium Chabazite

- Philip S. Neuhoff and Jie Wang
  Isothermal Measurement of Heats of Hydration in Zeolites by Simultaneous Thermogravimetry and Differential Scanning Calorimetry

- Etienne Balan, Emmanuel Fritsch, Thierry Allard, and Georges Calas
  Inheritance versus Neof ormation of Kaolinite During Lateritic Soil Formation: A Case Study in the Middle Amazon Basin

- M.V. Villar
  Water Retention of Two Natural Compacted Bentonites

- Fabienne Trolard, Guilhem Bournié, Moustapha Abdelmoula, Philippe Relait and Frédéric Fogerite, A New Mineral of the Pyrophyllite–Sowite Group: Description and Crystal Structure

CLAY MINERALOGISTS IN THE NEWS

Fibrous Minerals, Genetics, and Health

Mineralogists A. Umran Dogan1,2 and Meral Dogan3,4 participated in a recent study investigating the possible links between exposure to a zeolite-group mineral and mesothelioma. A summary of this work follows.

Erionite is a zeolite-group mineral and is categorized as a Group-I human carcinogen. Erionite—like some asbestiform minerals—is associated with mesothelioma, a rare lung disease with no known cure. Since 2000, morphological, compositional, and structural aspects of erionite from the Cappadocian region of Turkey have been studied in detail (Dogan et al. 2006 among many others).

Dogan et al. (2006) studied exposures to erionite in several Turkish villages with extremely high rates of mesothelioma. The original hypothesis was that individuals in certain homes in these villages were exposed to a more carcinogenic variety of erionite because mesothelioma occurs only in specific houses. However, Dogan et al.’s mineralogical studies indicated no significant differences in the erionite between affected and unaffected households, and pedigree studies indicated that malignant mesothelioma was prevalent in some families and not in others; they interpreted these results to indicate that mesothelioma development occurs in genetically predisposed individuals. This is the first time that genetics is shown to play a direct role in mineral fiber carcinogenesis.

The Dogan et al. (2006) study shows that quantitative mineralogical characterization can facilitate the interpretation of epidemiological data. Similar investigations of the mineralogy, morphology, chemical composition, and structure of a mineral as a function of different geological environments are also needed to help in the interpretation of regional- to national-scale epidemiological data sets. Epidemiological...
Professor Rolf Nüesch passed away on Christmas Day, 2006. Rolf was president of the DTTG, which is the clay minerals group of Germany, Austria, and Switzerland. He was the director of the Institute for Technical Chemistry, Water and Geotechnology Section, at the Forschungszentrum Karlsruhe, Germany, and a full professor of applied mineralogy. Born in Switzerland in 1954, he received his PhD at ETH Zurich in 1991 with a thesis on the mechanical behavior of Opalinuston. He took his position in Karlsruhe in 1999, where he established the divisions of environmental microbiology and nanomineralogy.

As a scientist, Rolf was highly creative and observant. For example, he noticed the formation of tiny bubbles and white spots when aluminum plates, used as XRD mounts for clays, were left to soak in water. He analyzed the bubbles and spots, found hydrogen gas and bayerite, and thereby discovered that clay could catalyze the corrosion of Al metal. He directed much of his research toward solving societal problems. Some of his ideas, at first sight, seemed strange, but he had the courage and persistence to carry them through. For example, he found a method for transforming anhydrite into gypsum in the quarry; the method involved using saline suspensions and reworking deposits with explosives and heavy machinery. He worked on a project to prevent scale formation in pipes by using intermittent magnetic fields—over 250 communities in Germany and Switzerland now rely on this system. He worked on improving the durability of construction materials for buildings and roads; on recycling phosphorous for agriculture; on prevention of ground water pollution from contaminated sites using bioleaching, biosorption, biomineralization, and bentonite liners; and on the delamination of kaolinite to develop a polymer-clay nanocomposite for use as a diffusion barrier.

As an administrator, Rolf was remarkable for his kindness. He was sometimes frustrated by administration, but was noted for his determination to find creative and humane solutions. He had a way of listening to all ideas and of finding a compromise that opened new opportunities. He loved to discuss and to argue, never taking personal offense, and he enjoyed good jokes.

Rolf is sorely missed by all who knew him, and our sympathy and love are extended to his wonderful family: to his wife, Ruth Hass, and to his children, Fabian, Simon, Sarah, and Stefan.

Peter Weidler and Dennis Eberl

studies would also benefit greatly from detailed modern mineralogical and geochemical characterization of the minerals in air samples collected from the living areas of potentially affected individuals.

REFERENCE

1 Department of Geological Engineering, Ankara University, Ankara, Turkey
2 Department of Chemical and Biochemical Engineering, University of Iowa, Iowa City, Iowa, USA
3 Department of Geological Engineering, Hacettepe University, Ankara, Turkey
4 Department of Civil and Environmental Engineering, University of Iowa, Iowa City, Iowa, USA

WORKSHOP LECTURE SERIES VOLUMES
THE CLAY MINERALS SOCIETY

4 Clay-Water Interface and its Rheological Implications (1993) 
N Güven, RM Pollastro (eds) 244 pp, ISBN 978-1-881208-04-4 
$23 ($18)

$23 ($18)

$20 ($15)

7 Scanning Probe Microscopy of Clays (1994) 
$26 ($21)

$23 ($18)

$23 ($18)

$26 ($21)

11 Teaching Clay Science (2002) 
$26 ($21)

$26 ($21)

$26 ($21)
Robert F. Martin of McGill University was awarded the Ambrose Medal at the annual luncheon of the Geological Association of Canada (GAC) in Yellowknife on May 23, 2007. The medal, named after the first GAC president, J. Willis Ambrose, was awarded to Bob for sustained dedicated service to the Canadian Earth science community as editor of *The Canadian Mineralogist*. We are delighted by this recognition from our sister organization and are pleased to reproduce the citation.

"Since 1982, Dr. Martin has been editor-in-chief of *The Canadian Mineralogist*. This Canadian scientific journal publishes research articles on minerals and ore deposits, not only in Canada, but also internationally. Most journal editors serve for 3 to 10 years, so Dr. Martin’s 25-year tenure has been an exceptional contribution to the entire Earth science community in Canada. In that time, he has raised the stature of *The Canadian Mineralogist* into the top ranks of international mineralogy journals. His detailed and thorough scientific editing has mentored many young scientists in how to clearly and concisely convey their most significant scientific results to other scientists.

