

Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology

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Carbon Dioxide Sequestration

DAVID R. COLE and ERIC H. OELKERS, Guest Editors

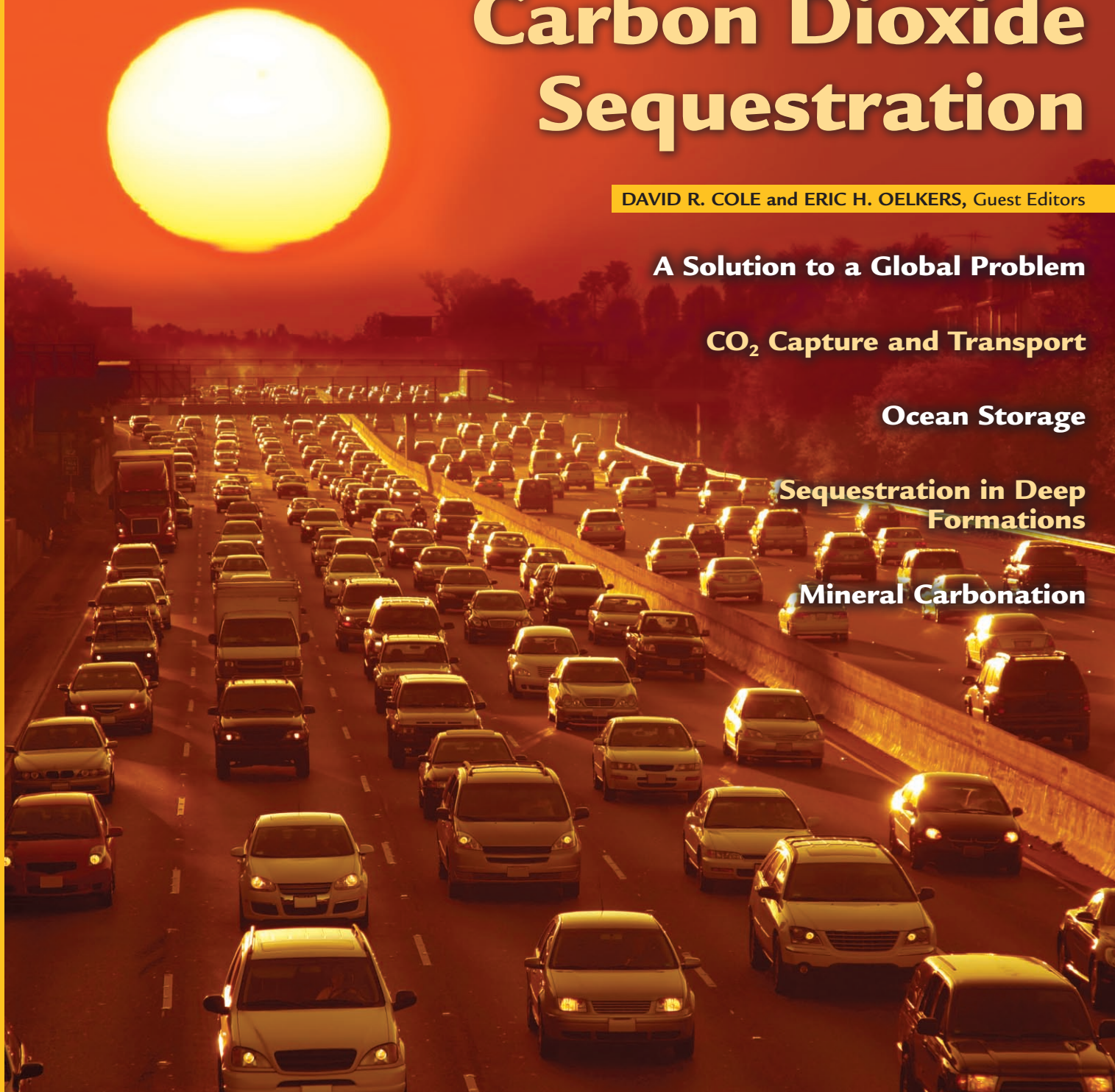
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Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology



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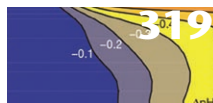
Carbon Dioxide Sequestration: A Solution to a Global Problem

Eric H. Oelkers and David R. Cole



CO₂ Capture and Transport

Edward S. Rubin



Ocean Storage of CO₂

E. Eric Adams and Ken Caldeira



CO₂ Sequestration in Deep Sedimentary Formations

Sally M. Benson and David R. Cole



Mineral Carbonation of CO₂

Eric H. Oelkers, Sigurdur R. Gislason, and Juerg Matter

ABOUT THE COVER:
Exhaust from traffic in Los Angeles, USA, and in other cities around the world contributes to the increasing budget of atmospheric greenhouse gases. Each car adds an estimated 2.7 metric tons of carbon dioxide (CO₂) per year. Atmospheric CO₂ concentration has increased to ~385 parts per million by volume from the preindustrial levels of approximately 280 ppm. While still controversial, many experts point to this increase as a primary cause of global warming. Feedbacks to increased global temperatures include stronger hurricanes, decreasing ocean thermohaline circulation, and rising sea levels. Unless aggressive measures are taken in the form of conservation, energy efficiency, and carbon capture and sequestration, we may trigger unexpected behavior in our global climate that will put humankind and the biosphere at risk. © ROZA / DREAMSTIME.COM

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The Mineralogical Society of America is composed of individuals interested in mineralogy, crystallography, petrology, and geochemistry. Founded in 1919, the Society promotes, through education and research, 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 series and Monographs, *Elements*, 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 an international society for all those working in the mineral sciences. The Society aims to advance the knowledge of the science of mineralogy and its application to other subjects, including crystallography, geochemistry, petrology, environmental science and economic geology. The Society furthers its aims through scientific meetings and the publication of scientific journals, books and monographs. The Society publishes three journals, *Mineralogical Magazine* (print and online), *Clay Minerals* (print and online) and the e-journal *MINABS Online* (launched in January 2004). Students receive the first year of membership free of charge. All members receive *Elements*.

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

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The Clay Minerals Society (CMS) began as the Clay Minerals Committee of the US National Academy of Sciences - National Research Council in 1952. In 1962, the CMS was incorporated with the primary purpose

of stimulating research and disseminating information relating to all aspects of clay science and technology. The CMS holds an annual meeting, workshop, and field trips, and publishes *Clays and Clay Minerals* and the CMS Workshop Lectures series. Membership benefits include reduced registration fees to the annual meeting, discounts on the CMS Workshop Lectures, and *Elements*.

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The Geochemical Society is an international non-profit organization for scientists involved in the practice, study, and teaching of geochemistry.

Membership includes a subscription to *Elements*, access to the online quarterly newsletter *Geochemical News*, as well as an optional subscription to *Geochimica et Cosmochimica Acta* (24 issues per year). Members receive discounts on publications (GS Special Publications, MSA, Elsevier and Wiley/Jossey-Bass) and on conference registrations, including the V.M. Goldschmidt Conference, the fall AGU meeting, and the annual GSA meeting.

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The European Association for Geochemistry was founded in 1985 to promote geochemical research and study in

Europe. It is now recognized as the premiere 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 Geochemistry (IAGC) has been a pre-eminent international geochemical organization for over 40 years. Its

principal objectives are to foster cooperation in, and advancement of, applied geochemistry, by sponsoring specialist scientific symposia and the activities organized by its working groups and by supporting its journal, *Applied Geochemistry*. The administration and activities of IAGC are conducted by its Council, comprising an Executive and ten ordinary members. Day-to-day administration is performed through the IAGC business office.

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The Société Française de Minéralogie et de Cristallographie, the French mineralogy and crystallography society, was founded on March 21,

1878. The purpose of the Society is to promote mineralogy and crystallography. Membership benefits include the "bulletin

de liaison" (in French), the *European Journal of Mineralogy* and now *Elements*, and reduced registration fees for SFMC meetings.

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The Association of Applied Geochemists is an international organization founded in 1970 that specializes in the field of applied geochemistry. 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, and encourage research and development. AAG membership includes the AAG journal, *Geochemistry: Exploration, Environment, Analysis*; the AAG newsletter, *EXPLORE*; and *Elements*.

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The Deutsche Mineralogische Gesellschaft (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 M. v. Laue, 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*, the DMG Forum, *GfM*, and now *Elements*.

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The Società Italiana di Mineralogia e Petrologia (Italian Society of Mineralogy and Petrology), established in 1940, is the national body

representing all researchers dealing with mineralogy, petrology, and related disciplines. Membership benefits include receiving the *European Journal of Mineralogy*, *Plinius*, and *Elements*, and a reduced registration fee for the annual meeting.

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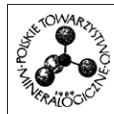
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The International Association of Geoanalysts is a worldwide organization supporting the professional interests of those involved in the analysis of geological and environmental materials. Major activities include the management of proficiency testing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

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The Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), founded in 1969, draws together professionals and amateurs

interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The Society promotes links between mineralogical science and education and technology through annual conferences, field trips, invited lectures, and publishing. There are two active groups: the Clay Minerals Group, which is affiliated with the European Clay Groups Association, and the Petrology Group. Membership benefits include subscriptions to *Mineralogia Polonica* and *Elements*.

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The Spanish Mineralogical Society (Sociedad Española de Mineralogía, SEM) was founded in 1975 to

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

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Affiliated Societies

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

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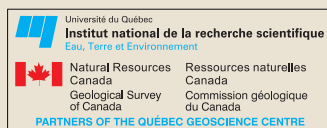
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THE CO₂ CHALLENGE – A CALL TO ACTION



Susan L. S. Stipp

Since we first walked upright and contemplated our destiny, humankind has recognised its struggle with Nature. Humans were fragile, at the mercy of wind, sun, water, hunger and disease. Our ancestors soon began to engineer their world, to build, to cut forests and plough, to rearrange water and rock, and to make ever more dramatic changes to the face of the Earth.

Civilisation developed, but people were still at the mercy of the elements. Even as late as the mid-eighteenth century, when Rousseau, Voltaire and other philosophers were debating Man and Nature, human existence was fragile. Now, our engineering has improved the quality of life, but has also triggered unexpected consequences that put humankind and the biosphere at risk. Nature has become fragile.

We learned to make fire and our thirst for energy began, but it was only when fossil fuels came into widespread use that the carbon cycle became unbalanced. Extra CO₂ in the Earth's atmosphere holds in heat, thus warming permafrost, promoting the release of more carbon dioxide and methane, increasing the heat-holding capacity of our global greenhouse. Global warming and climate change are one risk. In the air and in the sea, CO₂ reacts with water, forming carbonic acid, H₂CO₃, driving pH down. More acidic seawater is a second risk.

Concern about the effects of increased CO₂ is not a sudden development. I remember people talking about "heat pollution" more than 30 years ago. I remember my children having less snow to roll in than I had as a child. Many of us remember Bob and Betty Berner's book on the carbon cycle. Scientists have been publishing clear results for years, but society, government and industry did not hear the message. In the 1990s, models developed by John Edmonds and many others were predicting serious consequences if CO₂ emissions were not cut. I heard a talk by Fred Mackenzie at a conference in Granada in December, 2000, when he presented modelling results that showed that even if we stopped burning fossil fuel that day, global temperature increase would not be stemmed for many years. The message was clear that it was already too late to prevent global warming, but it took several more years before the message began to be heard. This is not a question of belief. One cannot ask if one "believes" in global warming the way one might ask another if he believes in Santa. Now, abundant evidence leaves little room for doubt that climate is changing. Eleven of the last twelve winters have been the warmest since record taking began. Ice over the Arctic Ocean and Antarctica is thinning. Continued warming will have dramatic and devastating consequences for populations living near sea level – for humans as well as biota.

One wonders what made society begin to hear the wake-up call. Was it more frequent and more violent storms and droughts than we remember? A documentary by a prominent American politician? The alarming number of threatened species? Polar bears drowning from exhaustion? It has become an emotional and controversial topic. In society, in the press and at scientific meetings, new ideas are being discussed, new technologies developed. Now, in some countries, there is a strong desire in industry and government to respond. There is talk of stronger global agreements. But there is also complacency – or worse, an attitude that it is "too expensive" to change our energy-greedy lifestyle. We are beginning to hear about models that promote a business-as-usual scenario, that optimise on the best adaptation strategies. People *are* adaptable – at least those who have resources. For those who do not, drought, flooding and changes in disease patterns will bring suffering.

In August, at a conference in London, I heard Fred Mackenzie speak again, this time on changes in seawater acidity. The pH of the world's oceans

has already dropped by 0.1 pH unit as a direct result of CO₂ uptake. Corals are already threatened, and other calcium carbonate-producing organisms will soon follow because CaCO₃ stability depends on pH. Fred talked about a "tipping point", when the buffer capacity of seawater is exhausted. The resulting pH drop would have dramatic consequences for marine organisms. An example is *Emiliania huxleyi*, a species of algae that blooms during the North Atlantic summer. It is characterised by elaborate, microscopic coccolithospheres of calcite.

The algae produce oxygen and fix carbon dioxide in mineral form. Species death caused by ocean water pH below that of calcite stability could alter global O₂ and CO₂ balances and remove a link in the food chain. There are many other examples. Ocean acidification puts biodiversity at risk.

The geological record might offer some comfort. It tells us that conditions on the Earth have never been constant. Climate has changed and species have evolved in response. Slow change has promoted diversity. However, the rock history book also warns us that catastrophic changes in conditions are accompanied by mass extinctions. The concern about warmer climate and more acidic oceans is that change is occurring very fast – too fast for species to adapt.

Of course we must stop burning fossil fuels and develop sustainable alternatives, such as wind, solar, wave and geothermal power. We should not be burning hydrocarbons; they are too valuable a resource for petrochemical production. But even if we stop burning oil, gas and coal tomorrow, it would take years for CO₂ concentration to return to early-twentieth-century levels. And we cannot stop using fossil fuels tomorrow. In this issue of

Humankind
has engineered
its way out of its
vulnerability in the
hands of Nature.
Now, we stand
with fragile Nature
under our feet.

Cont'd on page 292

THIS ISSUE

This issue presents the current state of science on the topic of CO₂ sequestration. Five thematic articles discuss the technical aspects and the logistical pros and cons of the various CO₂-storage options now being evaluated. This issue required extraordinary care and attention to detail because of its relevance to the ongoing debate about climate change, and Principal Editor Susan Stipp worked very hard with the guest editors and authors to ensure a timely and balanced coverage. We thank them all for their commitment and patience.

In this issue, our thematic coverage is preceded by three short pieces providing perspectives from industry, science, and the political domain. They set the stage for the articles that follow. We plan to use this format from time to time, when the subject matter would benefit from such a presentation.

ELEMENTS' 2007 IMPACT FACTOR AT 2.23

Since its first issue was published, in 2005, *Elements* has seen its impact factor climb from 0 to 2.23 in 2007. Considering the rate of increase, it is likely to continue its upward trend. Here is a list of the 10 most cited articles as of mid-September, 2008:

- Charlet L, Polya DA (2006) Arsenic in shallow, reducing groundwaters in southern Asia: An environmental health disaster. *Elements* 2: 91-96 (16 citations)
- Self S, Thordarson T, Widdowson M (2005) Gas fluxes from flood basalt eruptions. *Elements* 1: 283-287 (14)

- Harley SL, Kelly NM, Moller A (2007) Zircon behaviour and the thermal histories of mountain chains. *Elements* 3: 25-30 (13)
- Ohtani E (2005) Water in the mantle. *Elements* 1: 25-30 (13)
- Vaughan DJ (2006) Arsenic. *Elements* 2: 71-75 (12)
- Ferris JP (2005) Mineral catalysis and prebiotic synthesis: Montmorillonite-catalyzed formation of RNA. *Elements* 1: 145-149 (11)
- Morin G, Calas G (2006) Arsenic in soils, mine tailings, and former industrial sites. *Elements* 2: 97-101 (10)
- Campbell IH (2005) Large igneous provinces and the mantle plume hypothesis. *Elements* 1: 265-269 (10)
- Wignall P (2005) The link between large igneous province eruptions and mass extinctions. *Elements* 1: 293-297 (10)

SOCIETY NEWS HIGHLIGHTS

As managing editor, I get to read the society news pages several times, and I always find lots of interesting items. Here are some I found particularly interesting in this issue. The International Association of Geoanalysts reports that a new osmium isotope reference material is now available for distribution (page 346). The Mineralogical Society of Great Britain and Ireland announces that it will cease publication of *MinAbs Online* at the end of 2008. On page 343 you can read a succinct history of *Mineralogical Abstracts*, which has been published since 1920. The

Mineralogical Society of America reports on its plan for moving *American Mineralogist* to a paperless world (page 340). As most of the societies publishing a journal will eventually have to face this situation, we can take inspiration from their conclusions. I was also interested to read in the SFMC news (page 344) about the virtual gallery of mineralogy launched by the Museum National d'Histoire Naturelle. Relive or get a taste of the 2008 Goldschmidt Conference by checking the two-page spread provided by the Geochemical Society and the European Association for Geochemistry on pages 352 and 353.