"During Dr. Martin’s tenure as editor, the journal expanded from four to six issues a year and quadrupled the number of published pages—a success story that can be attributed to the respect the scientific community holds for the journal and the meticulous work of its editor. This was done while he maintained a role as a full-time professor, mineralogical researcher, and graduate student supervisor. In addition, he served as departmental chair at McGill for five years. In recent years his distinguished service and extraordinary contributions to the Earth science communities within Canada and abroad have been recognized by other societies, with the awarding of the Berry Medal from the Mineralogical Association of Canada (2001) and the Distinguished Service Medal from the Mineralogical Society of America (2004).

"Dr. Martin has impacted immensely on the Earth science community through his selfless efforts as ‘editor extraordinaire’ over the past quarter century."

Sarah Gleeson obtained a BA in geology from Trinity College, Dublin, and a PhD from Imperial College, London. She held postdoctoral positions at the Natural History Museum, London, and the University of Leeds. She is currently an associate professor at the University of Alberta. Sarah is primarily interested in hydrothermal systems and mineral deposits. She uses a range of geochemical techniques to recognize and trace paleofluid flow in crustal rocks. Much of her current research is focused on using the halogen and chlorine stable isotope compositions of fluid inclusion leachates to understand mineralizing processes and chlorine cycling in the crust.

Marc Constantin received a BSc and MSc in geology from Université Laval, Québec, and obtained a PhD in marine geosciences from the Université de Bretagne Occidentale, France. He was a postdoctoral fellow at the University of Toronto and Laurentian University and was appointed assistant professor at Université Laval in 2000. His research interests include the petrology, geochemistry, and metallogenesis of magmatic Ni–Cu–PGE deposits in mafic–ultramafic intrusions located in a variety of geological contexts, including high-grade metamorphic terrains in the Grenville and Superior provinces, massif-type anorthosites, and the Sudbury igneous complex. Marc was the 2005 president of the Québec section of the CIMM and he filled a vacant position on MAC Council in 2006–2007.

Michelle DeWolfe received her undergraduate degree in geology from St. Mary’s University, Halifax, in 2001. In 2003 she received a master’s degree in geology from Laurentian University, where she studied the morphology and emplacement of the North Rhyolite unit associated with the giant Kidd Creek volcanicogenic massive sulfide deposit (copper, zinc, tin, silver). Currently in the third year of her doctorate at Laurentian, Michelle focuses her research on the volcanic reconstruction of mafic to intermediate flows and associated volcanioclastic units directly overlying the massive sulfide deposits (copper, zinc, gold) at Flin Flon, Manitoba.
FROM THE QUEBEC CITY OFFICE

The Canadian Mineralogist in GeoScienceWorld

After deliberating for two years, MAC Council voted last May to become one of the participating publishers of GeoScienceWorld (GSW). The launch of our journal The Canadian Mineralogist is planned for July. The Millennium Collection will provide users with all issues of the journal from 2000. In addition, the archives of all back issues starting at volume 6 (PDF files only) will be posted on GSW. Individual MAC members who get an electronic or printed subscription to the journal will be given free access to our journal via GSW.

GSW has been very successful since its launch. In its first full year of operation, it has welcomed over 200 subscribers, the majority of which are consortia of several universities, and returned significant income to the participating publishers. By participating in GSW, we will be able to offer a much more sophisticated online access: both PDF and HTML files, reference linking, etc. Check www.geoscienceworld.org

New Short Course Volume – Geology of Gem Deposits

At the time of writing, MAC’s new short course volume on the geology of gemstone deposits has just gone to press. It is going to be a terrific volume, with many color plates at the end of most chapters. This volume of gemstone deposits has just gone to press. It is going to be a terrific volume.

Pierrette Tremblay
MAC Coordinator

AESRC 2007: CONFERENCE SUMMARY

The sixth annual Advances in Earth Sciences Research Conference (AESRC) was held on April 12 and 13 and organized by the graduate students of the Department of Earth Sciences, University of Ottawa, Ottawa, Ontario. The 2007 AESRC was entitled “Exploring the Earth Sciences: From Rocks to Rain” and consisted of two broad themes that reflected the expanding multidisciplinary nature of Earth sciences research. The “Solid Earth Sciences” theme focused on processes occurring in the Earth. The “Surficial and Environmental Sciences” theme involved processes that occur on the Earth. The two oral sessions were opened by keynote addresses by Dr. Mark Hannington, Goldcorp Chair in Economic Geology at the University of Ottawa and chief editor of Economic Geology, and Dr. Alfonso Rivera, chief hydrogeologist at the Geological Survey of Canada (Québec), program manager of the Earth Science Sector Groundwater Program, and adjunct professor at Université Laval. The student poster and networking session during Friday’s lunch was well received and featured information booths from the Canadian Society of Petroleum Geologists, the Canadian Water Network, and the Mineralogical Association of Canada.

The over 60 registered attendees included professors, students, and representatives from several universities and organizations.

Twenty-five students presented their research over the two days. Best oral presentation went to Emily Bamforth from Queen’s University and best poster presentation to Liz Ross from Carleton University.

Next year’s AESRC will be hosted by Carleton University in January 2008. For additional information contact Deanne van Rooyen (dvrooyen@connect.carleton.ca).

AESRC 2007 Organizing Committee

Geology of Gem Deposits

Mineralogical Association of Canada Short Course Volume 37

Editor: Lee A. Groat

Gem deposits are rare because in general the conditions that promote their formation are unusual and thus worthy of scientific study. Recently, modern geological and analytical techniques have been applied to gem occurrences in Canada and elsewhere, and our models and understanding of their formation are being radically altered. Short course volume 37 looks at gemstones from a geological perspective and reviews our current understanding of diamond, ruby, sapphire, jade, and emerald deposits and the lesser-known colored gems.


TABLE OF CONTENTS

1. Diamond – Thomas Stachel
2. The Geology and Genesis of Gem C...
THE FÉDÉRATION FRANÇAISE DE GÉOLOGIE IS BORN!

SFMC is one of the four founding societies of the new Fédération Française de Géologie (FFG). The other societies are the Société Géologique de France (SGF), the Union Française des Géologues (UFG) and the Comité National Français de Géologie (CNFG), which is the French representative in the International Union of Geological Sciences (IUGS).

Now, twelve French geological and Earth science societies are federated (in addition to the aforementioned: AFEQ, AHSP, ASF, CNF-INQUA, GFG, SAID, SGMB, and AFK). The objectives of the FFG are:

- To increase visibility at national and international levels
- To develop scientific, educational, and patrimonial activities
- To promote relations with the general public and decision makers for advances and challenges in Earth sciences

The constitutive assembly held in Dijon during the Réunion des Sciences de la Terre on 7 December 2006 elected an administrative council (four members from the founding societies and eight representatives from the other societies). One of the first activities of the FGF will be to prepare and coordinate the French program of the International Year of Planet Earth. An organizing committee was created, the CNF-IYPE, with D. Neuville as president (d.neuville@brgm.fr) and J. Y. Renaud as secretary (jyr@mnhn.fr).

The executive council is composed of the following members, from left: Guglielmina Oliveros-Toro, treasurer (AHSP); Alain Blieck, secretary (CNFG); Pierre Mauriaud, vice-president (UFG), and Alain-Yves Huc, president (SGF).

The SFMC Haüy-Lacroix Award for 2007 is open to PhD students (thesis completed in 2006) and will be presented in June 2007.

SOCIETY NEWS

For only 50 (35 for students) you will:

- receive by e-mail the electronic version (.pdf file) of the Bulletin de Liaison, which contains information and news from the society
- receive six issues of Elements magazine
- have free internet access to the European Journal of Mineralogy
- benefit from reduced fees for all SFMC activities and all activities organized by the new Fédération Française de Géologie

The SFMC Hauy-Lacroix Award for 2007 is open to PhD students (thesis completed in 2006) and will be presented in June 2007.
Association of Applied Geochemists

HIGHLIGHTING OUR PUBLICATIONS

The Association of Applied Geochemists (AAG) has a long history of publishing applied science in a variety of fields—it has been our strength for more than 35 years. We have two flagship publications: Geochemistry: Exploration, Environment, Analysis (GEEA) and Explore.

Geochemistry: Exploration, Environment, Analysis

Our recent arrangement with the Geological Society of London for the publication of our journal Geochemistry: Exploration, Environment, Analysis (GEEA) has been very productive. The editor-in-chief is Gwendy E.M. Hall (Canada) and the associate editors are R. Bowell (England), C.R.M. Butt (Australia), P. Freyssinet (France), and C. Reimann (Norway). The journal covers all aspects of the application of geochemistry to the exploration and study of mineral resources, as well as applications in related fields, including the environment. Topics include the description and evaluation of new and improved methods of geochemical exploration (sampling, analytical techniques, and methods of interpretation); geochemical distributions in and around mineralized environments; and processes of geochemical dispersion in rocks, soils, vegetation, water, and the atmosphere. Papers that seek to integrate geological, geochemical, and geophysical methods of exploration are particularly welcome. Given the many links between exploration and environmental geochemistry, the journal encourages the exchange of concepts and data, with a view to reconciling mineral resource development with environmental protection. Readers are encouraged to submit letters to the editor should they wish to comment on papers that have been published in the journal.

Communications with the editorial office of the journal should be sent to

EDITORIAL OFFICE MANAGER
Geochemistry: Exploration, Environment, Analysis
P.O. Box 26099, 72 Robertson Road
Nepean, Ontario K2H 9R0, CANADA
Tel.: 613-828-1222 • Fax: 613-828-2567 • E-mail: geea@sympatico.ca

Explore

The AAG’s newsletter, Explore, is a highly professional publication produced quarterly by a small group of volunteers led by editor Beth McClenaghan (Canada). The newsletter provides a forum for:

• The speedy publication of recent advances in exploration geochemistry
• Material on multidisciplinary applications, environmental geochemistry, and analytical technology.
• Case histories
• New concepts and modeling improvements
• Descriptions of recently discovered deposits
• The exchange of ideas and “lively” discussion on wide-ranging topics

• Reviews of new software and books
• Geoscience meeting and conference announcements
• Specific AAG issues and directions
• Bibliographies of recent geochemically oriented papers
• Advertisements by geochemical labs, consultants, computer and data service groups, etc.
• Information on other AAG publications and special book offers

To contribute to EXPLOR E, please contact Beth at bmcclena@NRCan.gc.ca. You may download PDF files of previous issues of the newsletter at the AAG website.

Explore Newsletter Editor Beth McClenaghan (GSC, Ottawa) (right) with her student, Gabby Budulan from the University of Ottawa, during their 2006 field season; they were collecting till samples for the GSC-CAMIRO indicator mineral case study around Ni deposits in the Thompson Nickel Belt, northern Manitoba (Canada).

GEEA editor Gwendy Hall (GSC, Ottawa) filtering and preserving well waters for an arsenic study in West Bengal

EXPLORATION’07

Exploration in the New Millenium

FIFTH DECEN TENNIAL INTERNATIONAL CONFERENCE ON MINERAL EXPLORATION – TORONTO, CANADA • SEPTEMBER 9–12, 2007

EXPLORATION’07 WILL REVIEW THE CURRENT STATE OF THE ART IN GEOCHEMISTRY, GEOPHYSICS, REMOTE SENSING, DATA PROCESSING, AND INTEGRATION. GIVEN THE INDUSTRY-WIDE EMPHASIS ON BETTER INTEGRATION OF SCIENTIFIC CAPABILITIES AND BUSINESS IMPERATIVES, THE MEETING WILL SEEK TO HIGHLIGHT THE STRATEGIC LINKS BETWEEN THE TECHNOLOGICAL AND COMMERCIAL SIDES OF THE EXPLORATION INDUSTRY, FROM PRIMARY ORE DISCOVERY TO RISK MANAGEMENT, THROUGH THE ENTIRE MINING CYCLE.

TECHNICAL PROGRAM: Plenary session: The Leading Edge • Plenary session: Technology-driven Discovery • Regional-Scale Geochemical Methods • Prospect-Scale Geochemical Methods • Frontiers in Geochemistry • Geophysics Airborne • Geophysics Ground and Borehole • Geophysics Inversion and Modeling • Applications Regional Exploration • Applications Mine Site Exploration and Ore Delineation • Applications 3-D Visualization and Data Integration • Plenary session: Putting Technology to Work – Linking Ore Deposit Models and Technology


WWW.EXPLORATION07.COM

SOCIETY NEWS
Type mineral specimens are the material used to obtain data for the original description of a new mineral species and are the only proof of the examinations. The definition of a type mineral specimen (ideally a holotype or cotype) is furthermore necessary to address doubts and questions that could arise from erroneous or incomplete original descriptions. Incompleteness can occur if the relevance of certain attributes of a new mineral were not known at the time of the original description or if scientific instruments necessary for the determination of certain attributes did not exist at the time.

In consequence – and for their historical value as a new discovery – such type mineral specimens are kept in permanent scientific depositories to guarantee their availability for scientific re-examinations and their professional curation at any time. Nowadays, the Commission on New Minerals, Nomenclature and Classification (CNMNC) of the IMA requires that the type material be deposited in a professionally curated museum when a new mineral species is accepted.