MULTI-SOCIETY CATALOGUE

Our 2009 multi-society mineralogy/geochemistry catalogue is being mailed with this issue of *Elements*. This is the fourth catalogue we have published, and it is a collaborative effort among the participating societies. Please keep it as a reference for the coming year or give it to a colleague or student as an encouragement to join one of the participating societies. If each of us did this, the mineralogy-geochemistry-petrology community could double instantly. Imagine our impact! Membership in any of the participating societies includes a subscription to *Elements*.

Pierrette Tremblay, Managing Editor

We thank the Chemical Sciences, Geosciences and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy (DOE) for financial support of this issue.

EDITORIAL (Cont'd from page 291)

Elements, we present ways to remove CO₂ from the atmosphere and sequester it in a way that minimises risk to life at the Earth's surface. Also in this issue, we introduce a new feature called "Perspectives". The short articles, written by well-respected leaders from industry, academia and government, are intended to provide a platform that will stimulate constructive and cooperative discussion and development of solutions.

Humankind has engineered its way out of its vulnerability in the hands of Nature. Now, we stand with fragile Nature under our feet. Global warming is a serious concern. Increased acidity in the oceans is changing biological habitats.

It will take a concerted effort, and there will be tough choices for society, science, government and industry, in both the developed and the developing worlds. We need to reduce personal consumption of goods and energy. Society needs to accept responsibility and bear the costs of a lower-CO₂ world. We need serious commitment, now, from government and industry, at a global scale, but particularly from the developed countries. Hard decisions will require political and industrial leaders with courage, who are steadfast, especially in the shadow of a financial crisis.

The best way to meet the CO₂ challenge is through fundamental understanding of how our world works, in order to (1) provide the fastest and most direct way to develop sustainable energy-production methods and more efficient manufacturing, heating/cooling and transport, and (2) capture CO₂ from fixed-source contributors such as power plants and industry and convert it back to rock form, stable for geological time. A key is basic understanding of how rocks weather in the biosphere and how new minerals are formed. Our scientific community is the only one with the necessary set of skills to tell the world how to transfer carbon from the atmosphere into a stable environment. This is THE geochemical/mineralogical/petrological theme of the decade! How can we focus more of our creativity, training and academic positions on solving this problem? We have the opportunity – and a heavy responsibility – to pass to our children a world that they will be able to live in.

Western society has been dozing for 30 years, choosing to ignore the warnings, or believing they were wrong. They are not wrong. It's time to wake up, get our heads out of the sand, and do something.

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THE CHALLENGE OF CO₂ STABILIZATION¹

Steven E. Koonin², Chief Scientist, BP

Stabilizing atmospheric greenhouse gas concentrations by mid-century is one of the world's great challenges; it will require a complex mix of technology, economics, and politics. In order to appreciate what might be done to move toward that goal, I review the energy landscape as important context to understanding the political and technical steps that might be taken.



Steven E. Koonin

THE GLOBAL ENERGY LANDSCAPE

The world's demand for energy today is characterized by a large, slowly growing per capita consumption among the one-sixth of the global population that lives in the developed world and by a small, rapidly growing per capita consumption in the developing world.

Plausible projections to mid-century (FIG. 1) show growth of future demand driven both by the economic improvement of one-third of humanity and by population growth, from the present 7 billion to an approximate maximum of about 9 billion. Energy demand is expected to increase by some 40% by 2030 and almost double by mid-century, with 75% of this increase coming from the developing world.

Now, and in a future projected from historical trends, the great majority of the world's primary energy comes from fossil fuels. Coal, oil, and gas provide almost 80% of today's primary energy. Even though the use of renewable energy sources is expected to grow strongly, by 2030 it will still account for only a very small fraction of the world's energy

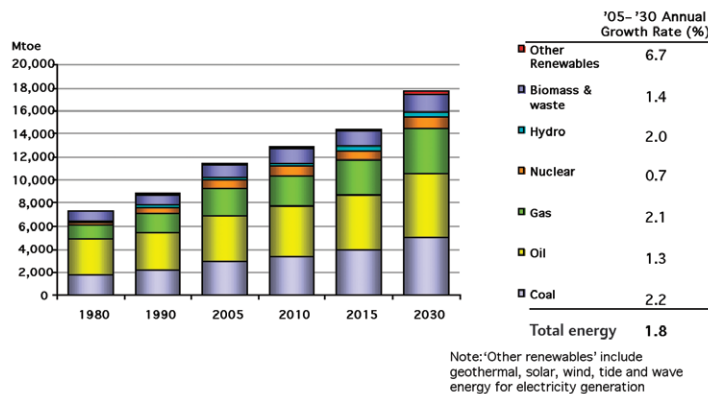


FIGURE 1 Global energy demand and supply through 2030. Mtoe = million tons of oil equivalent. SOURCE: IEA WORLD ENERGY OUTLOOK 2007 (REFERENCE CASE)

1 This paper contains material adapted from a Drell Lecture at Stanford University in January, 2008, and an Edison Lecture at the University of California at San Diego in July, 2008. A more complete presentation of some of the material can be found at <http://clients.mediaondemand.net/BP/>.

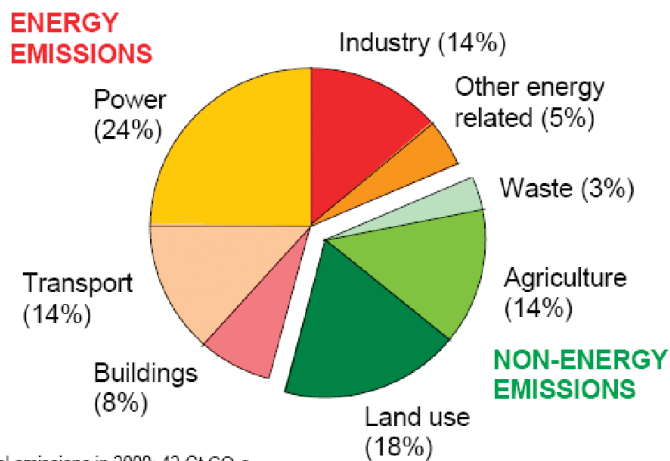
2 Steven E. Koonin has served as chief scientist of BP, the world's second-largest independent oil company, since 2004. As chief scientist, Koonin is responsible for BP's long-range technology plans and activities, particularly those "beyond petroleum." Koonin received his BS in physics at Caltech and his PhD in theoretical physics from MIT. In 1975, he joined the faculty of Caltech, became a full professor in 1981, and served as provost from 1995 to 2004. Koonin is a fellow of the American Physical Society, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences, as well as a member of the Council on Foreign Relations and the Trilateral Commission.

production. Projections show that for the next many decades, most of our energy will still come from fossil fuels, because of their availability, low cost, and ease of use.

At current consumption rates, 40 years of conventional oil and 60 years of gas are known to be economically recoverable, with further, equal amounts of each that will likely be identified. And there is at least 150-years worth of coal, conceivably much more. Among these various fossil fuels, oil is particularly important for transport because of its high energy density; on the other hand, coal is used almost exclusively for electric power generation, and gas consumption is split among power production, industrial processes, and building-heat applications.

The much-discussed "peaking" of oil refers to reaching a maximum in the production of conventional crude. Whether or not that occurs in the next several decades, there is a variety of sources from which other liquid hydrocarbons can be produced; these range from tar sand oil and shale oil to coal-derived liquids and biofuels, which can significantly supplement conventional crude production. The extent to which these alternatives will be deployed will depend upon economics, technology, and security of supply.

The conventional use of fossil fuels adds greenhouse gases (GHGs), predominantly CO₂, to the atmosphere, as shown in FIGURE 2. Indeed, 60% of anthropogenic emissions arise from energy production, of which roughly 40% each come from power and heat and 20% from transport. Agriculture and deforestation make substantial non-energy contributions to the balance. The various GHGs have a range of atmospheric lifetimes; CO₂ has the longest, on the order of a thousand years.



Total emissions in 2000: 42 Gt CO₂e.
Energy emissions are mostly CO₂ (some non-CO₂ in industry and other energy related).
Non-energy emissions are CO₂ (land use) and non-CO₂ (agriculture and waste).

FIGURE 2 GHG emissions by source in 2000

Greenhouse gases have accumulated in the atmosphere to the point where they are very likely contributing to the climate change we are observing, and they will likely influence the climate even more strongly as they accumulate further in the coming decades. While the detailed impacts of future anthropogenic climate change are not known, we do know broadly that they will cause disruptions and entail costs that could range from merely inconvenient to catastrophic. The much-discussed increase in global temperature, whatever it turns out to be, is not particularly reflective of the possible consequences. These include increased desertification and precipitation, shifts in vegetation and fauna, sea level rise, severe storms, and so on. These are not things we'd want to happen.

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The cumulative nature of the GHG problem implies that drastic reductions in emissions are essential if we are to make a meaningful impact on concentrations. The usual societal response of dealing incompletely with a problem will only delay—not prevent—dangerous conditions. Emissions by the end of this century must be reduced by about a factor of two from their current value if we are to have any hope of stabilization. This requirement flies in the face of an anticipated doubling of energy demand by the middle of the century. So we must cut the carbon intensity of our energy system by a factor of four or so.

Complicating the situation is the heterogeneity of the emissions rates across the globe. As is the case for energy, per capita GHG emissions in the developed world (OECD nations) are large but growing relatively slowly, while those in the developing world were, until recently, much smaller, but are rising rapidly, as shown in FIGURE 3.

From this figure and related data, it is easy to see that: (1) emissions from the developing world now exceed those from the developed world; (2) with current trends, every 10% reduction that the developed world makes in its emissions (something it has not yet managed to do) is offset by less than four years of growth in the developing world; and (3) if the per capita emissions of either China or India were to grow to be equal to those of Japan (one of the least emitting of the developed countries), global emissions would increase by 40%. This contrasts sharply with the 50% decrease required by the end of this century for GHG stabilization.

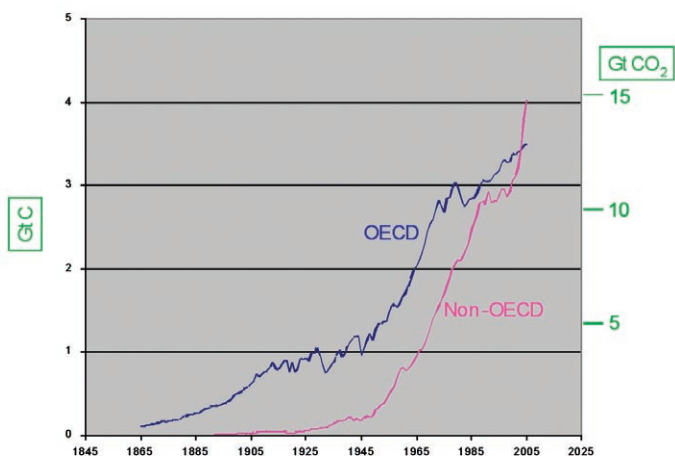


FIGURE 3 Annual CO₂ emissions from fossil fuels for OECD and non-OECD nations, 1865–2005. Source: Adrian Ross, October 6, 2008

MEASURES TO STABILIZE GHG CONCENTRATIONS

The picture painted by the factual discussion above suggests that it will not be a simple matter to stabilize atmospheric GHG concentrations. Three categories of measures could or should be taken to move toward that goal.

Promote Conservation

The most straightforward and cost-effective measure to reduce GHG emissions is conservation: the use of less energy. For example, about half of the world's energy is consumed in buildings for heat, light, and ventilation, and there are already many technologies that would enable this energy to be used more efficiently. Yet these technologies are not aggressively deployed, because of economic and social barriers.

Urban energy systems are another potential big win. Today, half of the world's people lives in big cities; by 2030, it will be 70%. Urban development with careful attention to building design, the integration of residential, commercial, and industrial spaces, and efficient transport systems for people, goods, and information could significantly reduce

energy use. However, greater efficiency does not guarantee conservation (for example, air conditioners that run with less energy would cost less to operate and thus lead to wider use). Higher prices and/or policies are needed to guarantee conservation, but these are politically difficult steps.

Decarbonize the Energy Supply

Assigning a serious cost to GHG emissions is an almost-essential policy measure, and this is now being implemented in some places around the world. Simple considerations show that in the developed world, a price of about \$50/t CO₂ would induce significant decarbonization (emissions reduction) of the energy supply, principally in power generation and heat. In transportation, reducing carbon emissions from mobile sources would require prices four to five times higher. This asymmetry is fortunate; stationary sources are responsible for 80% of energy-related emissions.

At a meaningful carbon price, the supply side of the heat and power sector would respond by increasing the proportions of gas power, onshore wind power, and nuclear power. Carbon capture and storage (CCS) will become increasingly attractive as a technology that can scale to a meaningful amount at reasonable cost. All of the above-ground elements of CCS have been demonstrated, but they have not yet been implemented on a commercial scale. The long-term integrity of below-ground containment is plausible, but also remains to be demonstrated. Monitoring criteria, liability, and public acceptance are all crucial issues to be worked on. The fully mature technology is expected to have costs comparable to those of nuclear power.

Several nations in the developed world are moving at various speeds toward pricing carbon, although it remains to be seen whether the price can be maintained at a high-enough level for a long-enough time to induce change. It is more difficult to imagine a meaningful price coming into effect in the developing world for many decades. Differing carbon prices around the world would surely impact trade patterns, industrialization, and outsourcing.

Adaptation and Geoengineering

Given the current energy landscape and its likely evolution, there is the possibility, if not the probability, that the world's best conservation and decarbonization efforts will not reduce emissions enough, and rapidly enough, to prevent concentrations rising above perceived dangerous thresholds. The obvious question "What then?" has seen little public discussion, perhaps for fear of distracting from the goal of mitigating emissions. Yet, given the realities, I believe it is irresponsible not to be considering this matter seriously.

Adaptation is already going on in parallel with mitigation efforts. Changes in infrastructure, agriculture, and behavior must be a major response to cope with a changing climate. Since adaptation can occur proportionally to the degree of climate change and since it is immediate in space and time, adaptation is likely to be the dominant response from society. There are reasons to believe that adaptation will be effective, given the extreme range of environments that humans already inhabit. However, it will be more difficult in the developing world, particularly in regions whose population lives at close to subsistence level (to say nothing about the risks to the biosphere).

And should the worst of the possible climate changes come to pass, geoengineering could emerge as the least bad of several bad choices. We are already intervening inadvertently in the climate system through GHG emissions. Other, more intentional, actions that one can imagine, such as removing GHG from the atmosphere through large-scale biosphere or thermochemical interventions or decreasing by a small amount the sunlight absorbed by the Earth, may offer a temporary, palliative response to a climate system gone awry. Apart from technical challenges, geoengineering presents difficult social issues, including questions such as "Who gets to decide?" or "What are the trigger points for intervention?" or "Who bears the liability for unintended consequences?" It is a route that future generations might very reluctantly consider as a last-ditch response to catastrophic climate change. ■

CO₂ CAPTURE AND STORAGE: POSSIBILITIES AND PERSPECTIVES

Wallace S. Broecker*, Professor, Columbia University

Few concerned with the need to stem the ongoing buildup of CO₂ in our atmosphere believe that this can be accomplished solely by some combination of conservation and non-fossil fuel energy sources. While both of these components are absolutely essential to any solution, even according to the most optimistic projections, they will fall short of the requirement to halt the CO₂ rise. Here, I present an objective description of solutions that have been proposed and end with my opinions, based on a long career of studying global chemical cycles.



Wallace S. Broecker at Hellisheidi, Iceland

The CO₂ rise must be halted, but the methods to accomplish this are still under debate. The facts are as follows. The growing demand for energy in developing countries certainly will far outstrip attempts at energy savings by the leading world powers. Coal will remain the cheapest source of energy for a very long time, and enough exists to fuel the planet for at least 150 years. The technology already exists to convert coal to gasoline at a cost less than what we now pay for petroleum. Thus, in the absence of some miracle that reduces the price of solar electricity or other renewable energy forms, additional options for halting the

CO₂ rise will be required. These options fit into a single category: CO₂ capture and storage (IPCC 2005). If we are to halt the rise in CO₂, we will have to implement technologies to capture it at its source in electrical power plants, and also to pull it back out of the atmosphere. And, of course, means for storing or disposing of this CO₂ will also have to be developed.