Currently the Mineralogical Museums and Collections Working Group of the German Mineralogical Society (DMG) is compiling a type specimen catalogue for type materials retained in Germany. The catalogue is available online at www1.uni-hamburg.de/mpi/typkatalog/. With this catalogue, the working group – a network of the numerous mineralogical collections and museums in Germany – preserves the inventory of German type mineral specimens for the future and offers the scientific community swift access to information and material. At this time, 201 of the expected 250 type specimens are compiled in the catalogue. The illustrated catalogue lists all type specimens currently present in German museums. The type minerals are described in detail. Entries offer information about the museums and scientists in charge of specimens and collection. Furthermore information about the nature of the type specimens and their associated minerals, references to their original descriptions and their history are given (Fig. 1).

In addition Type Specimen Catalogue Germany offers a free-download geo reference file, which links the type localities of the type specimens as well as the locations of the relevant German museums with the free software GoogleEarth. If GoogleEarth is installed on the computer, double-clicking on the downloaded .kmz file will start GoogleEarth and present lists of type specimens, type localities, and museums. By clicking on entries in those lists, GoogleEarth will navigate to the chosen locality (Fig. 2). Clicking on a mineral name on the GoogleEarth maps will redirect you to the Type Specimen Catalogue Germany.

Information about the type localities of many older type specimens are sparse, so the geo reference data are classified into three categories of accuracy: precise, near, and approximate. If you can help us with corrections or suggestions concerning the validity or accuracy of our coordinates of the type localities, don’t hesitate to send an e-mail to kurtz@mineralogie.uni-hamburg.de, subject “Type Catalogue.”

Jochen Schlüter
Reinhardt Kurtz
Hamburg, Germany
Italian Society of Mineralogy and Petrology

NATIONAL GROUP OF MINERALOGY

The National Group of Mineralogy (GNM – Gruppo Nazionale di Mineralogia) is an informal body that includes professors and researchers in mineralogy from Italian universities and from public and private research institutes. PhD students and graduates, as well as professors and researchers in related disciplines, are welcome to participate in GNM activities.

GNM was founded in 1991 to promote and coordinate didactic and scientific initiatives for the advancement of basic and applied knowledge in mineralogy. More specifically, the GNM aims are:

- To establish a reference for the mineralogical scientific community in relation to the various national (SIMP) and international (IMA, EMU, etc.) bodies
- To promote and spread mineralogical knowledge at all levels, by organizing schools, congresses, study days, etc.
- To provide information and coordination for members regarding initiatives of interest to mineralogy

In order to pursue these objectives, since 1992 GNM has organized Mineralogy Schools and Study Days, with the active involvement of the entire national mineralogical scientific community. Schools are mainly intended for PhD and undergraduate students, but they are also actively attended by young researchers. They address important issues of cutting-edge scientific interest, are presented by specialists in the sector, and are often complemented by field trips. So far 11 schools, with a typical duration of five days, have been organized.

Study Days are intended for a more varied public and are dedicated to teaching more general issues, including systematics, instrumental techniques, and applications. So far 17 Study Days have been organized.

Teaching material (as either PowerPoint presentations or text documents) is available at the GNM website (http://simp.dst.unipi.it/GNM/) for the more recent schools (Microstructures: Analysis and Applications to Geologic Materials, September 2006; Properties and Applications of Minerals at the Nanoscale, June 2004; Metallic Minerals and Metallurgy between Past and Present, June 2002; Phase Equilibria and Geothermobarometry, September 2001) and study days (The Amorphous State in the Mineral Kingdom, March 2005; Mineralogical Engineering, May 2003; Biominerals, November 2001).

In addition to these official initiatives, the Group has stimulated discussion among its members, promoted the creation of common national and international research programs, and contributed to initiatives for the coordination of teaching of all mineralogical disciplines at the university level.

The Group was born thanks to the efforts of several colleagues. A special mention should be made about the contribution of Curzio Cipriani, former director of the Natural History Museum at the University of Firenze, who has coordinated GNM activities since the beginning and who chaired the Group for a decade (1991–2000). GNM has since been chaired by Marcello Mellini, University of Siena (2001–2003), and Giovanna Vezzalini, University of Modena and Reggio Emilia (2004–2006). At the last GNM assembly (held during the SIMP national meeting, September 2006), Gabriella Lucchetti (lucchetti@dipteris.unige.it) was elected as the new president. She is a full professor of mineralogy at the University of Genova and will chair GNM for the next triennium (2007–2009). She will have the cooperation of board members Luciano Secco (secretary), Paolo Ballirano, Emanuela Cipriani, former director of the Natural History Museum at the University of Firenze, who has contributed to initiatives for the coordination of teaching of all mineralogical disciplines at the university level.

It takes its name from the medieval mining town of San Silvestro, now abandoned. It takes its name from the medieval mining town of San Silvestro, now abandoned. It takes its name from the medieval mining town of San Silvestro, now abandoned.

The school entitled Microstructures: Analysis and Applications to Geological Materials, organized under the auspices of SIMP by the Gruppo Nazionale di Mineralogia (GNM), in collaboration with the Gruppo Nazionale di Petrografia (GNP), Gruppo Nazionale Georisorse, Ambiente e Beni Culturali (GaBeC), and Gruppo Informale di Vulcanologia (GIV), was held in the conference centre of Villa Lanzi (Campiglia Marittima, LI), in the heart of the archeological park of San Silvestro, from 19 to 23 September 2006. The archeological park is a unique region in Tuscany, where one can find traces of mining and metallurgy dating from Etruscan times to the present. It takes its name from the medieval mining town of San Silvestro, now abandoned.
CERTIFIED REFERENCE MATERIALS DEVELOPMENT PROGRAMME

As current head of the IAG’s Certification Committee I would like to highlight our activities to the broader geochemical community, and Elements provides an excellent forum for doing exactly this. The history of our programme to develop new reference materials (RMs) got going in 2002 when the IAG established a committee devoted to the production of Certified Reference Materials (CRMs). The long-term goal of this initiative was to produce geologic RMs of the highest metrological standard which would be distributed to the global analytical community. Obviously, if all laboratories used the same calibration materials – be they rock powders for bulk analyses or glass and mineral samples for microanalytical work – and if their compositions were very well characterized, then the integration of results reported by multiple labs would become much more meaningful. Gone would be the days when each lab needed to rely on the quality of its own “in-house standards.”

From the very beginning this IAG initiative has striven to comply with the guidelines set out by the International Standards Organization (ISO). Thus, before setting out to produce and characterize new rock powders, it was mandatory for the IAG to define a formal protocol for the certification of new RMs. Under the leadership of Jean Kane, the Certification Committee’s first chairperson, such a protocol was published in Geo standards Newsletter in 2003. This publication outlined the procedure that the IAG would follow during the production, characterization and follow-on testing of the products it certifies; as such it is the most closely ISO-compliant protocol existing for RMs used for geoanalytical work. Then, in 2004, the IAG was granted official liaison status on ISO’s Committee on Reference Materials (ISO-REMCO), thereby giving the analytical geochemist a voice in the world of reference materials alongside other institutions such as the IAEA and UNESCO.