Evidence from studies of ice core and sediments demonstrates that since agriculture began ~8000 years ago, the climate has remained remarkably stable (Broecker 1997). This is in stark contrast to the preceding ~100,000 years, when there were very significant temperature fluctuations, from warm to glacial in just a few decades. Such rapid change suggests sensitivity to internal or external climate feedback. Also, the abrupt changes in paleotemperatures and atmospheric CO₂ concentrations (e.g. Petit et al. 1999) estimated from the ice and rock record may be telling us that the Earth's climate system has several distinct modes of operation and that it can jump from one mode to another in a matter of a decade or so. The only element of our climate system that has multiple modes of operation is the ocean's thermohaline circulation, which is sensitive to the fresh-water budget at high latitudes (Broecker 1997). This raises the question of whether the mode shifts revealed in the climate record were initiated by the oceans, and if so, what influence would there be from a rise in temperature driven by greenhouse gases (GHG). Increased polar ice melting from GHG-induced global warming could, in turn, influence thermohaline circulation. Rather than showing a linear evolution, the climate might follow a nonlinear path with sudden and dramatic surprises when GHG levels reach an as-yet-unknown trigger point.

* Wallace S. Broecker is the Newberry Professor at Lamont-Doherty Earth Observatory of Columbia University. He is internationally recognized for his research on climate change (*Elements* 3: 88 and page 300 this issue). He is a coauthor of *Fixing Climate: What Past Climate Changes Reveal About the Current Threat – and How to Counter It*, just published by Hill and Wang, New York.

OVERVIEW OF POSSIBILITIES

Capture of CO₂ Emissions from Electrical Power Plants

Currently, roughly one-third of the CO₂ produced from fossil fuel burning in the USA is emitted from electric power plants. Retrofitting coal-fired plants currently in use for CO₂ capture is in many cases more expensive than replacing these plants with a new breed in which coal is treated with steam, thereby creating carbon monoxide and hydrogen (Rubin 2008 this issue). These gases would be oxidized in fuel cells, creating CO₂ and H₂O as end products. But this option currently does not cover the remaining two-thirds of American fossil fuel energy use. Hence, were there only the capture option, some means of extending its reach would have to be developed. For example, automobiles could be run on the hydrogen or the electricity generated by these plants, or gasoline and jet fuel could be manufactured by combining the hydrogen and carbon dioxide.

Capture of CO₂ Directly from the Atmosphere

Lackner et al. (1999) point out that despite the fact that air contains far less CO₂ than the gas emitted from an electric power plant, the cost of capture is dominated by the portion that represents release of the CO₂ from the capture medium. Thus, capture from air is as feasible as direct capture from a smoke stack. Lackner et al. (1999) also point out that a wind turbine moving at a reasonable wind velocity would only have to be two orders of magnitude larger than a collector that captures CO₂ to compensate for the emissions from a diesel engine that generates the same amount of electricity. Hence, just as wind turbines are competitive, so also should be air capture. The problem is that no one has yet demonstrated that CO₂ can be captured from air at an acceptable energy cost. To my knowledge, only one serious effort is underway to develop such a system. GRT, a company in Tucson, Arizona, USA, has been working on this problem for almost five years. They claim to have found the key and promise that by 2010 a commercial prototype will be available.

CO₂ Burial in Spent Petroleum Reservoirs

At best, only about half of the petroleum contained in oil fields comes out easily. As this resource becomes ever more scarce, hence more expensive, it will become financially favorable to implement what is known as improved (IOR), enhanced (EOR), or tertiary oil recovery (Lake 1989). In one method, CO₂ is pumped into the reservoir, where it entrains part of the remaining petroleum, decreasing the oil's viscosity. The CO₂ is carried back to the surface and is then separated from the petroleum and reinjected. In itself, this is not a storage solution, but because large quantities of CO₂ are needed and must be transported to the reservoir, future demand by oil companies could provide a jumpstart for the commercial implementation of CO₂ capture and transport. Also, when the enhanced recovery process has run its course, the spent reservoir can become a CO₂ storage depot. Oil-reservoir storage is discussed in detail by Benson and Cole (2008 this issue).

CO₂ Burial in Saline Aquifers

Large regions of every continent are underlain by sedimentary rocks. Below a depth of a kilometer or so, the pores in sedimentary rocks are generally filled with hypersaline water, which is of no value for agriculture. A strategy for CO₂ disposal is to drill into these aquifers and pump in liquid CO₂, displacing the resident water. The Norwegian company Statoil is already successfully disposing of CO₂ separated from natural gas in such an aquifer beneath the North Sea (Torp and Gale 2004).

CO₂ Disposal in the Deep Sea

The ultimate fate of the majority of fossil fuel CO₂ is dissolution in sea water. There, it is neutralized to HCO₃⁻ by reacting with carbonate and borate and with the CaCO₃-rich sediment that covers much of the deep sea floor. However, the deep sea is ventilated on a time scale of many centuries, so little of the excess CO₂ produced during this century would be neutralized in this way. However, an option to short-circuit

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the slow delivery pathways is to pump liquid CO₂ down into the deep sea. CO₂ delivered to depths exceeding 3.5 km is denser than seawater and would sink to even greater depths (IPCC 2005; Adams and Caldeira 2008 this issue). Further, it rapidly reacts with seawater to form an even more dense clathrate slush, which would accumulate on the ocean floor and then gradually dissolve and disperse.

CO₂ Disposal in Basalt

Layered basalt provinces, such as the Columbia River sequence in the USA, the Deccan Traps in India, the Siberian Basalts in Russia, and many more, offer not only storage depots for captured CO₂ but, more importantly, a means of low-temperature mineralization. Water charged with abundant CO₂ reacts with basalt, releasing Mg bound in pyroxene and olivine, which then combines with carbonate to form highly stable MgCO₃ (magnesite). Water with lower quantities of CO₂ reacts with plagioclase, releasing Ca which forms CaCO₃ (calcite). While these reactions have been carried out in the laboratory and are known to occur in nature, many questions still exist about their kinetics and by-products (McGrail et al. 2006; Matter et al. 2007; Oelkers et al. 2008 this issue). What fraction of the CO₂ injected into basalts can react before it finds its way back to the surface? Do the carbonate minerals so formed clog the plumbing? Will alteration by-products (silica, clay minerals, zeolite, etc.) coat the surfaces, slowing the reaction between the CO₂-charged water and the rock? Clearly, experiments must be conducted to answer these and other questions.

Disposal in Lakes Beneath Ice Caps

Although very likely unacceptable from an environmental perspective, disposal of CO₂ in lakes beneath the Antarctic ice cap is certainly a geochemically sound storage option. At the temperatures and pressures prevailing in that environment, CO₂ would form a clathrate that would settle to the rock floor beneath the lake. Unlike disposal in the deep sea, the clathrates would not dissolve because, in the closed system of the lake, the overlying water would quickly become saturated in CO₂ gas. Although the formation of clathrates (6H₂O-1CO₂) would remove CO₂ from the lake's water, the heat released during their formation would melt a nearly equivalent amount of ice from the lake's roof.

Mineralization of Magnesium-rich Rocks

In the long term, it might turn out that the best option is to mine ultramafic rock (i.e. rock made almost entirely of magnesium and silicon oxides), grind it in a processing plant, and react it with captured CO₂ to form MgCO₃ (magnesite) (Seifritz 1990; Lackner et al. 1995). The products would be stored in the pits created by the mining. The main obstacle is to find a means to do it economically in terms of both money and energy costs (IPCC 2005).

Seafloor Disposal

Going a step beyond storage in the deep sea, it has been proposed that CO₂ be injected into the basalts that line the mid-ocean ridge crest or in CaCO₃-rich sedimentary sequences (House et al. 2006; Levine et al. 2007).

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A FEW WORDS IN PERSPECTIVE

After this brief, objective summary of capture and storage options, I now add my own opinions. These are based on a long career, much of it spent studying global geochemical cycles.

With regard to capture, I strongly favor direct capture from the atmosphere. For a number of reasons, I consider it an absolutely essential component of any strategy designed to stem the buildup of CO₂:

1. Because facilities for such capture are not linked to the energy grid, they can be located anywhere on the planet.
2. As envisioned by Global Research Technologies, GRT, the company in Texas developing this technology, the individual units will be "Toyota"-sized (each capable of capturing one ton of CO₂ per day), as opposed to "battleship"-sized coal-gasification facilities. As a result, they could be mass produced and more easily distributed. As is the case of automobiles, the design could be continually upgraded, making them ever more durable, efficient, and economical.
3. Once the rise in CO₂ has been stemmed, air capture can be used to bring the CO₂ content of the atmosphere back to an acceptable level.
4. Because some sort of international agreement regarding the distribution of future CO₂ emission rights will eventually have to be negotiated, as a bargaining chip, the rich nations could offer to remove a portion of the CO₂ released during the preceding decades. In this way the playing field can be leveled.

With regard to disposal, I lean toward the deep ocean as the most favorable early-stage option. However, in response to the strong Greenpeace stand against what they refer to as ocean "point pollution," little is being done to explore either the costs or the environmental consequences of this option. Their stand includes a threat to disrupt any attempt to conduct pilot experiments, so in a sense, they hold a pocket veto. I consider this to be an extremely unfortunate circumstance, and I have initiated a campaign aimed at convincing them to abandon such aggressive tactics.

I am also convinced that, in the long term, we must turn to solutions that involve chemical neutralization (immobilization) of CO₂, as opposed to simply storing it in gaseous form. Hence, I consider petroleum reservoirs and saline aquifers as interim storage solutions. Ultimately, we must learn to economically bind CO₂ with the magnesium and calcium contained in silicate rocks, whether it be under in situ or ex situ conditions. As a participant in the basalt storage project currently underway in Iceland (Oelkers et al. 2008 this issue), I have become aware of the complexity of the required research.

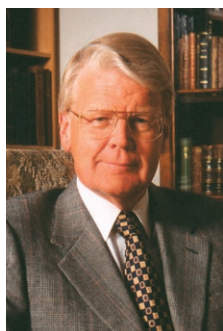
Looming in the wings is yet another technological fix designed to deal with the rise in greenhouse gases. It involves purposely altering our planet's albedo by delivering large quantities of SO₂ to the stratosphere (Wigley 2006). Once there, it would be oxidized to form H₂SO₄ aerosols. These aerosols would reflect sunlight away, thereby countering greenhouse warming. I do not consider this to be a solution, but rather an insurance policy against a bad CO₂ trip. As we have assumed the role of planetary stewards, we must strive to clean up our waste products, rather than treat them with Band-Aids!

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SOLVING THE BIGGEST PROBLEM

Ólafur Ragnar Grímsson, President of Iceland

Important decisions concerning the future direction of mankind must be based on the best available scientific knowledge. Real progress is achieved when we succeed in bringing together, for a common purpose, scientists and decision makers. In that spirit, I have supported cooperation between universities in Iceland, Europe and the United States aimed at sequestering carbon dioxide in basaltic rock, hoping that we can prove that it will stay there in solid form forever.



Ólafur Ragnar Grímsson, the President of Iceland

Over a decade ago, when I delivered as President my first New Year's Address to the people of Iceland, I emphasised the importance of dealing with the threat of climate change. I referred to the scientific work of Dr. Wallace C. Broecker, professor at Columbia University. At the time, I had never met him, but I was impressed by his research into the conveyor belt of the ocean currents and how it advanced our understanding of global climate.

When Wally Broecker and I subsequently met at the Global Roundtable on Climate Change, convened in New York at Columbia University, I discovered his interest in Iceland, and thus I decided to encourage cooperation among Wally,

his Columbia colleagues, Klaus Lackner and Juerg Matter, and outstanding Icelandic scientists.

It was both a pleasure and an honour to be able to invite Wally Broecker to Iceland to deliver the first Presidential Lecture, a new series which I initiated early in 2006. During his stay in Iceland, we decided to establish cooperation among the Icelandic scientific community, energy companies, environmental agencies and international experts to further Wally's idea of setting up a scientific consortium in Iceland which would conduct a pilot project on binding carbon in Icelandic basaltic rocks.

I believed that if we could succeed in getting such players interested in the project, it could lead to a major contribution from Iceland to the fight against climate change.

The Icelandic people have for centuries been proud of Iceland Spar, the mineral that shines like silver; in our language it is called "silver-rock". We know that it is formed through the interaction of carbon, oxygen and basalt. Thus it is exciting for us to find out whether this compound can be created in a special way; whether carbon dioxide can be bound chemically into a solid form underneath the beautiful Icelandic landscape instead of being released into the atmosphere.

We succeeded in establishing a fully fledged scientific project involving world-class scientists, professors, doctoral students and energy-company experts. They were all enthusiastic. It has been a great pleasure for me to work with Sigurður Reynir Gíslason and other professors at the



The CarbFix CO₂ injection site in southwest Iceland. The Hellisheidi power plant under construction is in the lower right, the moss-covered basaltic lava flow in the center of the figure, and the basaltic hyaloclastite (broken glass) mountains in the distance. The injection well is located in the lava fields in the upper left part of the photo. PHOTO: S. R. GÍSLASON



Helgi Arnar Alfreðsson, one of several PhD students in the CarbFix project, sampling one of the monitoring wells at the Hellisheidi site. PHOTO: E. S. EIRKSDÓTTIR

University of Iceland, the experts at Reykjavík Energy and foreign scientists, such as Eric Oelkers, who has been firmly behind the project from the very beginning.

It is still too early to predict a breakthrough from this intriguing project, but when international journalists or world leaders want to know more, my answer has always been: these outstanding scientists and experts would not be spending their valuable time on this effort if there was not at least a reasonable probability of success. When we know the results, and if they are positive, we will be able to engage in discussions with government leaders, scientific institutions, universities and other organisations in Russia, India, the United States and other countries where there are huge expanses of basaltic rock.

I welcome the opportunity to share these reflections with your readers and thus encourage scientists to work hand in hand with policy-makers in order to solve the biggest problem facing mankind at the dawn of the 21st century. ■

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UNDERSTANDING THE TRIPLE POINT

Timothy L. Killeen¹ and Teofilo (Jun) Abrajano²



Timothy L. Killeen



Teofilo Abrajano

A column called “Triple Point” is an apt venue for an essay on some of the biggest challenges in geosciences research today. The triple point of water is the intersection of the stability fields of vapor, solid, and liquid water, and understanding the

processes governing the distribution, transport, and storage of water in all its forms is one of the most compelling research challenges facing our community. The extent to which the water cycle varies in space and time is inextricably linked to other parts of the climate system, as well as to land- and water-use decisions. Hence, the confluence of three divariant fields at the triple point is a powerful reminder of the nexus of water-cycle research, climate-change prediction, and the healthful sustainability of the human environment.

Consider, for a moment, the dilemmas of our generation: the world’s population has doubled to over 6.5 billion in the last century; water use has accelerated about six fold over the same time frame; our climate is undoubtedly changing, although regional- and decadal-scale changes remain uncertain; and—a sobering reality—human impact now rivals natural processes in affecting mass transfer at the Earth’s surface. The flip side of these changes is the increasing demand for more precise prediction of water sustainability, ecosystem and soil quality, and human hazards (e.g. floods) on a regional scale and at human time frames. Is our community poised to make precise predictions about the response of the water cycle to our changing environment? Are our predictions sufficiently reliable to guide policies and plans for society?

So, yes, there are reasons for concern and urgency. The great majority of today’s active geoscientists were trained to be specialists and reductionists. We break down complex systems into fundamental component parts and we understand them at that level, and then we understand the whole by probing the summative interactions of the component parts. Traditional disciplinary field boundaries have developed in the science of the component parts. In the case of water, for example, meteorologists focus their attention on atmospheric phenomena affecting precipitation; hydrologists study water sources and transport on and beneath the ground; soil scientists focus on the reaction of water with weathered rocks; biogeochemists and ecologists worry about the coupled cycles of water, organic components, and nutrients; sedimentologists track water transport and deposition of soil and sediment particles; and geomorphologists are primarily concerned with the sculpturing of landscapes by water. Programs at research institutions have generally mirrored this intellectual alignment, and funding agencies have provided support for understanding the core science. This approach has served us well in the past and will continue to be the foundation of important

“The human right to water is indispensable for leading a life in human dignity. It is a prerequisite for the realization of other human rights.”

—U.N. Committee on Economic, Social and Cultural Rights

discoveries in the future. But large-scale issues need a sophisticated understanding of the non-linearly interacting parts. The difficulty of upscaling behavior and properties known at smaller scales has challenged traditional reductionist approaches, and we are only beginning to recognize the full complexity and emergent properties of larger Earth systems (e.g. large watersheds, regional basins).

The Earth’s surface is complex and dynamic, and a holistic understanding of its interacting parts is required if we are to make precise predictions of future water balance in any region of the world, under scenarios of changing climate and land use. This paradigm shift requires new tools and approaches, and regional-scale observatories and modeling of the coupled climate–water cycle at a compatible scale are at the core of the needed approach.

We must continue to make observations at many temporal and spatial scales to help drive our emerging theoretical understanding. Regional observatories focused on water balance and cycles are examples of an emerging large-scale observatory approach supported by the National Science Foundation of the U.S.A. For example, Earthscope is a downward-looking observatory that assesses surface movement and stress release at the subcontinental scale. Both the Ocean Observatory Initiative (OOI) and the National Ecological Observatory Network (NEON) will likewise be deploying cyber-accessible, interactive, remote systems to observe interconnected processes in the Earth’s ocean and terrestrial ecosystems, respectively. We use the word “telepresence” to indicate that such systems are here for all, and, in building these observing systems, we are accelerating our journey from sampling science to network science.

Terrestrial observatories (e.g. NSF-funded critical zone observatories and WATERS test beds) are in their infancy, but they are critical testing grounds for the development and deployment of new observational methods to predict coupled atmosphere–land processes and water balance in terrestrial environments at watershed-to-regional scales. These observatories are platforms for studying the fundamental water and surface processes in real time (i.e. hours, seasons, years, decades), and they are designed to uncover both long-term trends

and abrupt or extreme events. They will complement time-continuous remote observations that are already in place, as well as the observations of ecological processes that will be the focus of NEON. The deployment of such observation systems is also designed to study interconnected processes (atmosphere, hydrosphere, biosphere, pedosphere), and this will feed much-needed data to validate and constrain coupled, regional models of climate and the water cycle. Terrestrial observatories are purposely networked at the national scale in order to aid in understanding regional, continental, and global patterns. Hence, the key output of terrestrial observatories is a fundamental understanding of the interlinked parts: regional climate; spatial and temporal patterns of precipitation distribution; and the partitioning of precipitation among runoff, evapotranspiration, soil moisture, and groundwater recharge. This partitioning is specific to the regional landscape, ecology, soil lithology, development and land use, season, prior soil saturation, and the time–space heterogeneity of the precipitation events. This is important, challenging science.

Large-scale terrestrial observatories are unlikely to be a panacea for our current limitations in predicting the complex response of the water cycle to climate change and land- and water-use decisions. At the very least, however, they will be a major step towards understanding the improvements needed in our predictive capabilities and towards the development of strategies to reduce predictive-model uncertainties. Region-specific models and mechanistic generalizations derived from such models will be our main tools for predictions that need to be made at the scales required to inform policy and water-resource-management decisions. Ralph Waldo Emerson said: “Nothing great has ever been accomplished without enthusiasm.” We are going to need all our collective enthusiasm to succeed in solving these tough scientific challenges.

¹ **Timothy L. Killeen** is the Assistant Director for Geosciences, National Science Foundation since July 2008. Prior to this appointment, Killeen was director of the National Center for Atmospheric Research (NCAR) for eight years. He came to NCAR from the University of Michigan where he was professor of atmospheric and space sciences. Killeen received a BSc in physics and a PhD in atomic and molecular physics from the University College, London. Killeen is past president of the American Geophysical Union (AGU).

² **Teofilo (Jun) Abrajano** is the head of the Surface Earth Processes Section (GEO Directorate) at the National Science Foundation and, concurrently, professor and director of Environmental Science at Rensselaer Polytechnic Institute, Troy, New York. His research focuses on contaminant fate and transport in aquatic systems, biogeochemistry of marine and terrestrial freshwater systems, and Holocene paleo-climate/environments.

ABOUT MINERAL COLLECTIONS IN SMALL DEPARTMENTS

I read the "Triple Point" essay by Rodney Ewing, "Museums Are Not Attics" (*Elements*, August 2008), then thought about it for a while. Ewing only touched the tip of an iceberg. I am retired, but work part-time for the geology department (a small department with 4–5 full-time staff) at California State University, Bakersfield. During one quarter, I taught the mineralogy and petrology classes and had my nose rubbed in the working collection of minerals and rocks. There I found nice quartz crystals (without a label) in a coffee can; fine samples of twinned epidote pushed to the far back of a cabinet; a great example of chevron folds used as a door stop; an excellent technical sample of analcime in a pasteboard box tossed in with 40 miscellaneous, dirty rock samples; and hundreds of samples with no labels or documentation. I found these only because I was looking for example samples for my classes. I greatly doubt that such archival problems are unusual for small departments.

The geology department has one (shared) technician to care for the samples, as well as to provide equipment and support for all the laboratory classes. This explains the pasteboard boxes and coffee cans and the fact that one corner of a crowded supply room houses all the supplies and equipment for all the classes offered by the department. A year later, I proposed a solution:

- creation of a rock and mineral library (I used the term "library" instead of "collection" because the former more correctly indicates the function and purpose of the collection)
- donation of one half of my time (if I could have afforded it, I would have donated all of my time)
- development of a labeling system and a computer-generated documentation system that would be designed to facilitate addition of samples and system maintenance

- sorting and weeding out of the existing samples
- purchase of 50 lockable drawer cabinets that could be housed in a couple of rooms (this was the main cost)
- hiring of a student laboratory assistant for a year

I estimated the cost at about \$90,000 for one year, with minor upkeep once the system was set up. The department staff thought it was a great idea. The Science Division and the university didn't have the money and were not interested. I tried again two years later—same result. This was, of course, right when the university was developing a Division I athletic program (as opposed to a Division II program).

From the viewpoint of the rest of the university, what was the point? These were just rocks, and you can pick up rocks anywhere or buy them cheaply from any science supply house; nor would they disappear like some endangered species. Most of the rest of academia (also, unfortunately, many of our colleagues) do not understand the utility of carefully labeled, described, and preserved samples; nor do they appreciate the beauty and rarity of a 1.5 cm long, twinned crystal of epidote. On the other hand, we mineralogists and petrologists have not done a very good job of explaining the utility of such a "library."

If you really want to feel upset, multiply this by several hundred small geology departments around the world with inadequate support and space. My personal collection (from over 40 years of geology work) of mineral and petrology samples is worth ~\$5000 and is fully labeled and documented. There are a few very rare or world-class samples, but nothing a museum would want. I am 74 years old and not much longer for this world. Would I donate this collection to a small geology department? Knowing what I do, not very likely. Would I recommend that other people donate their samples to a small department? No. Do I cry? Yes, some.

Dr. Wallace Kleck
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BALZAN PRIZE FOR SCIENCE OF CLIMATE CHANGE TO WALLACE S. BROECKER



Wallace S. Broecker. PHOTO
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The International Balzan Foundation awarded one of its prestigious prizes to **Wallace S. Broecker** "for his extraordinary contributions to the understanding of climate change through his discoveries concerning the role of the oceans and their interactions with the atmosphere, as well as the role of glacial changes and the records contained in ice cores and ocean sediments. His contributions have been significant in understanding both gradual and abrupt climate change."

The goal of the International E. Balzan Prizes is to foster culture, the sciences and the most meritorious humanitarian initiatives of peace and brotherhood among peoples, regardless of

nationality, race or creed. Each prize has a value of one million Swiss francs (about 650,000 euros); half of the prize must be designated by the prize-winner for research work, preferably involving young scholars. The International Balzan Foundation was established in 1956 by Angela Lina Balzan in memory of her father, Eugenio Balzan, who was co-publisher for many years of the *Corriere della Sera*, an influential Italian newspaper. It awards four prizes every year in the fields of natural sciences, humanities, social sciences, and art.

A prolific researcher, teacher and author, Broecker has published more than 400 scientific articles and is the author or coauthor of several textbooks. He is the Newberry Professor of Earth and Environmental Sciences at Columbia University. Among his many awards and citations, Broecker was elected to the National Academy of Sciences in 1979. He is also a member of the American Academy of Arts and Sciences and a Fellow of both the American and European Geophysical Unions. In 1996, he was presented with the National Medal of Science by President Bill Clinton and he was the recipient of the Blue Planet Prize. He was also awarded the 2006 Crafoord Prize in Geosciences.

INAUGURAL IMA MEDAL TO CHARLES T. PREWITT

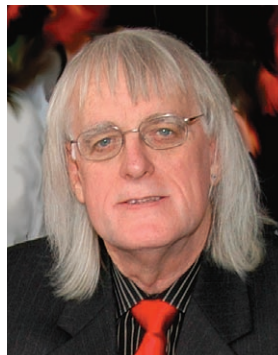


Charles T. Prewitt

The IMA is proud to announce that **Professor Charles T. Prewitt** of the Carnegie Institution has been designated as the first recipient of the IMA Medal for Excellence in Mineralogical Research. The IMA expressed admiration for his research eminence in developing a wide variety of new fields in crystal chemistry, materials science and mineral physics.

In crystallography he was one of the pioneers in the use of the single-crystal diffractometer, creating computer programs to handle diffraction data, and more recently in his use of synchrotron radiation for solving problems in mineral physics. In experimental techniques he was in the forefront of the development of new methods in high-temperature and high-pressure mineral synthesis. Charles Prewitt has not only produced an enormous number of extraordinary publications, he is also responsible for directing much larger research projects on an international basis. He was director at the Geophysical Laboratory in 1986–1999. His research on silicates and oxide materials, specifically, his development of the principles of ionic radii in these materials, has been highly influential in the Earth and materials sciences over the past 40 years. Charles Prewitt will receive the award and also give a lecture during the 2009 Goldschmidt Conference in Davos.

KILLAM PRIZE TO FRANK HAWTHORNE



Frank C. Hawthorne

Frank C. Hawthorne, University of Manitoba, was awarded the Killam Prize in Natural Sciences for 2008 by the Killam Foundation of the Canada Council for the Arts. Isaac Walton Killam was one of the most successful Canadian business and financial figures in the first half of the 20th century. His wife formed the Killam Foundation, which provides funds for the Canada Council for the Arts to award annual Killam Prizes in Natural Sciences, Health Sciences, Engineering, Social Sciences and Humanities. Worth \$100,000 each, they are among Canada's most prestigious awards. This is only the second time that the prize has been awarded to a geoscientist.

Frank Hawthorne's work on quantitatively predicting mineral stability as a function of chemical bonding at the atomic level has advanced mineralogy beyond traditional descriptive methods. He combines chemical theory and mathematics with new and innovative ways of understanding minerals. He has done groundbreaking research on crystal structures and crystal chemistry of complex minerals and has contributed to advances in a number of topical areas, including environmental mineralogy (e.g. the disposal of high-level wastes). Dr. Hawthorne has received many awards, including the principal medals for research from the Royal Society of Canada, the Mineralogical Association of Canada, the Mineralogical Society of Great Britain and Ireland, and the Geological Association of Canada. He was awarded a Canada Research Chair in Crystallography and Mineralogy (2001). He is an Officer of the Order of Canada (2006), and a Foreign Member of the Russian Academy of Sciences (2006).

DONALD B. DINGWELL NOMINATED TO ACADEMIA EUROPAEA

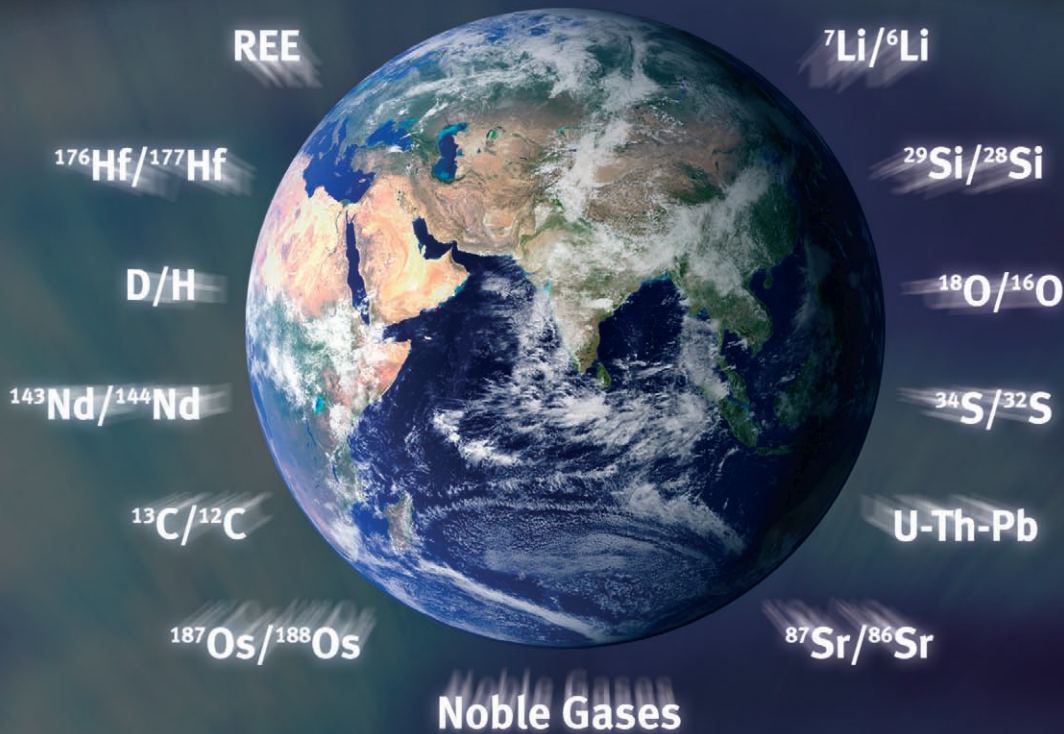


Donald B. Dingwell

Donald B. Dingwell has been named Chair of the Earth and Cosmic Sciences section of the Academia Europaea, Europe's Academy of Arts and Letters. The Academy is composed of 14 sections. Earth and Cosmic Sciences is one of the oldest, with over 300 members. The section chair represents the section in the Council of the Academy.

Dingwell is Chair of Mineralogy and Petrology at the LMU University of Munich and currently serves as the Director of Earth and Environmental Sciences. In 2007, he was awarded a research professorship via the Bundesexzellenzinitiative.

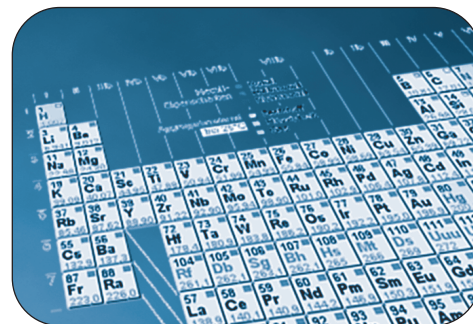
He has been a member of the Deutsche Mineralogische Gesellschaft for 20 years; he is also a member of the Mineralogical Society of America, the Mineralogical Association of Canada, and the Geochemical Society.



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KAREN L. VON DAMM (1955–2008)



Karen Von Damm, a full professor and world-renowned researcher in marine geochemistry at the University of New Hampshire, passed away at her home in Durham, New Hampshire, USA, on August 15, 2008, after being diagnosed with liver cancer in April, 2008. She was 53 years old.

Professor Von Damm received her BS degree in geology and geophysics in

1977 from Yale University, where she completed a senior thesis in geochemistry under the tutelage of Professor Karl Turekian. Karen's graduate studies were in the Woods Hole Oceanographic Institution (WHOI) and Massachusetts Institute of Technology (MIT) Joint Program in Oceanography, under the supervision of the late Professor John Edmond. She received her PhD in oceanography from WHOI-MIT in 1983. In her dissertation, she described the fluid chemistry of the first deep-sea high-temperature "black smoker" hydrothermal vents to be sampled on a mid-ocean ridge (on the East Pacific Rise at lat 21° N, and in Guaymas Basin, Gulf of California).

She subsequently spent two years as a National Research Council post-doctoral associate in the laboratory of Dr. James L. Bischoff at the U.S. Geological Survey in Menlo Park, where she conducted experiments to determine the solubility of quartz in seawater at elevated temperatures and pressures. Following this, Professor Von Damm spent four years as a staff geochemist and environmental scientist at the Oak Ridge National Laboratory in Knoxville, Tennessee. She concurrently was a research associate professor at the University of Tennessee in Knoxville, where she continued her research on mid-ocean-ridge hydrothermal systems. Since 1992, Professor Von Damm was on the faculty at the University of New Hampshire (UNH) in Durham, New Hampshire, as a professor of geochemistry in the Department of Earth Sciences and as a researcher at the Institute for the Study of Earth, Oceans, and Space. She also served briefly as an assistant director of the Complex Systems Research Center at UNH. Karen was highly committed to teaching thousands of UNH undergraduate students in oceanography and geochemistry courses, and to careful training of her graduate students and postdoctoral associates. In these capacities, she was a powerful role model for young female scientists. At the national level, she served as chair of the RIDGE Steering Committee from 1995 to 1998, and more recently

as chair of a committee to design a 21st-century research submersible for the U.S. science community. She was held in highest esteem by her students and by her colleagues at UNH and around the world.