With a protocol in place, the next step was to assess its functionality under real-world conditions. The decision was made to evaluate the protocol using the OU-6 slate, which had been distributed in one of IAG’s earlier bulk powder proficiency testing rounds. This test was largely successful, and the results, in the form of a Certificate of Analysis for OU-6, were published in Geo standards in 2005. This first project also identified a number of practical issues related to the protocol, resulting in an update to the protocol, which is currently being prepared for publication.

The IAG’s Certification Committee has now turned its attention to the routine production of new CRMs, with the goal of releasing a new material every 12 to 18 months. Initially, we will develop rock powders for which our committee has identified a need in industry or basic research. Furthermore, the IAG is supporting other reference material producers in offering our services for the production of samples which carry an IAG Certificate of Analysis. So please watch for the release of our next CRM, scheduled for 2008: a harzburgite powder with certified concentrations for platinum-group and many other trace elements.

Thomas Meisels
(Thomas.meisels@mu-leoben.at)
Chairperson, IAG Certification Committee

REFERENCE MATERIAL MARKETING

Having developed a capability of producing new CRMs, the IAG needed to establish a mechanism for distributing the new materials. To fill this gap the IAG Governing Council voted in September 2004 to create a not-for-profit company, fully owned by the IAG, which was established under British law. And so IAGeo Ltd. came into being.

As one might suppose, formally registering a company and addressing such issues as obtaining a VAT registration number took some time. It was not until late 2006 that a web presence was launched at www.IAGeo.com. Since then it has been possible for analysts to order 40 g packets of the IAG’s first Certified Reference Material: the OU-6 Penrhyn Slate. This rock powder has certified abundances for 10 major and 35 trace elements and, in view of the low uncertainties quoted for these values, represents one of the best characterized silicate rock samples in existence. In the coming months the IAG also intends to start marketing material that remains from earlier rounds of its GeoPT proficiency testing programme. Though not of the same high metrological standard as OU-6, these materials may prove useful to labs wishing to establish new analytical techniques or needing material for general data quality assessment. We invite geochemists to periodically visit the IAGeo website to see what new material is on offer.

IAG’s philosophy is to use income generated by IAGeo, a not-for-profit company, to fund the production and certification of new reference materials while keeping the cost to the user as low as possible. Although it is expected that the data for future certifications will be donated by top analytical labs, substantial costs are nonetheless associated with such work. With contamination-free milling, blending and packaging of samples, and holding meetings of the IAG Certification Committee, the costs of producing a single CRM are significant. Analysts who place an order with IAGeo can rest assured that their purchase will contribute towards ongoing RM development.

Michael Wiedenbeck (michawi@gfz-potsdam.de)
IAG President and Member of Certification Committee

Geostandards Newsletter
http://geoanalyst.org

International Association of Geoanalysts
MESSAGE FROM THE PRESIDENT

The next three years will be a busy time for IAGC. This message provides a brief update on IAGC activities in 2007 and those planned for 2008 and 2009.

A Very Busy 2007

The IAGC 40th anniversary celebration will be held at the Earth Sciences Department at the University of Cologne (Germany) on Saturday 18 August (for agenda, see Elements 3: 139). The first set of IAGC awards will be announced at the ceremony, but will be presented officially on 22 August during the Goldschmidt Conference, at the Geochemical Society and European Association for Geochemistry awards ceremony. A formal business meeting of the IAGC Council, open to all members, will be held at the same location between 8:30 am and noon. Please send the IAGC business office an e-mail message if you plan to attend, so we know how many people to expect.

The 17th Annual Goldschmidt Conference will be held at the University of Cologne from 19 to 24 August. Although IAGC is not financially cosponsoring the meeting this year, we will be sponsoring and organizing two symposia. The first symposium will be a tribute to Al Levinson, one of the founders of IAGC, who passed away in December 2005. Entitled “Applied Geochemistry – From Brines to Diamonds: Memorial Symposium for A.A. Levinson,” it will be chaired by Brian Hitchon. The second symposium, “Continental-Scale Earth Surface Geochemical Mapping – Recent Progress and Future Directions,” is being organized by Clemens Reimann. Both of these symposia are “open” sessions consisting of volunteered papers.

The proceedings of the symposium in memory of Al Levinson will be published in Applied Geochemistry, with Brian Hitchon as guest editor. Manuscripts for inclusion in Applied Geochemistry should be submitted directly to Brian Hitchon (send three paper copies to Box 79088, Sherwood Park, Alberta T8A 5S3, Canada) and not in electronic form to Elsevier. The manuscripts should conform to the guidelines for authors provided on the back cover of Applied Geochemistry and will be reviewed to the same standards as regular manuscripts. The deadline for submission for this special issue is 1 September 2007. Manuscripts received after this date cannot be guaranteed inclusion.

Every three years since 1974, the Working Group on Water–Rock Interaction of the IAGC, one of our most long-lived and successful working groups, has conducted a conference in a different world setting. Scientists from all over the world will gather in Kunming, in the center of the Yunnan-Guizhou plateau of southwestern China, July 31–August 5 for the 12th International Symposium on Water–Rock Interaction (WRI-12; www.wri12.org). IAGC will have a booth and make a strong effort to recruit members at the conference.

The 7th International Symposium on Applied Isotope Geochemistry will be held in Stellenbosch, South Africa, from September 10 to 14, 2007. This is a meeting of the IAGC Working Group on Isotope Geochemistry and will be the first conference at which the new policy on registration fees for IAGC-sponsored meetings will be implemented (i.e. all participants will be charged a one-year IAGC membership as a part of the meeting registration fee), so the IAGC business office will not need to have a booth and make a recruitment effort at this meeting. For those interested in participating, the meeting website is http://academic.sun.ac.za/geology/aig7.htm.

IAGC will be present at the Geological Society of America annual meeting, which will be held in Denver, Colorado, October 28–31, 2007. We will have a booth at the meeting, and the recipients of the IAGC’s Vernadsky Medal, Ebelmen Award, and Hitchon Award will be showcased in the Affiliated Societies Gallery during the course of the meeting. IAGC will sponsor a session entitled “Sources, Transport, Fate, and Toxicology of Trace Elements in the Environment,” which will be co-chaired by LeeAnn Munk, Dave Long, and Berry Lyons. Additional information is available at the GSA website www.geosociety.org.