Professor Von Damm's seagoing and laboratory research forms the cornerstone to our understanding of seafloor hydrothermal systems and was crucial to the spectacular advances made in this field since the discovery of scalding "black smoker" hot springs on the mid-ocean ridge in 1979. Exploration of hydrothermal vents along the mid-ocean ridge was one of the most important developments in marine science during the last quarter of the 20th century, because this research changed preexisting paradigms for the chemical budget of the oceans, accretion of oceanic crust along the mid-ocean ridge, biology of the deep sea, and origin of life on Earth. Much of what was learned depended directly or indirectly on accurate measurements of the temperatures and compositions of vent fluids, which were made by Professor Von Damm and her students and coworkers on samples collected in three oceans (Pacific, Atlantic, Indian) during hundreds of submersible dives to the deep ocean floor. Karen's careful analyses and innovative data interpretation were groundbreaking, and they illuminated linkages between the chemical, physical, and biological processes controlling marine hydrothermal-fluid properties and chemical fluxes. In 2002, Professor Von Damm was elected as a Fellow of the American Geophysical Union (AGU) for her "unparalleled contributions to exploring and understanding the chemistry of submarine hydrothermal systems, and for her leadership and service to the mid-ocean-ridge scientific community." This is a significant honor, since only 0.1% of the AGU membership (totaling 48,000 scientists in 2008) can be elected an AGU Fellow. In 2008 Professor Von Damm also was elected Fellow of both the European Association for Geochemistry and the Geochemical Society. From 1991, Professor Von Damm was engaged in exciting studies of how the fluid chemistry at hydrothermal vents changes with time, before, during, and after mid-ocean-ridge volcanic eruptions. She and her colleagues received grants from the National Science Foundation (NSF) to monitor the East Pacific Rise at lat 9–10° N, which is the only location on the mid-ocean ridge where two successive volcanic eruptions have been observed (in 1991–1992 and 2005–2006) and is one of only four "Integrated Study Sites" being studied under the auspices of the NSF Ridge 2000 Program. In addition to the many research articles that Professor Von Damm published in scientific journals, expeditions in which she participated have been featured in venues for the general public, including educational broadcasts on public television, IMAX films, Internet websites, and an ocean-science encyclopedia.

Professor Von Damm conducted her extensive teaching and research despite lifelong health problems. She was brilliant and dauntless, and had great intellectual and personal integrity. Karen will be missed immeasurably by the many people whose lives and work were influenced by her and by her contributions to science. She is survived by her mother, Louise, who supported and nurtured Karen through her career and illness.

Dr. Rachel Haymon

University of California, Santa Barbara



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Meet the Authors



E. Eric Adams is a senior research engineer in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology. He holds degrees from Harvey

Mudd College (BS) and MIT (MS and PhD). His professional interests include environmental fluid mechanics, physical and mathematical modeling of pollutant transport and mixing, and the design and environmental evaluation of effluent disposal systems. His recent research has focused on multiphase plumes with applications to ocean carbon sequestration, the fate of deep-sea oil spills, and dredged material disposal.



Sally M. Benson is the executive director of Stanford University's Global Climate and Energy Project and a professor (research) in the Department of Energy Resources

Engineering in the School of Earth Sciences. She is an internationally recognized expert in the storage of carbon dioxide in geological formations and was a coordinating lead author for the IPCC Special Report on Carbon Dioxide Capture and Storage, published in 2005. She is currently the coordinating lead author of the chapter on carbon dioxide capture and storage for the Global Energy Assessment (GEA). Benson graduated from Barnard College with a BA in geology. She completed her MS and PhD at the University of California, Berkeley, in materials science and mineral engineering.



Ken Caldeira is a climate scientist and chemical oceanographer at Carnegie Institution's Department of Global Ecology at Stanford University since 2005. He studies the global

carbon cycle; marine biogeochemistry and chemical oceanography, including ocean acidification and the atmosphere/ocean carbon cycle; land cover and climate change; the long-term evolution of climate and geochemical cycles; and energy technology. Caldeira was a coordinating lead author of an Intergovernmental Panel on Climate Change (IPCC) report on carbon storage in the ocean. From the early 1990s to 2005, he was with the Energy and Environment Directorate at the Lawrence Livermore National Laboratory. Caldeira received his

BA from Rutgers College and both his master's (1988) and PhD (1991) in atmospheric sciences from New York University.



David R. Cole is a Distinguished Staff Scientist and head of the Aqueous Chemistry and Geochemistry Group in the Chemical Sciences Division at Oak Ridge National Laboratory,

Tennessee. He obtained his PhD in geochemistry and mineralogy from the Pennsylvania State University. His research interests include the application of conventional stable isotope and ion microprobe techniques to problems of transport in high temperature magma-hydrothermal systems, diagenesis in sedimentary basins, alteration in geothermal systems, and paleoclimate reconstruction. He has been engaged in both bench-scale and field-scale studies of water-rock interaction relevant to subsurface CO₂ injection. He is an associate editor of *Geochimica et Cosmochimica Acta* and *American Mineralogist*. He is the International Program Chair for the 2010 Goldschmidt Conference to be held in Knoxville, Tennessee.



Sigurdur Reynir Gislason is a research professor and chair of the aquatic geochemistry group at the University of Iceland's Institute of Earth Sciences, where he studies

water-rock, water-air and water-biomass interactions by field and laboratory experimental studies. Gislason was educated at the University of Iceland and at the Johns Hopkins University, USA, where he earned his PhD in geochemistry in 1985. He is the chair of the scientific steering committee for the CarbFix project. He currently serves on the editorial board of *Chemical Geology*, and he chairs the Geochemistry of the Earth's Surface (GES) Working Group of the International Association of GeoChemistry.



Juerg Matter is a Doherty Associate Research Scientist at the Lamont-Doherty Earth Observatory of Columbia University in New York, USA. Juerg studied Earth sciences at the Swiss

Federal Institute of Technology in Zurich (ETHZ), Switzerland, where he received a Master of Science degree before completing his PhD in natural sciences at ETHZ. His

main research interests center on permanent carbon dioxide sequestration through mineralization in reactive rocks, including basalt and ultramafic rocks, and through storage in suboceanic sediments. He is currently working on assessing the in situ mineral-carbonation potential of basalt and ultramafic rocks and is developing monitoring techniques to trace CO₂ transport and reactivity in the geologic subsurface. He is involved in several geologic sequestration field projects in the U.S., Iceland, Oman, and India.



Eric H. Oelkers is a research director at the CNRS in Toulouse, France. Eric received BS degrees in chemistry and in Earth and planetary science from MIT

before completing his PhD at the University of California, Berkeley. He is currently president of the European Association for Geochemistry, coordinator of the MIR and MIN-GRO European Research and Training Networks, and member of the Scientific Steering Committee of CarbFix. Eric's research is aimed at providing the fundamental basis for sustainable development. This research includes developing the thermodynamic and kinetic framework for (1) predicting the fate and consequences of CO₂ during sequestration efforts, (2) enhanced oil recovery, (3) understanding ore-forming processes, and (4) toxic/radioactive waste immobilization.

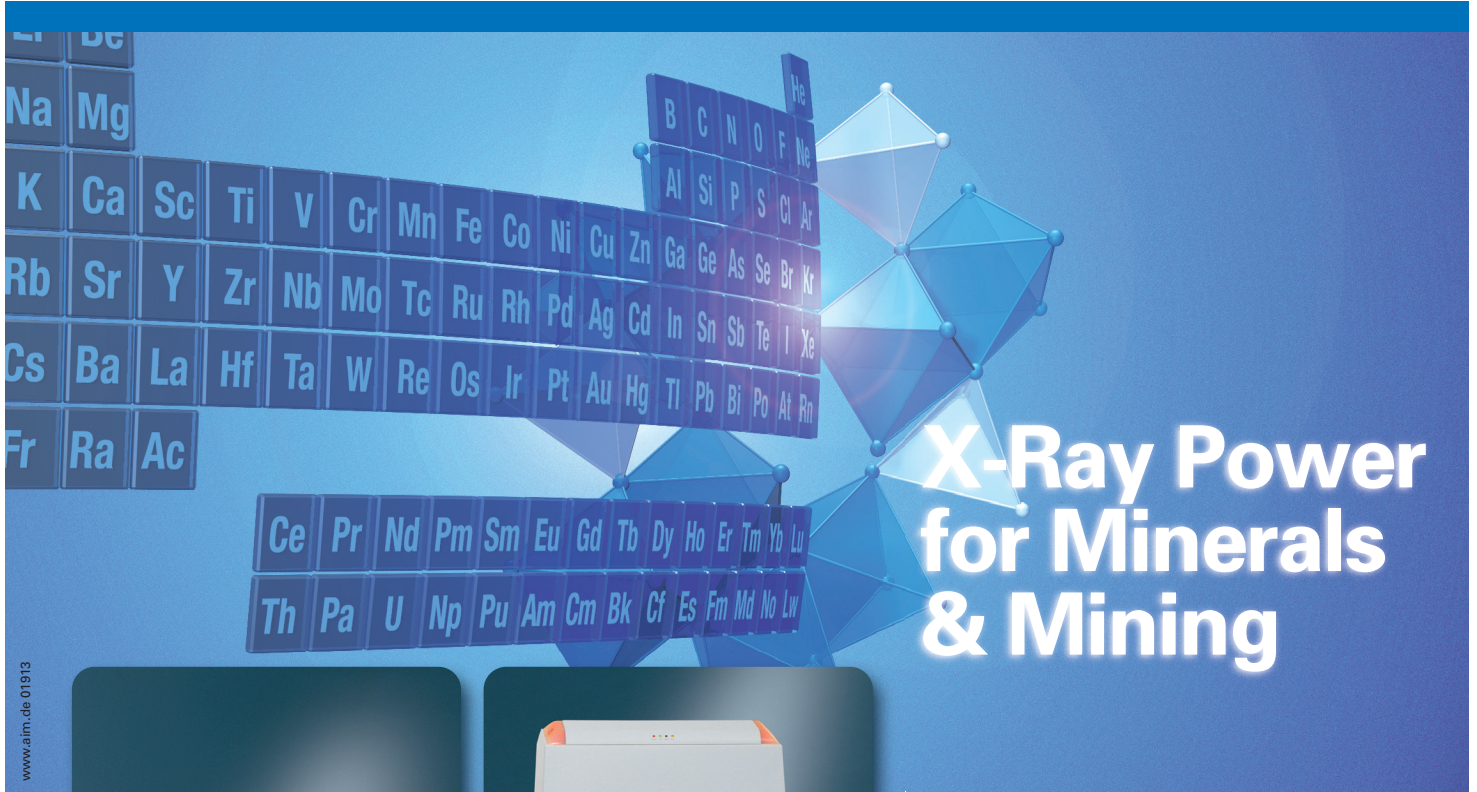


Edward S. Rubin is the Alumni Professor of Environmental Engineering and Science and holds joint appointments in the departments of Engineering and Public Policy and

Mechanical Engineering at Carnegie Mellon University. He was founding director of the Center for Energy and Environmental Studies and the Environmental Institute. He was a coordinating lead author of the Special Report on Carbon Dioxide Capture and Storage by the Intergovernmental Panel on Climate Change (IPCC). He serves on advisory committees of the U.S. Department of Energy, the U.S. National Academies of Science and Engineering, and the National Research Council's Board on Energy and Environmental Systems.



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Eric H. Oelkers¹ and David R. Cole²

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Human and industrial development over the past hundred years has led to a huge increase in fossil fuel consumption and CO₂ emissions, causing a dramatic increase in atmospheric CO₂ concentration. This increased CO₂ is believed to be responsible for a significant rise in global temperature over the past several decades. Global-scale climate modeling suggests that the temperature increase will continue, at least over the next few hundred years, leading to glacial melting and rising sea levels. Increased atmospheric CO₂ also leads to ocean acidification, which will have drastic consequences for marine ecosystems. In an attempt to solve these problems, many have proposed the large-scale sequestration of CO₂ from our atmosphere. This introductory article presents a summary of some of the evidence linking increasing atmospheric CO₂ concentration to global warming and ocean acidification and our efforts to stem this rise through CO₂ sequestration.

KEYWORDS: global carbon cycle, CO₂ sequestration, global warming, ocean acidification

CO₂ AND GLOBAL CLIMATE CHANGE

Few subjects have been more polarizing over the past decade than global warming. A large body of evidence demonstrates that global temperatures are rising. Eleven of the past 12 years rank among the 12 warmest since the 1850s, when temperature began to be regularly recorded (IPCC 2005). This temperature increase has been linked to more-intense precipitation events, including hurricanes (Groisman et al. 2005), a decrease in ocean thermohaline circulation (where higher-density, cold, saline water drags ocean currents down) (Broecker 1997), and rising sea levels in response to glacial melting (e.g. Manabe and Stouffer 1994; Rignot 1998). Rising sea level can lead to the flooding of vast stretches of the coast. It has been estimated that an increase in sea level of just 4 meters would displace over 300 million people and flood 1.7×10^6 km² of land (equivalent to the combined land area of France, Spain, Germany, and Italy) (Rowley et al. 2007). A temperature increase can also have significant effects on global ecosystems (Cole and Monger 1994), including plant distribution (McKenney et al. 2007), and has already led to the extinction of numerous species, particularly in polar and mountain-top environments (Parmesan 2006). Other investigations suggest that an increase in global temperature can significantly increase the number and extent of diseases that can infect humans (Patz et al. 1996).

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Residents of the Gulf Coast of the USA flood the highways in an attempt to escape the wrath of Hurricane Rita in September, 2005. Loss of life, widespread property damage, and disruption of gasoline supplies are stark reminders of how fragile we are in the face of Nature's fury. Many climatologists suggest that the severity and frequency of hurricanes, the duration of droughts, and flooding due to record precipitation may be related to global warming. Increasing atmospheric greenhouse gases, such as CO₂, are thought to be a principal driver of global climate change. PHOTO WIKIMEDIA COMMONS COURTESY SHINODA 28107

Many attribute this recent global warming to human influence on atmospheric composition (e.g. Crowley 2000; Karl and Trenberth 2003). Global circulation models suggest that much of the observed global temperature increase stems from an increase in atmospheric CO₂ (Manabe and Stouffer 1994; Johns et al. 2003). These models

are apparently confirmed by correlations between historic CO₂ concentration and temperature. An example of one such correlation is shown in FIGURE 1. A strong connection exists between temperature and atmospheric CO₂ content, as shown by data covering the past 400,000 years from Antarctic ice cores. Perhaps most disconcerting is that there may be a positive feedback between increasing atmospheric CO₂ concentration and climate. This positive feedback results from a decreasing ability of the terrestrial biosphere to act as a carbon sink as temperature increases (Cox et al. 2000). As a result of the combined effects of human CO₂ emissions and this positive feedback, global climate models predict average temperature increases of 2 to 5°C by 2100 (Johns et al. 2003). Reducing the impact of CO₂ emissions on the atmosphere and global climate change is thus considered one of the main challenges of this century (e.g. Gunter et al. 1996; Lackner 2003; Pacala and Socolow 2004; Oelkers and Schott 2005; Broecker 2005; Schrag 2007).

The link between increased atmospheric CO₂ content and global warming is not without its controversies. Some evidence suggests that increased atmospheric CO₂ content in the past followed, rather than led, global warming events. In a high-resolution analysis of Antarctic ice-core data, Stott et al. (2007) observed that the beginning of the rise in CO₂ content lagged the increase in global temperature by 700 to 1000 years. The possibility that increased atmospheric CO₂ follows global warming is consistent with the retrograde solubility of CO₂ in seawater. As temperature increases, the solubility of CO₂ in the oceans decreases. Thus, with increasing temperature, CO₂ would exolve from the oceans, increasing the proportion of CO₂ in the atmosphere. There are indications that global warming and polar-ice melting could provoke a new ice age. Global cooling could be triggered

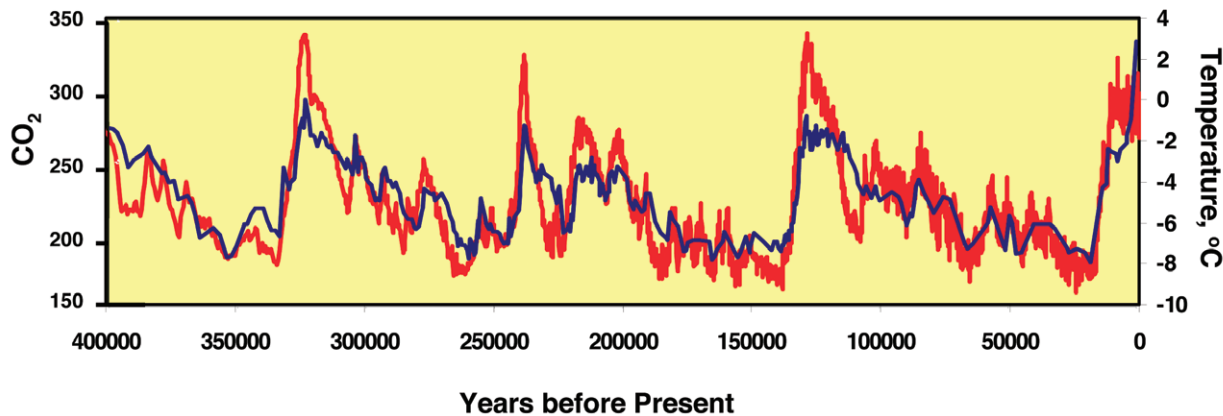


FIGURE 1 Atmospheric CO₂ concentration (in ppm per volume) compared with global temperature as derived from Antarctic ice-core data over the past 400,000 years. DATA FROM PETIT ET AL. (1999)

by the decreasing salinity of the oceans as the glaciers melt; decreased ocean salinity could dramatically decrease thermohaline ocean circulation, leading to slowing of the currents that carry warm Gulf of Mexico water north of Britain and Norway, thus cooling the North Atlantic (Rahmstorf and Ganopolski 1999; McManus et al. 2004).