Three IAGC events in 2008

The major event on the IAGC calendar for 2008 is the 33rd International Geological Congress (IGC), which will be held in Oslo, Norway, August 6–14, 2008. A special session on geochemistry will be organized by Andrew Parker as a part of the International Year of Planet Earth and the IGC official technical program. The session will consist of two parts: (1) a historical review of geochemistry and its applications and (2) a series of presentations on future developments in geochemistry and its potential to solve environmental problems in the 21st century. Plans are underway to have the proceedings of these sessions published in book form by Elsevier. IAGC Council has already approved $5000 in financial support for this important initiative, and the Steering Committee of IYPE is being asked to provide matching funds.

The Statutes-mandated IAGC Quadrennial Council Meeting will be held during the 33rd IGC. With elections held during early 2008, the transition from the 2004–2008 to the 2008–2012 officers and council members will take place during this meeting.

The third IAGC event will be the 8th Conference on Geochemistry of the Earth’s Surface. Sponsored by the IAGC Working Group on Geochemistry of the Earth’s Surface, the UK Mineralogical Society, and the British Natural History Museum, this meeting will be held in London, UK, August 17–22, 2008 immediately following the 33rd IGC.

An Important New Initiative in 2009

Following approval by both the IAGC Council and the Steering Committee of the Association of Applied Geochemists, IAGC and AAG will join together to organize and conduct the 2009 International Applied Geochemistry Symposium, which most likely will be held in Denver, CO. It is anticipated that the meeting will feature an Ingrerson International Lecture and the presentation of the IAGC awards for 2009. If this initiative turns out to be successful in the opinion of both societies, the stage will be set for a full IAGC–AAG partnership in future International Applied Geochemistry Symposia.

I look forward to seeing many of you over the next three years at one of these various IAGC events.

Russell S. Harmon
Interim President
MINERALOGICAL SOCIETY OF POLAND

INTERNATIONAL EXHIBITION AND TRADE FAIR OF MINERALS, FOSSILS AND JEWELLERY

On December 2 and 3, 2006, the thirtieth International Exhibition and Trade Fair of Minerals, Fossils, and Jewellery was held by the Geological Museum of the AGH University of Science and Technology in Kraków. It is one of the oldest and biggest exhibitions in Poland, with around eight thousand visitors each time. The honorary patrons were the rector of the AGH, the dean of the Faculty of Geology, Geophysics and Environmental Protection AGH, the president of the Polish Mineralogical Society, and the Committee of the Miners’ Days at the AGH.

Several thematic collections were awarded a prize: “Minerals of Bajkal and Spitsbergen” (A. Pasek and A. Laskowska); “Agates of Lower Silesia, Poland” (P. Szczerbin); “Minerals of Morocco” (E. Mathia and P. Budzyński); “Minerals of the World” (J. Krzywda, K. Krzywda, and A. Górny); “Upper Carboniferous Fossilized Tree Trunks” (D. Stryjniak); “Jurassic Fossils from the Vicinity of Kraków” (W. Bogacz); and “Banded Chert Articles” (D. Wachowiak and J. Wachowiak).

The International Exhibition and Trade Fair of Minerals, Fossils, and Jewellery will be held again at the Academy of Mining and Metallurgy on June 9 and 10 and July 28 and 29, 2007, in Kraków.

ACCESSORY MINERALS IN-SITU: MICROANALYTICAL METHODS AND PETROLOGICAL APPLICATIONS

Kraków, Poland, 15-16 September 2007

Accessory minerals play an important role in petrological studies. They provide a wide spectrum of information on the P-T-t-d (pressure–temperature–time–deformation) evolution of rocks. The last decade was a time of significant advances in our knowledge of accessory-mineral reactions, advances that were accompanied by, and facilitated by, the development and application of new microanalytical techniques. This workshop will provide a forum to present and discuss new analytical techniques and their application to accessory-minerals research. Topics of interest include:

- Monazite analysis and dating by ion probe, proton microprobe, and electron microprobe
- Experimental techniques and new experimental data concerning accessory-mineral equilibrium and reaction processes
- Electron backscatter diffraction techniques and applications

The two-day workshop will include invited presentations, general discussion, presentations of analytical techniques, software, laboratory tours, and more.

Articles related to the workshop materials and presentations will be published in Mineralogia Polonica.

THE WORKSHOP REGISTRATION DEADLINE IS JULY 30, 2007

For further information, please visit www.ptmin.agh.edu.pl/Workshop/home.html
NEW VIEWS OF THE MOON

In the 1990s the Galileo, Clementine, and Prospector missions infused lunar science with new photographic, spectroscopic, and geophysical data: the South Pole Aitken basin was extensively imaged for the first time; the Th-rich Procellarum-KREEP terrain was recognized; and there were global measurements of surface composition, gravity, and shape. New Views of the Moon (NVM), edited by Bradley L. Jolliff, Mark A. Wieczorek, Charles K. Shearer, and Clive R. Neal, was conceived in large part to report on the advances fueled by these new data.

Although NVM reports on the quality of these data and their application in nearly every aspect of lunar science, NVM’s emphasis is the perspective these data provide. Most of the book consists of well-researched and well-balanced reviews of the major aspects of lunar science, which lead into state-of-the-art models, detailed discussions, partisan conclusions, and suggestions for future work.

What makes NVM different from many other reviews is that for many controversial topics there are two or more treatments. For example, lunar mantle composition is addressed separately in terms of seismology, melting models, and geochemistry. There is much repetition in these treatments, but not a lot of agreement. Ideally, one expects a streamlined, consensus judgment in a review, but such an endeavor inevitably eliminates much of the nuance that underlies opposing views. NVM retains nuance and promotes insight.

Finally, although NVM will be a valuable resource for planetary scientists for many years to come, it truly distinguishes itself in the final of the seven chapters with an exercise in imagination: what would our understanding of the Moon be like if we had explored it as we have Mars—only with satellites and rovers. Granted we would have been aware of the South Pole Aitken basin a lot sooner, but at what loss: radiometric ages, the Eu-anomaly, basalt and impact melt textures, regolith chemistry, siderophile elements, oxygen isotopes, the seismic network. NVM at once provides a hopeful view of the rich scientific rewards awaiting a return to the Moon, as well as a sobering view of where we might have gone if an earlier generation of planners had lacked vision.