It has also been argued that celestial factors have a significant effect on climate. Marsh and Svensmark (2003) presented evidence suggesting that variations in solar activity have had an important influence on the Earth's climate in the past. Veizer (2005) reviewed models advocating cosmic-ray flux as the principal driver of global temperature variation. Hays et al. (1976) proposed that variations in the Earth's orbit could affect global temperature. Model results of Stott et al. (2003), however, suggest that although solar forcing likely played a large role in controlling global mean temperatures during the first half of the twentieth century, greenhouse gas increases were responsible for most of the warming observed during the last 60 years.

THE GLOBAL CARBON CYCLE

Carbon dioxide is a trace gas in the Earth's atmosphere. Its current overall concentration is ~385 parts per million (ppm) by volume or 582 ppm by mass. Pre-industrial levels are estimated at ~280 ppm by volume. The variation in CO₂ concentration measured at the Mauna Loa, Hawai'i, observatory is shown in FIGURE 2. This concentration has increased from roughly 325 ppm in 1970 to 380 ppm at the beginning of this century. The smaller seasonal variation stems from biological activity: CO₂ is consumed by biota during the summer and released in the winter. In urban areas, CO₂ is generally higher, and indoors it can reach 10 times the background outdoor concentration. The mass of the Earth's atmosphere is 5.14×10^{18} kg (Trenberth et al. 1988), so the total mass of carbon dioxide can be estimated to be $\sim 3.0 \times 10^{15}$ kg, which is 3000 gigatons (Gt) of CO₂ or 800 Gt of carbon (1 Gt = 10^9 metric tons).

The atmosphere, however, is one of the smallest global CO₂ reservoirs. The world's oceans contain ~39,000 Gt of carbon, while soils, vegetation and detritus contain ~2000 Gt C and carbonate rocks (limestone, marble, chalk) ~65,000,000 Gt C. So, in total, the atmosphere only contains roughly 0.001% of the carbon present in the atmosphere-ocean-upper crust system. Moreover, the mass of carbon in the lower crust and mantle far exceeds that found in these near-

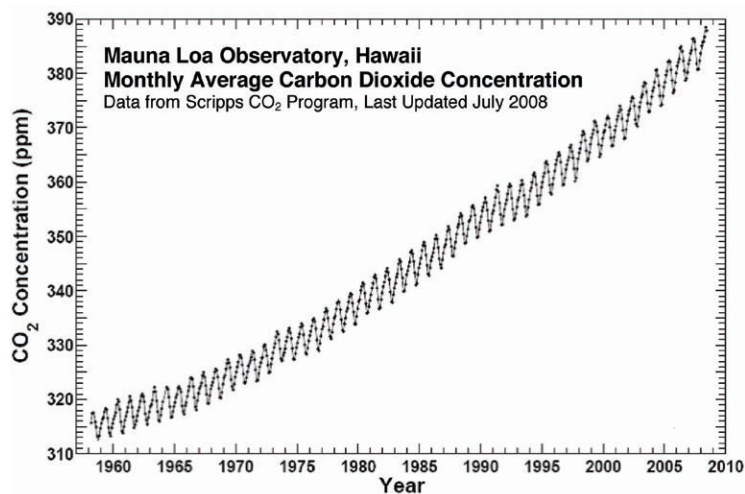


FIGURE 2 Atmospheric CO₂ concentration (in ppm) measured at the Mauna Loa observatory over the past 50 years

surface reservoirs (Holland 1978). There are huge exchanges among these reservoirs (FIG. 3). Each year, the atmosphere exchanges an estimated 90 Gt C with the surface ocean and 110 Gt C with vegetation (Houghton 2007). These numbers imply that the residence time of CO₂ in the atmosphere is no more than ~4 years. CO₂ exchange currently sequesters roughly half the annual anthropogenic global CO₂ emissions into the oceans and soils. This large-scale natural sequestration provides confidence that it may be feasible to remove CO₂ from the atmosphere and sequester it in other reservoirs in quantities sufficient to moderate the effects of anthropogenic CO₂ emission (Lal 2008).

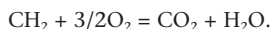
CO₂ AND OCEAN ACIDIFICATION

CO₂ exchange between the atmosphere and the ocean is so rapid that the increase in the atmospheric concentration of CO₂ has already had substantial effects on marine chemistry (Caldeira and Wickett 2003). The pH of the ocean's surface water has already decreased by 0.1 units compared to pre-industrial values (Haugan and Drange 1996). Model calculations indicate that continued anthropogenic CO₂ emissions could lead to a pH decrease in the oceans by as much as 0.3 to 0.4 units by the end of this century (Orr et al. 2005). This pH decrease would destabilize calcite and aragonite, the minerals that form the shells of many marine organisms (Andersson et al. 2006). As a consequence, it has been suggested that calcifying organisms, including corals,

coralline algae, molluscs and foraminifera, would have difficulties building their skeletons. This could have drastic implications for marine ecosystems, including disaster for some planktonic species, which would affect the entire food chain, and vast expanses of coral reefs (Andersson et al. 2006).

THE HUMAN IMPACT ON THE GLOBAL CARBON CYCLE

Many people are not aware of just how much CO₂ each of us produces. Many car drivers fill their gas tank at least twice a month. Each fill-up uses about 50 litres of gasoline. The density of gasoline is roughly 730 grams per litre, so the mass of each fill-up is about 36.5 kilograms. Gasoline is a mixture of hydrocarbons, including alkanes (straight chain molecules) such as heptane (C₇H₁₆) and aromatic (ring) compounds such as benzene (C₆H₆); gasoline can be represented by the general formula CH₂. When burned, it produces energy by the reaction:



The molecular weight of CH₂ is 14 g/mole, and that of CO₂ is 44 g/mole, so ~3.1 kg CO₂ is produced for every kilogram of gasoline burned. It follows that each 50 litre tank of gasoline produces about 113 kg CO₂, which, for 24 annual fill-ups, translates to roughly 2.7 metric tons of CO₂ per year! If this CO₂ were stored mineralogically by creation of calcite (CaCO₃), in accord with the reaction:



the mass of waste increases even more; the molecular weight of calcite is 100, so each kilogram of CO₂ would create 2.3 kg of calcite. To fix the CO₂ produced annually by this car in mineral form, where it would be geologically stable, one would need to produce 6.2 metric tons of calcite, a volume of 2.3 m³.

By this simple example, it is easy to imagine how the world's 6.6 billion people can contribute so much CO₂ annually to the Earth's atmosphere. Manufacturing, transport of goods, and production of cement all add to the total. Human industrial CO₂ emissions, primarily from the use of coal, oil and natural gas, and from the production of cement, currently contribute about 8 Gt C (29 Gt CO₂) per year. The evolution of global CO₂ emissions over the past 250 years is shown in FIGURE 4. Total human addition to the atmosphere since 1751 is estimated to be 315 Gt C (Marland et al. 2007). Of the current CO₂ emissions, 18% originate from burning natural gas, 42% from oil, 36% from coal, and 4% from making cement. In addition, the human population produces an estimated 0.6 gigatons of CO₂ per year just by exhaling.

Biofuels have been proposed as a solution, because the CO₂ produced by burning came originally from the atmosphere and was fixed by plants via photosynthesis. However, the production and burning of biofuels (1) requires substantial energy for farming, transport and processing, thus producing substantial CO₂; (2) requires the use of land, water and fertilizer that could otherwise be used to produce food; and (3) generates aldehydes and other compounds that are dangerous to humans, animals and the Earth's ozone layer.

The global average per capita CO₂ emissions over the past 50 years are presented in FIGURE 5. Emissions roughly doubled over two decades, from 0.65 tons in 1950 to 1.2 tons in 1970, and have remained relatively stable since. Per capita emissions vary greatly from country to country. The top 10 emitters for 2004, on a per capita basis, are listed in TABLE 1. Oil-producing countries dominate. The United States and Canada are high on the list, with an average of >5 t C per person per year. Most European countries emit between

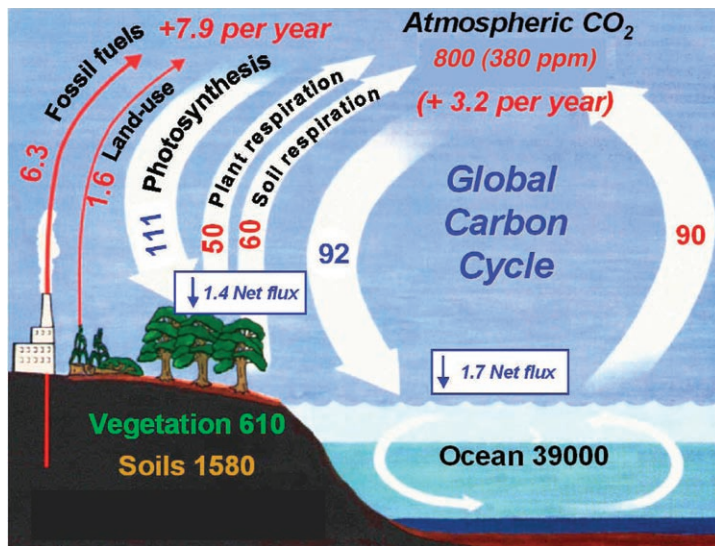


FIGURE 3 Schematic diagram of part of the global carbon cycle. Fluxes (arrows) are reported in units of gigatons of carbon per year (Gt C/year), whereas masses of the various reservoirs are presented in Gt C.

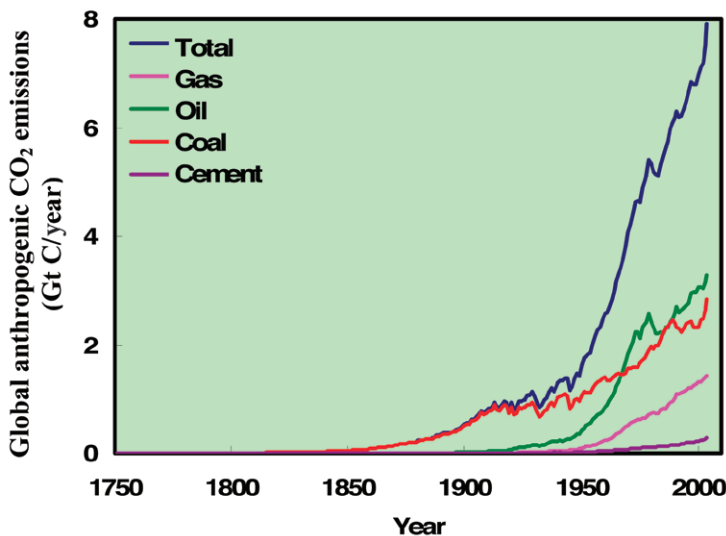


FIGURE 4 Annual global human CO₂ emissions to the atmosphere since 1751. AFTER MARLAND ET AL. (2007)

TABLE 1 TOP 10 CO₂-EMITTING COUNTRIES IN 2004 ON A PER CAPITA BASIS (MARLAND ET AL. 2007)

Rank	Country	Per capita carbon emissions (ton C/year)
1	Qatar	21.63
2	Kuwait	10.13
3	United Arab Emirates	9.32
4	Aruba	8.25
5	Luxembourg	6.81
6	Trinidad and Tobago	6.80
7	Brunei	6.56
8	Bahrain	6.53
9	United States	5.61
10	Canada	5.46

1.5 and 3 t C per person per year while less-industrialized Asian and African countries average <0.03 t C per person per year. The top overall CO₂ emitters are listed in TABLE 2. Industrialized countries currently lead, and those in a phase of active growth, such as China and India, will increase emissions dramatically as their economies grow.

CO₂ SEQUESTRATION EFFORTS

CO₂ storage and mineralization or immobilization, whether natural or engineered, depend on a complex set of chemical processes to assure capture, transport and final deposition (IPCC 2005). Capture is complicated by the diverse nature of CO₂ sources (Rubin 2008 this issue). Roughly 60% of emissions originate from large stationary facilities such as

power plants, cement production and oil or gas refineries. Such emissions are commonly a mixture of gases (CO₂, NO_x, SO_x, where x represents an integer), often requiring some sort of separation prior to CO₂ storage (Rubin 2008). In the ideal case, capture results in a concentrated CO₂ stream that can readily be collected and transported. The rest of the CO₂ originates from moving sources such as motor vehicles and airplanes. Capturing CO₂ emissions from these sources may require direct removal of CO₂ from the atmosphere.

Three major types of carbon storage have been proposed: geological storage, ocean storage, and mineral carbonation. In this issue, each of them is explored in detail in separate articles (Benson and Cole 2008; Adams and Caldeira 2008; Oelkers et al. 2008). In addition, there may be some potential for increasing the amount of CO₂ that is stored as biomass in forests and soils.

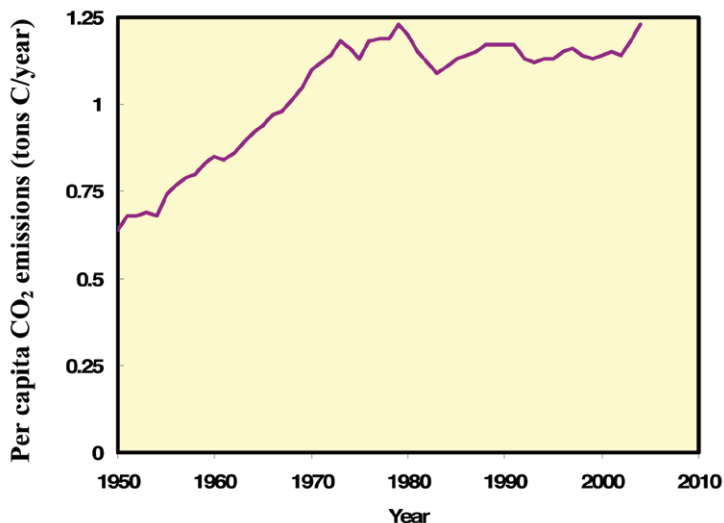


FIGURE 5 Annual global per capita CO₂ emissions to the atmosphere since 1950. After Marland et al. (2007)

TABLE 2 TOP 20 CO₂-EMITTING COUNTRIES IN 2004 (MARLAND ET AL. 2007)

Rank	Country	CO ₂ emissions (gigatons C/year)
1	United States	1.65
2	China	1.37
3	Russian Federation	0.46
4	India	0.37
5	Japan	0.34
6	Germany	0.22
7	Canada	0.17
8	United Kingdom	0.16
9	South Korea	0.13
10	Italy	0.12
11	Mexico	0.12
12	South Africa	0.12
13	Iran	0.12
14	Indonesia	0.10
15	France	0.10
16	Brazil	0.09
17	Spain	0.09
18	Ukraine	0.09
19	Australia	0.09
20	Saudi Arabia	0.08

Geological Storage

Geological storage relies on the injection of CO₂ into porous rock formations (Holloway 2001; Friedmann 2007; Benson and Cole 2008). CO₂ storage reservoirs include sedimentary basins, depleted oil reservoirs and non-economic coal beds. An impermeable cap rock is essential because CO₂ density is generally less than that of water, so buoyancy tends to drive CO₂ upwards, back to the surface. Several industrial-scale geologic CO₂ storage programs are already underway, including the Norwegian Sleipner project in the North Sea (Korbøl and Kaddour 1995) and the Weyburn project in Canada (Emberley et al. 2004); at these sites, a million tons or more of CO₂ is injected into the subsurface each year. CO₂ can also be injected into oil field reservoirs in an attempt to enhance petroleum recovery (known as EOR). Despite the apparently large annual injected volume, these projects, and other similar efforts, currently store less than one-tenthousandth, 0.01%, of the global annual anthropogenic CO₂ production.