John Longhi
Lamont-Doherty Earth Observatory
Columbia University
Palisades, NY


MINERALS ON CD AND DVD

Why buy a CD or a DVD on minerals in these days of widespread Internet use? I started looking at the Photographic Guide to Mineral Species and the Photo-Atlas of Minerals with this question in mind. Both are labors of love by committed mineralogists, mineral collectors, and developers; this has allowed keeping both products at very reasonable prices. Their focus is different, however, as one strives to illustrate as many mineral species as possible and the other concentrates on the more aesthetic members of the mineral family. Both would make an easy-to-use reference on minerals and provide a never-ending supply of mineral pictures to illustrate talks and lectures. (In both products, the photographers are the copyright holders of the photographs, and copyright permission would need to be obtained for official use.) I found both very easy and intuitive to use. Either would make a welcome addition to the bookshelf of anyone interested in minerals or teaching mineralogy or related topics. Read on to decide which one might be more suitable for you.

Photographic Guide to Mineral Species 2nd Edition

The CD-ROM Photographic Guide to Mineral Species by Jeffrey G. Weissman and Anthony J. Nikischer contains more than 7600 images, including some 750 images from world-renowned photographer Jeff Scovill and others. Like the first edition published in 1999, this CD-ROM emphasizes rare minerals, i.e. species rarely pictured in books and other media sources. Hence, 80% of the 4200 or so approved mineral species are shown on this CD. This is not surprising considering that one of the authors, Tony Nikischer, owns Excalibur Mineral Corporation, the largest dealer in rare species in the U.S. and, perhaps, the world. The Excalibur inventory contains more than 200,000 samples, and at any point in time, over 3100 different mineral species are in stock. According to the authors, photographs of at least 1500 minerals are available only on this CD. They are not necessarily the best samples of the given mineral but are representative of what a typical researcher or collector might encounter.

Interestingly, this CD will run on any computer with a CD player and a web browser like Netscape or Explorer, and no Internet connection is required. Image quality has also been improved to higher resolution standards for this version but is still quite variable. Of course, many of the mineral species illustrated are found only as tiny hard-to-photograph crystals.

A complete database of all approved mineral species published through the end of 2004 is included, courtesy of webmineral.com, making this CD a powerful reference work in an easy-to-access, simple format. The database provides a wide variety of information, including chemical formula, compositional data, physical and optical properties, crystallographic data, radioactivity, cataloguing information (validity, name origin, type locality, etc.), plus links to additional information available on the Internet. These data are given for every valid mineral whether pictured or not. Also of interest are the cross-references to obsolete names. Some information is available on mineral localities, but the treatment is not exhaustive.

Cont’d on page 220

The Photo-Atlas of Minerals Version 2.0

The Photo-Atlas of Minerals DVD is produced by the Gem & Mineral Council of the Natural History Museum of Los Angeles County. The project started in 1992 when project developer George Gerhold asked the executive council of Friends of Mineralogy to endorse the production of a video disk of mineral specimen pictures. Lou Perloff provided over 2000 of his mineral slides for the project, but funding was not obtained. Over the next three years George worked with IBM and National Geographic to produce some of the first multimedia CD ROMs, and in 1995, with this new experience, he decided to try again. Help was provided by Anthony Kampf, who brought his expertise and his credibility with the mineral community. Importantly he also brought financial support via the education budget of the Gem and Mineral Council of the Natural History Museum of Los Angeles County. The first version was launched at the Tucson Gem and Mineral Society Show in 1998. Four updates, at roughly 18-month intervals, contained data corrections, additional photos, and other refinements. In 2002, technological advances allowed work on version 2 to start. A new screen size was chosen, photos were reprocessed at higher resolution, and about 10,000 new photos were added. Version 2 was launched early this year.

The newly released DVD contains 16,000 high-resolution images. Coverage is not uniform: for many minerals there are no pictures, but for photogenic calcite there are about 400. Photographs of some 1600 mineral species have been provided by several well-known photographers and collaborating photographers, and minerals from more than 3500 different localities are represented. In order to reach the educational market, which version 1 did not do to any great extent, crystal form and atomic structure drawings (links provided by Steven Weber and Robert Downs) were added to this new version.

A wealth of information is provided on all minerals, including a pronunciation guide, crystal and atomic structure drawings, the origin of mineral names, and the standard descriptive and crystallographic data. Among the many different features are the ability to add one’s own images; the possibility of searching by properties, by localities, and by chemistry (though this is restricted to one element); and the possibility to set up slideshows based on certain criteria (macroscopic minerals, gemstones, inclusions, etc.).

Pierrette Tremblay
Québec, Canada

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November 11–16 18th International Symposium on Environmental Biogeochemistry (ISEB-18), Taupo, New Zealand. Web site: www.isebiogeochemistry.com/ISEBXXVIII.htm

November 19–23 Cities on Volcanoes 5, Shimabara, Japan. E-mail: convention@citiesonvolcanoes5.com; website: www.citiesonvolcanoes5.com

November 26–30 Materials Research Society Fall Meeting, Boston, MA, USA. Details: Duane Dimos; e-mail: dbdimos@sandia.gov; web page: www.mrs.org/s_mrs/sec.asp?CID=4749&DID=164574

December 4–7 8th European Meeting on Environmental Chemistry (EMECEB), Inverness, Scotland. E-mail: EMECEB@uhic.ac.uk; webpage: emec8.uhi.ac.uk

December 10–14 AGU Fall Meeting, San Francisco, California, USA. E-mail: meetingsinfo@agu.org; web page: www.agu.org/meetings

2008

January 22–25 Terrestrial Planets: Evolution Through Time, Ahmedabad, India. E-mail: djoncoff8@prl.res.in; web page: http://www.prl.res.in/~djoncoff8/


March 9–13 TMS Annual Meeting & Exhibition, New Orleans, LA, USA. E-mail: mtgserv@tms.org


April 6–10 American Chemical Society 235th National Meeting, New Orleans, LA, USA. E-mail: natlmtsac@sacs.org; web page: www.chemistry.org/portal/a/c1/s1/acsdisplay.html?DOC=meetings&%Scategory

April 20–23 AAPG Annual Convention and Exhibition, San Antonio, TX, USA. Web page: www.aapg.org/meetings/misc_mtg.cfm

May 12–16 ISA 2008 – 37th International Symposium on Archaeometry, Siena, Italy. Details: Isabella Memmi Turbanti; e-mail: memmi@uniisi.it; web page: www.unisi.it/eventi/isa2008


May 31–June 5 American Crystallographic Association (ACA) Annual Meeting, Knoxville, TN, USA. Details: Paul Butler, e-mail: butler@nist.gov; web page: www.mrs.org/meetings/mrsemail/ACA/meetingspg_list/futuremeetings.html


June 29–July 4 Gordon Conference on Geochemistry of Mineral Deposits, Il Ciocco, Italy. E-mail: gordon@edw.ethz.ch; websites: www.grc.org/conferences.aspx?id=0001113, www.grc.org/sites.aspx?id=10&tab=0