Ocean Storage

Ocean storage means the injection of captured CO₂ into the ocean, usually at depths greater than 1000 metres, where it would be isolated from the atmosphere (Adams and Caldeira 2008). CO₂ would subsequently dissolve into the ocean and become part of the global carbon cycle. This storage method has yet to be attempted at a pilot scale. Ocean storage capacity may be enhanced by the formation of CO₂ hydrates or by the creation of liquid CO₂ lakes on the ocean floor.

Mineral Carbonation

Mineral carbonation aims to create stable carbonate minerals such as magnesite (MgCO₃) and calcite (CaCO₃) by reacting CO₂ with silicate minerals containing magnesium and calcium (Oelkers et al. 2008). Such minerals are stable over geologic timescales, so sequestration by this method would minimise risk of later leakage back to the atmosphere. Mineral carbonation mimics natural weathering, but an industrial-scale operation may require the mining and grinding of suitable Mg- and Ca-bearing silicate minerals and the disposal of vast quantities of end-product carbonate minerals. On the positive side, the resulting material could be used as a building material, as an additive to concrete or paper, or as a soil amendment to improve texture, pH and fertility of low-productivity soils. This enhances overall carbon sequestration by increasing below- and above-ground biomass and soil organic-matter content.

Biomass and Soil

Partial alternatives to these industrial solutions may be to store CO₂ in forests and soils. The biomass of forests is both a sink and a source for atmospheric CO₂. Vegetation absorbs carbon through photosynthesis. Although some is emitted again during respiration, there is net CO₂ storage. The stored carbon eventually returns to the atmosphere when the biomass decays or is burned. Forests can be managed to increase their stored carbon, thus reducing atmospheric CO₂ concentrations. The use of forests for CO₂ storage will require (1) that forests be managed to grow continuously and (2) that the carbon harvested from forests not be returned to the atmosphere. Management practices to maintain, restore, and increase carbon storage in forest soil include: the use of fertilizer; increased density of agriculture and decreased slash-and-burn practices; the preservation of wetlands, peatlands, and old-growth forest; and the reforestation of degraded and nondegraded sites, marginal agricultural lands, and lands subject to severe erosion (Johnson 1992). One solution for storing carbon fixed by, then harvested from, forests is its addition to soils in the form of biochar, which also has the potential to greatly enhance soil fertility (SEE BOX). The potential for forests to sequester CO₂, however, is limited. Nilsson and Schopfhauser (1995) estimated that only 345 million hectares are available worldwide for afforestation (planting trees on land that has been without forest cover for more than 50 years); an afforestation program of this scale would fix only 1.5 Gt C/year, which is less than 20% of the current anthropogenic carbon input to the atmosphere. Moreover, even attaining this limited land area for afforestation is challenging due to pressure to use land for other purposes, in particular agriculture and development.

PERSPECTIVES

The public desire to address global warming, thus to sequester large quantities of CO₂ to stem the increase in atmospheric CO₂ content, poses many challenges and opportunities for the geological community. Our geochemistry, mineralogy and petrology community has unique expertise that is essential for designing successful, long-term strategies for storing CO₂. This expertise is essential for selecting suitable carbon-storage sites, designing the injection facilities, developing monitoring techniques, predicting the fate of CO₂ once injected into the subsurface, and assessing the reactivity of the host material with the CO₂ introduced, under a spectrum of diverse environments. This *Elements* issue is an attempt to further motivate our community to address these challenges.

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Box 1 CO₂ Sequestration in Soils

Carbon is a major component of soils. Globally the mass of soil organic carbon is more than that of carbon in living matter and in the atmosphere combined (Batjes 1996). Approximately 2 gigatonnes (Gt) of carbon is sequestered in soil organic matter annually (Lal 2003). This amounts to a quarter of the 8 Gt of anthropogenic carbon emitted to the atmosphere per year, making soil a substantial CO₂ sink. Carbon is added to soils naturally, by the cycling and burial of organic material from plants, animals and microbes, and agriculturally, by spreading manure. Organic carbon is rapidly released to the atmosphere again, through erosion and oxidation.

A way to increase the residence time of carbon in soils is to add it as biochar, which is charcoal produced by smoldering biomass in an oxygen-poor environment. Some heat is produced, but the low concentration of oxygen prevents burning, thus decreasing the amount of CO₂ released and stabilising the remaining carbon against further oxidation by bacteria. Evidence for long-term stability of biochar in soils is found in the carbon-rich Terra Preta de Indio black soils of the Amazon region. Glaser (2007) concluded that at least some of the carbon of the Terra Preta stems from biochar added to these soils over 500 years ago. The charcoal improves soil fertility by adding an adsorptive surface for retention of plant nutrients. The Terra Preta is more than twice as productive as nearby soils in the Amazon, and biochar is sold as a soil amendment. This suggests that, if properly managed, biochar addition to soil could sequester substantial quantities of CO₂, in a form that would make it stable over hundreds of years. Lehmann (2007) argued that the addition of biochar to soils could sequester ~10% of the annual US fossil fuel emissions, and Gaunt and Lehmann (2008) proposed that converting biomass to charcoal is more effective than using it as biofuel.

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CO₂ Capture and Transport



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International interest in CO₂ capture and storage (CCS), as a method of reducing carbon dioxide emissions linked to global climate change, has been growing in recent years. CCS is particularly attractive for large industrial facilities, especially electric power plants, which contribute a large share of global CO₂ emissions from combustion of coal and other fossil fuels. This paper describes the current status of technologies to capture CO₂ and transport it to a storage site. The performance and cost of capture technologies are discussed, along with related environmental issues and the outlook for improved, lower-cost strategies. The key need now is financing of full-scale demonstrations of CCS at the various types of large coal-based power plants.

KEYWORDS: CO₂ capture, CO₂ transport, carbon sequestration costs, postcombustion capture, precombustion capture, oxycombustion capture

INTRODUCTION

Recent reports illustrate the growing international interest in carbon capture and storage (CCS) as a potentially important climate-change mitigation strategy (IPCC 2007; Macfarlane 2007; Schrag 2007). Commercial technologies are available for separating CO₂ from industrial gas streams, a process typically employed as a purification step in manufacturing. For example, CO₂ is routinely captured during natural gas treatment and in the production of hydrogen, ammonia, and ethanol. In most cases, the CO₂ stream is simply vented to the atmosphere. CO₂ is also captured from the flue-gas stream at some power plants burning coal or natural gas and then sold as a commodity to nearby food-processing plants. Globally, however, only a small amount of CO₂ is used for industrial products and nearly all is soon emitted into the atmosphere (think about the fizzy drinks you buy). To date, however, there has been no attempt to capture CO₂ at a large fossil fuel power plant (e.g. at a scale of hundreds of megawatts), although designs of such systems have been studied and proposed. TABLE 1 lists definitions and abbreviations

CO₂ capture and storage is best suited for facilities with large CO₂ emissions. The three biggest CCS projects to date remove 1–3 million metric tons of CO₂ per year from treatment or manufacture of natural gas (IPCC 2005). Other sources, including refineries, chemical plants, cement plants, and steel mills, are potential candidates. However, power plants should be the principal target because they account for roughly 80% of global CO₂ emissions from large stationary facilities.

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Most CO₂ is formed by combustion, so capture technologies are commonly classified as pre- or postcombustion systems, depending on whether carbon is removed before or after a fuel is burned. In a third approach, called oxyfuel or oxycombustion—a process still under development—CO₂ isolation is easier. In all cases, the aim is to produce a concentrated CO₂ stream that can be transported to a sequestration site. To facilitate transport and storage, captured CO₂ is first compressed to a dense “supercritical” state in

which it behaves as a liquid, making it easier and cheaper to transport. The resulting high pressures, typically 11–14 MPa, are also required to inject CO₂ deep underground for geological sequestration (Benson and Cole 2008 this issue). Compression occurs inside the plant gate and is thus commonly included as part of the capture system.

CO₂ CAPTURE TECHNIQUES

Postcombustion Capture

In these systems CO₂ is separated from the flue gas produced when coal or other fuel is burned in air. Combustion-based systems provide most electricity today. In a modern pulverized coal (PC) power plant, the heat released by combustion generates steam, which drives a turbine generator (FIG. 1). Hot combustion gases exiting the boiler consist mainly of nitrogen (from air) and smaller concentrations of water vapor and CO₂. Other constituents, formed from impurities in coal, include sulfur dioxide, nitrogen oxides, and particulate matter (fly ash). These are pollutants that must be removed to meet environmental standards. Subsequently, CO₂ can be removed.

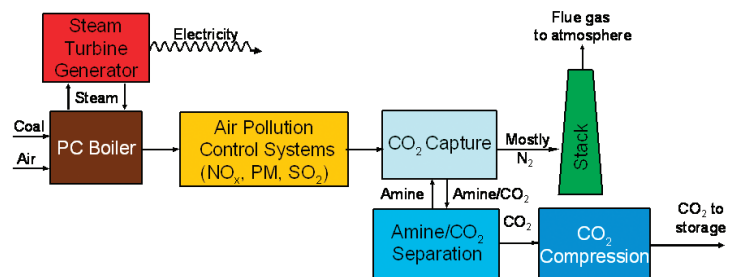


FIGURE 1 Schematic of a pulverized coal-fired (PC) power plant with postcombustion CO₂ capture using an amine system. Other major air pollutants (nitrogen oxides, particulate matter [PM], and sulfur dioxide) are removed from the flue gas prior to CO₂ capture.

Because the flue gas is at atmospheric pressure and the concentration of CO₂ is fairly low (typically 12–15% by volume for coal plants), the most effective method to remove CO₂ is by chemical reaction with a liquid solvent. The most common solvents are a family of organic compounds known as amines, one of which is monoethanolamine (MEA) (Rao and Rubin 2002). In a vessel called an absorber, the flue gas is “scrubbed” with an amine solution, typically capturing 85–90% of the CO₂. The CO₂-laden solvent is then pumped to a second vessel, called a regenerator, where heat releases the CO₂ as a gas. The resulting concentrated CO₂ gas stream is then compressed into a supercritical fluid for transport to the sequestration site, while the solvent is recycled (Fig. 2A).

Postcombustion capture can also be applied to natural gas combined cycle (NGCC) power plants, which have come into broad use over the past decade. In this type of plant, clean natural gas is combusted with compressed air to produce a high-temperature gas stream that drives a turbine. The hot exhaust from the turbine is then used to produce steam, which powers a second turbine, generating more electricity (hence the term “combined cycle”). Although the CO₂ in NGCC flue gas is even more dilute than in coal plants (about 3–5% by volume), high removal efficiencies are still achieved with amine capture. Amine capture technology is also widely used to purify industrial gas streams, as in the processing of raw natural gas to remove CO₂, a common impurity (Fig. 2B).

Precombustion Capture

To decrease CO₂ emissions, fuel-bound carbon can first be converted to a form amenable to capture. This is accomplished by reacting coal with steam and oxygen at high temperature and pressure, a process called coal gasification. By restricting the amount of oxygen, the coal is only partially oxidized, providing the heat needed to operate the gasifier. The reaction products are mainly carbon monoxide and hydrogen (a mixture commonly known as synthesis gas, or syngas). Sulfur compounds (mainly hydrogen sulfide, H₂S) and other impurities are removed using conventional gas-cleaning technology. The clean syngas can be burned to generate electricity in a combined cycle power plant similar to the NGCC plant described above. This approach is known as integrated gasification combined cycle, or IGCC.

To capture CO₂ from syngas, two additional process units are added (Fig. 3). A “shift reactor” converts the carbon monoxide (CO) to CO₂ through reaction with steam (H₂O). Then, the H₂-CO₂ mixture is separated into streams of CO₂ and H₂. The CO₂ is compressed for transport, while the H₂ serves as a carbon-free fuel that is combusted to generate electricity.

Although initial fuel-conversion steps are more elaborate and costly than postcombustion systems, the high pressures of modern gasifiers and the high concentration of CO₂ produced by the shift reactor (up to 60% by volume) make CO₂ separation easier. Thus, instead of chemical reactions to capture CO₂, commercial processes such as Selexol use

TABLE 1 DEFINITIONS OF SELECTED TERMS AND ABBREVIATIONS

Term or abbreviation	Definition
Carbon capture	Removal or separation of CO ₂ (or other carbon compound) from a gas stream, typically through a chemical or physical process
Storage/sequestration	A method or repository that prevents CO ₂ from entering the atmosphere. These two terms are often used interchangeably, though “storage” generally applies to CO ₂ captured from an industrial process, while sequestration is the more general (and rigorous) term, which also includes CO ₂ removed from the atmosphere by trees and soils.
CCS	Carbon (or carbon dioxide) capture and storage (or sequestration). This is the most widely used abbreviation for capture and sequestration of industrial CO ₂ .
EOR	Enhanced oil recovery – a major use for CO ₂ as an industrial commodity. CO ₂ increases mobility, thus increasing production.
ETS	Emissions trading system – a term commonly applied to the European Union’s cap-and-trade policy for CO ₂ emissions
IGCC	Integrated gasification combined cycle – a power generation technology typically fueled by coal or petroleum coke, which is converted to a gaseous fuel that is burned to generate electricity
NGCC	Natural gas combined cycle – a power generation system fueled by natural gas, which is burned to generate electricity using both a gas turbine (Brayton cycle) and a steam turbine (Rankine cycle)
PC	Pulverized coal – this term refers to the prevailing technology for coal-fired power plants, in which coal is crushed to a fine powder, then injected into a furnace (boiler) where it is combusted to generate steam, which drives a turbine to generate electricity.
SCPC	Supercritical pulverized coal – this term refers to a pulverized coal power plant in which steam is heated to a temperature and pressure above the thermodynamic “critical point,” enabling higher plant efficiencies than with conventional “subcritical” units, which operate at lower pressures and temperatures. The term “ultrasupercritical” (USC) designates a supercritical plant with even higher steam temperature and pressure than conventional SCPC units.

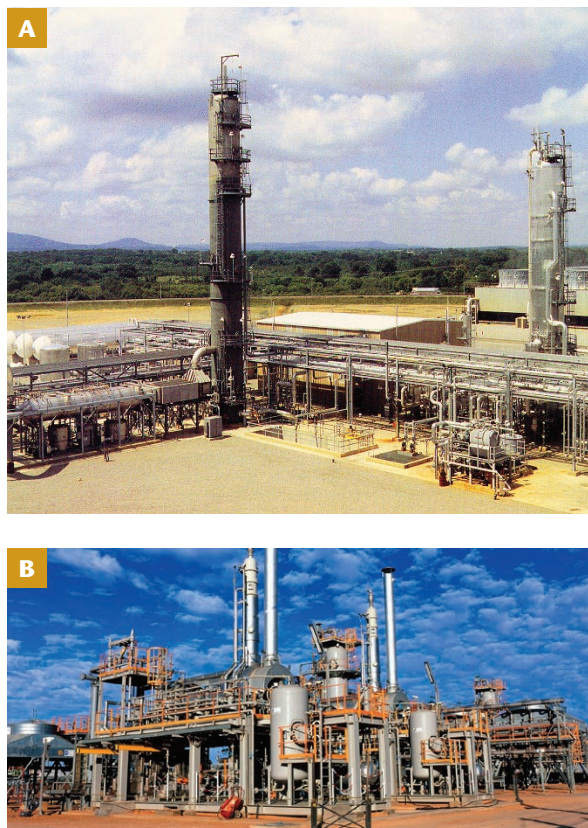


FIGURE 2 (A) An amine-based postcombustion CO₂ capture system treating a portion of the flue gas (~40 MW equivalent) from a coal-fired power plant in Oklahoma, USA. (B) An amine-based CO₂ capture system used to purify natural gas at BP’s In Salah plant in Algeria. Approximately 1 Mt/y of CO₂ is captured and transported by pipeline to a geological sequestration site. PHOTOS COURTESY OF U.S. DEPARTMENT OF ENERGY (A) AND IEA GREENHOUSE GAS PROGRAMME (B)

sorbents (e.g. glycol) to physically adsorb CO₂, then release it in a second vessel when the pressure is quickly reduced. This technology for precombustion capture is favored in a variety of processes, mainly in the petroleum and petrochemical industries (Fig. 4).