July 2008


July 13–18 Goldschmidt 2008, Vancouver, BC, Canada. E-mail: gold2008@the-conference.com; website: www.goldschmidt2008.org

July 14–18 Asteroids, Comets, Meteors 2008, Baltimore, MD, USA. E-mail: margaret.simon@juapl.edu; web page: http://acm2008.jhuapl.edu

July 28–August 1 Meteoritical Society Annual Meeting, Matsue, Japan. Details: Dr. Mitsuru Ebihara; e-mail: ebihara-mitsuru@c.metro-u.ac.jp; web page: www.metsco2008.jp

August 5–14 The 33rd International Geological Congress (IGC 33), Lillestrom (Oslo), Norway. Website: www.33jigc.org

August 17–21 American Chemical Society 236th National Meeting, Philadelphia PA, USA. Details: ACS Meetings, e-mail: natlmtsac@sacs.org; web page: www.chemistry.org/portal/a/c1/s1/acsdisplay.html?DOC=meetings&%Scategory

August 17–22 Geochemistry of the Earth’s Surface 8: Joint Meeting of the IAGC, MinSoc and the Natural History Museum (UK). Contact: M.E. Hodson, m.e.hodson@reading.ac.uk


August 18–24 IAVCEI 2008 General Assembly, Reykjavik, Iceland. Details: Dr. Armann Hoskuldsson, e-mail: armmh@hi.is; web page: www.iaavcei.org/meetings_w.html


September 7–9 10th International Conference on Mineralogy and Museums, Denver, Colorado, USA. Details: Paul Bartos; e-mail: pbartos@mines.edu

September 8–10 9th International Congress for Applied Mineralogy, Brisbane, Australia. Details: Alison M. McKenzie, e-mail: conference@ausim.com.au; website: www.icam2008.com/home.asp

September 8–12 Meteoritical Society Annual Meeting, Matsue, Japan. Details: Dr. Mitsuru Ebihara; e-mail: ebihara-mitsuru@c.metro-u.ac.jp

September 9–14 Second Central European Mineralogical Conference (11–14 September) and Workshop on Powder Diffraction Rietveld Refinement (9–10 September), Lower Silesia, Poland. Details forthcoming

September 24–28 4th Mid-European Clay Conference, Krakow, Poland. Details forthcoming; e-mail: gorniak@agh.edu.pl

October 5–8 Geological Society of America Annual Meeting, Houston, TX, USA. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings/index.htm

October 5–9 Materials Science & Technology 2008 Conference and Exhibition – MS&T ’08, combined with the American Ceramic Society (ACerS) 110th Annual Meeting, Pittsburgh, Pennsylvania, USA. Web page: www.ceramics.org/meetings/schedule.asp


The meetings convened by the societies participating in Elements are highlighted in yellow. This meetings calendar was compiled by Andrea Kozioł. To get meeting information listed, please contact Andrea at Andrea.Kozio@notes.udayton.edu.

29th FM-TGMS-MSA MINERALOGICAL SYMPOSIUM – CALL FOR PAPERS

The twenty-ninth annual Mineralogical Symposium sponsored jointly by the Friends of Mineralogy, the Tucson Gem and Mineral Society, and the Mineralogical Society of America will be held in conjunction with the Tucson Gem and Mineral Show, Saturday, February 16, 2008. The title of the symposium is “Classic United States Mineral Localities.” Presentations on descriptive mineralogy, paragenesis, classic and new locations, and related subjects are welcome. An audience of amateur and professional mineralogists and geologists is expected.

Authors wishing to present a paper should submit a 200–300 word abstract to Julian C. Gray, Weinman Mineral Museum, P.O. Box 3663, Cartersville, GA 30120; phone 770-386-0576, extension 415; fax 770-386-0600; e-mail juliang@weinman museum.org. Presentations will be twenty minutes in length including a brief question and answer period. Abstracts must be submitted by August 1, 2007 and will be published in The Mineralogical Record (subject to approval by the editor).

2008

January 22–25 Terrestrial Planets: Evolution Through Time, Ahmedabad, India. E-mail: djoncoff8@prl.res.in; web page: http://www.prl.res.in/~djoncoff8/


March 9–13 TMS Annual Meeting & Exhibition, New Orleans, LA, USA. E-mail: mtgserv@tms.org


April 6–10 American Chemical Society 235th National Meeting, New Orleans, LA, USA. E-mail: natlmtsac@sacs.org; web page: www.chemistry.org/portal/a/c1/s1/acsdisplay.html?DOC=meetings&%Scategory

April 20–23 AAPG Annual Convention and Exhibition, San Antonio, TX, USA. Web page: www.aapg.org/meetings/misc_mtg.cfm

May 12–16 ISA 2008 – 37th International Symposium on Archaeometry, Siena, Italy. Details: Isabella Memmi Turbanti; e-mail: memmi@uniisi.it; web page: www.unisi.it/eventi/isa2008


May 31–June 5 American Crystallographic Association (ACA) Annual Meeting, Knoxville, TN, USA. Details: Paul Butler, e-mail: butler@nist.gov; web page: www.mrs.org/meetings/mrsemail/ACA/meetingspg_list/futuremeetings.html


June 29–July 2 2nd International Congress on Ceramics, Verona, Italy. Web page: http://www.icc2.org/
Mineral collectors sometimes complain about the scarcity of field collecting opportunities due to mine closures, areas becoming off-limits, localities getting depleted, sites being paved over, etc. Because microscopic minerals are more common than their coarser brethren, they are relatively easy to find. Moreover, many mineral species are only found in the form of microscopic crystals. Therefore, to broaden one’s knowledge of mineralogy, a microscope becomes a necessity. A collector who does not utilize a microscope is missing out an opportunity to better understand minerals. Looking at a specimen under a microscope, one realizes that there are things of great beauty within an otherwise routine-appearing rock. The illustrated conichalcite specimen is a good example.

Conichalcite, CaCu(AsO$_4$)(OH), is a common secondary mineral with a habit of forming small radiating spheres. This specimen is from the Gold Hill Mine, Tooele County, Utah, U.S.A. Conichalcite from Gold Hill is, arguably, the world’s best. The Gold Hill Mine was opened in 1892 and produced arsenic, lead, copper, silver, and gold (Kokinos and Wise 1993). It is the type location for austinite, hidalgoite, and juanitaite. About fifty other mineral species occur there, making the mine well known to mineral collectors.

“All good things must come to an end” may apply in the case of the Gold Hill Mine, as it is scheduled for reclamation later this year. Considering the title of this feature, Parting Shot, images of conichalcite from Gold Hill are quite appropriate.

Patrick Haynes
Las Vegas

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