Oxycombustion Capture

Oxyfuel systems are similar to conventional combustion systems, except that oxygen is used rather than air to avoid nitrogen in the flue-gas stream. After the particulate matter (fly ash) is removed, the gas consists mainly of water vapor and CO₂, with low concentrations of pollutants such as sulfur dioxide (SO₂) and nitrogen oxides (NO_x). The water vapor is easily removed by cooling and compressing, leaving nearly pure CO₂ that can be sent directly to sequestration. Oxycombustion avoids the need for a postcombustion capture device, but most designs require additional processing to remove conventional air pollutants to comply with environmental requirements or CO₂ purity specifications. The system also requires an air-separation unit to generate the relatively pure (95–99%) oxygen needed for combustion (Fig. 5) and must be sealed against air leakage. Approximately three times more oxygen is needed for oxyfuel systems than for IGCC plants, which adds considerably to the cost. Because combustion temperatures in oxygen are much higher than in air, oxycombustion also requires roughly 70% of the inert flue gas to be recycled back to the boiler to maintain normal operating temperatures.

As a CO₂ capture method, oxycombustion has been studied theoretically and in small-scale test facilities. A major demonstration project (10 MW electrical equivalent) began in September 2008 at a pilot plant in Germany (Vattenfall 2008). Although, in principle, oxyfuel systems can capture all of the CO₂ produced, the need for additional gas treatment and distillation decreases the capture efficiency to about 90% in most current designs (IEA GHG 2005). For all approaches, higher removal efficiencies are possible, but more costly. Thus, engineers seek to optimize design to achieve the most cost-effective CO₂ capture.

OPTIONS FOR CO₂ TRANSPORT

Except in cases where an industrial plant is located directly above a suitable geological formation, captured CO₂ must be transported from the point of capture to a sequestration site. In the US, pipelines are the most common method for transporting CO₂. Many were built in the early 1970s in the western United States to transport CO₂, extracted mainly from natural geological sources, to depleted oil wells in western Texas for enhanced oil recovery (EOR). Today in the US, increasing numbers of EOR projects rely on a network of >4500 km of pipeline to carry >40 million metric tons of CO₂ per year from natural and industrial sources. The newest pipeline, operational since 2004, transports 3Mt CO₂/y from a coal gasification plant in North Dakota to the Weyburn and Midale oil fields, 320 km north in southern Saskatchewan (Fig. 6). This US-Canadian venture is the largest CCS project. The other two (each ~1 Mt CO₂/y) are the Statoil gas production facility at Sleipner, Norway, an offshore drilling platform where CO₂ is injected into a saline aquifer beneath the North Sea, and the BP gas treatment plant at In Salah, Algeria, where captured CO₂ is transported by pipeline to a nearby injection site at Krechba.

Other transport methods also have been considered. Compressed CO₂ can be transported in large tanker ships, similar to those used to transport liquefied natural or petroleum gas. This could become economical if CO₂ has to be moved large distances over water, as might occur with injection into the deep ocean (an option that remains controversial; Adams and Caldeira 2008 this issue). Other

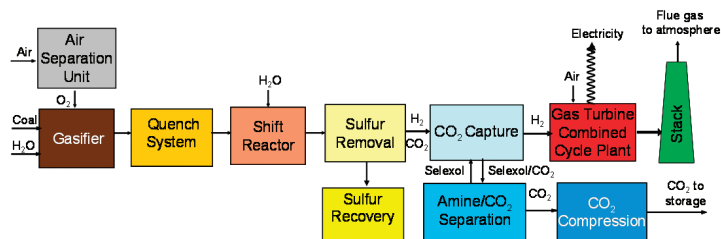


FIGURE 3 Schematic of an integrated gasification combined cycle (IGCC) power plant with precombustion CO₂ capture using a water–gas shift reactor and a Selexol CO₂ separation system



FIGURE 4 A precombustion CO₂ capture system used to produce synthetic natural gas (syngas) from coal at the Dakota Gasification Plant in North Dakota. About 3 Mt/y captured CO₂ is currently transported by pipeline to the Weyburn and Midale oil fields in Saskatchewan, Canada, where it is used for enhanced oil recovery and sequestered in depleted oil reservoirs. PHOTO COURTESY OF U.S. DEPARTMENT OF ENERGY

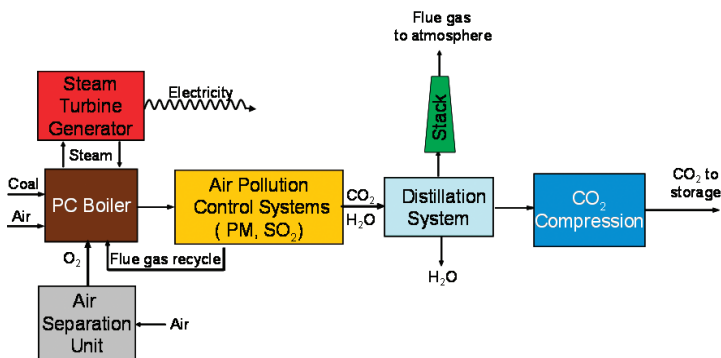


FIGURE 5 Schematic of a coal-fired power plant using oxycombustion. Approximately 70% of the CO₂-laden flue gas is recycled to the boiler to maintain normal operating temperatures. Depending on the purity of the oxygen from the air separation unit, small amounts of nitrogen and argon also enter the flue gas.



FIGURE 6 A portion of the pipeline delivering CO₂ to the Weyburn oil field in Saskatchewan, Canada. PHOTO COURTESY OF IEA GREENHOUSE GAS PROGRAMME

options include transport by truck or railroad in insulated tanks. Road and rail are used on a limited basis for small-scale shipments of industrial CO₂, but these options are not economical at the scale required for climate-change mitigation (IPCC 2005).

THE ENERGY PENALTY AND ITS IMPLICATIONS

Current CO₂ capture systems require large amounts of energy to operate. This decreases net efficiency and contributes significantly to CO₂ capture costs. Postcombustion capture systems use the most energy, requiring nearly twice that of precombustion systems (TABLE 2). Lower plant efficiency means more fuel is needed for electricity generation. For coal plants, this added fuel produces proportionally more solid waste and requires more chemicals, such as ammonia and limestone, to control NO_x and SO₂ emis-

sions. Plant water use also increases proportionally, with additional cooling water needed for amine capture systems. Because of efficiency loss, a capture system that removes 90% of the CO₂ within a plant actually reduces net emissions per kilowatt-hour (kWh) by a smaller amount, typically 85–88%.

In general, the more efficient the power plant, the smaller are the energy penalty impacts. For this reason, replacing or repowering an old, inefficient plant with a new, more efficient facility with CO₂ capture can still yield a net efficiency gain that decreases all plant emissions and resource consumption. Thus, the net impact of the energy penalty is best assessed in the context of strategies for reducing emissions across a fleet of plants, including existing facilities as well as planned new units. Innovations in power generation and carbon capture technologies are expected to further reduce future energy penalties and their impacts.

THE COST OF CO₂ CAPTURE SYSTEMS

TABLE 3 summarizes the cost of individual components of the CCS system. The broad ranges reflect different sets of assumptions used in various studies of hypothetical power plants in North America and Europe. The most costly component is capture, including compression. The lowest capture costs are for processes where CO₂ is separated as part of normal operations, such as during hydrogen production, where the added cost is simply for CO₂ compression.

FIGURE 7 depicts the cost of generating electricity with and without CCS, as reported in recent studies. The total electricity cost (\$/MWh) is shown as a function of the CO₂ emission rate (t CO₂/MWh) for new plants burning bituminous coal or natural gas. One sees a broad range of values. While variations in capture-system design contribute to this range, the dominant factors are differences in design, operation, and financing of the power plants to which capture technologies are applied. For example, higher plant efficiency, larger plant size, higher fuel quality, lower fuel cost, higher annual hours of operation, longer operating life, and lower cost of capital all reduce the costs, both of CO₂ capture and electricity generation. No single set of assumptions applies to all situations or all parts of the world, so estimated costs vary. An even broader range would appear if other factors were considered, such as subcritical boilers and nonbituminous coals.

Over the past several years, construction costs for power plants and other industrial facilities have escalated dramatically (CEPCI 2008). So too has the price of fuel, especially natural gas, making NGCC plants uneconomical in most

TABLE 2 REPRESENTATIVE VALUES OF CURRENT POWER PLANT EFFICIENCIES AND CCS ENERGY PENALTIES

SOURCES: IPCC (2005); EIA (2007)

Power plant type (and capture system type)	Net plant efficiency (%) without CCS*	Net plant efficiency (%) with CCS*	Energy penalty: Added fuel input (%) per net kWh output
Existing subcritical (PC) (+ postcombustion)	33	23	40%
New supercritical (SCPC) (+ postcombustion)	40	31	30%
New supercritical (SCPC) (+ oxycombustion)	40	32	25%
Coal gasification (IGCC) (+ precombustion)	40	34	19%
New natural gas (NGCC) (+ postcombustion)	50	43	16%

* All efficiency values are based on the higher heating value (HHV) of fuel, not the lower heating value (LHV) used in Europe and elsewhere, which yields greater efficiencies by omitting the fuel energy needed to evaporate water produced in combustion. For each plant type, there is a range of efficiency values around those shown here. See Rubin et al. (2007a) for details

TABLE 3 ESTIMATED COSTS OF CO₂ CAPTURE, TRANSPORT, AND GEOLOGICAL STORAGE (2007 US\$/T CO₂)

SOURCE: IPCC (2005) DATA ADJUSTED TO 2007 COST BASIS

CCS system component	Cost range (US\$)
Capture: Fossil fuel power plants	\$20–95/t CO ₂ net captured
Capture: Hydrogen and ammonia production or gas-processing plant	\$5–70/t CO ₂ net captured
Capture: Other industrial sources	\$30–145/t CO ₂ net captured
Transport: Pipeline	\$1–10/t CO ₂ transported
Storage: Deep geological formation	\$0.5–10/t CO ₂ net injected

Ranges reflect differences in the technical and economic parameters affecting the cost of each component.

locations where coal is also available at much lower cost. Uncertainty about future cost escalations further clouds the “true” cost of plants, with or without CCS. On a relative basis, however, CCS is estimated to increase the cost of generating electricity by approximately 60–80% at new coal combustion plants and by about 30–50% at new coal gasification plants. On an absolute basis, the increased cost of generation translates to roughly \$40–70/MWh for PC plants and \$30–50/MWh for IGCC plants using bituminous coal. The CO₂ capture step (including compression) accounts for 80–90% of this cost, while the remaining 10–20% results from transport and storage. Note, however, that consumers would see much smaller increases in their electricity bills because generation accounts for only about half the total cost of electricity supply, and only a gradually increasing fraction of all generators might employ CCS at any time in response to future climate policies.

FIGURE 7 can also be used to calculate the cost per ton of CO₂ avoided when a plant is built with CCS instead of without. For a new supercritical (SCPC) coal plant with deep aquifer storage, this is currently about \$60–80/t CO₂, which is the magnitude of the “carbon price” needed to make CCS cost-effective. For IGCC plants with and without capture, the CCS cost is smaller, about \$30–50/t CO₂. All costs are decreased when CO₂ can be sold for EOR with storage. The cost of CO₂ avoided depends on the type of “reference plant” used to compare with the CCS plant. For example, without capture, a SCPC plant today is about 15–20% cheaper than a similarly sized IGCC plant, making it preferred. But with CO₂ capture, an IGCC plant gasifying bituminous coal is expected to be the lower-cost system. Thus, it is useful to compare a SCPC reference plant without capture to an IGCC plant with CCS. In this case the cost of CO₂ avoided is roughly \$40–60/t CO₂.

The relative cost of SCPC and IGCC plants can change significantly with coal type, operating hours, cost of capital, and many other factors (Rubin et al. 2007a). Experience with IGCC power plants is still quite limited, and neither SCPC nor IGCC plants with CCS have been built and operated at full scale. Thus, neither the absolute nor relative costs of these systems can yet be stated with confidence. For existing power plants, the feasibility and cost of retrofitting a CO₂ capture system depends especially on site-specific factors such as plant size, age, efficiency, and space to accommodate a capture unit. For many existing plants, the most cost-effective strategy is to combine CO₂ capture with a major plant upgrade (repowering) in which an existing unit is replaced by a high-efficiency unit or a gasification combined cycle system (Chen et al. 2003; Simbeck 2008). In such cases, the cost approaches that of a new plant.

Outlook for Lower-Cost Technologies

Research and development (R&D) programs are underway worldwide to produce CO₂ capture technologies with lower cost and energy requirements (IEA GHG 2008). For example, the European CASTOR project aims at lower postcombustion capture costs by developing advanced amines and other solvents. In the US, electric utilities and equipment manufacturers are testing a postcombustion process using chilled ammonia in the hope of greatly reducing the CCS energy penalty, and with it, the cost of capture. Researchers in Australia, Europe, Japan, and North America are seeking major improvements also in precombustion capture with membrane technologies for oxygen and hydrogen production and CO₂ separation. A number of national and international programs are also pursuing new process concepts such as chemical looping combustion.

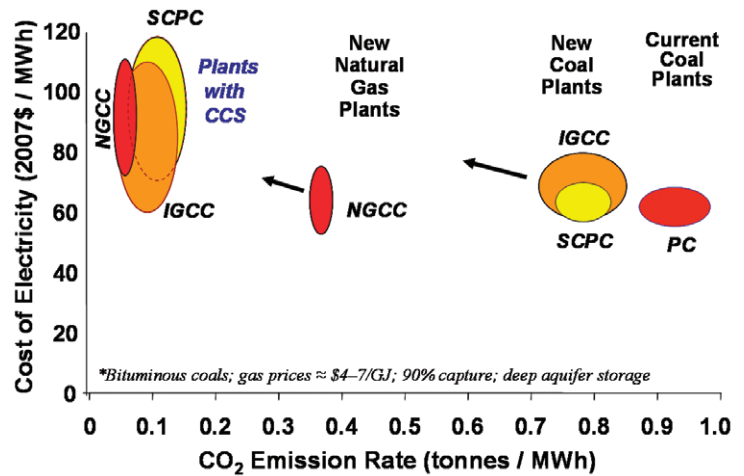


FIGURE 7 Cost of electricity generation (2007 US\$/MWh) as a function of the CO₂ emission rate (t CO₂/MWh) for new power plants burning bituminous coal or natural gas (PC = subcritical pulverized coal units; SCPC = supercritical pulverized coal; IGCC = integrated gasification combined cycle; NGCC = natural gas combined cycle). Ranges reflect differences in technical and economic parameters affecting plant cost. Figure based on data from NETL (2007); Holt (2007); MIT (2007); Rubin et al. (2007a); IPCC (2005), adjusted to 2007 cost

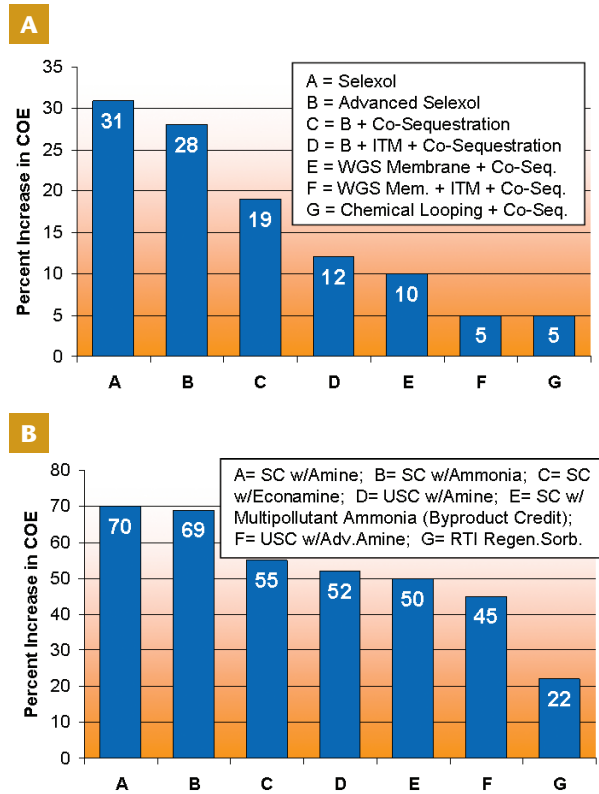


FIGURE 8 Projected increases in the cost of electricity (COE) for CO₂ capture and storage using current technology (bar A) and various advanced capture technologies for (A) an IGCC plant with precombustion capture (ITM = ion transport membrane; WGS = water gas shift) and (B) an SCPC plant with postcombustion capture (RTI = Research Triangle Institute). The height of each bar shows the percent increase in COE relative to a similar plant without CO₂ capture and storage. The absolute value of COE (in 2006 US cents/kWh) for the IGCC plant is projected to fall from 7.13 ¢/kWh currently to 5.75 ¢/kWh with advanced technology (bars F and G)—an overall COE reduction of 19%. For the PC plant, the COE falls from 8.77 ¢/kWh to 6.30 ¢/kWh—an overall reduction of 28%. A similar projection for a PC plant with oxycombustion (not shown in this figure) estimates that advanced technologies can reduce the total cost of electricity from 7.86 ¢/kWh (currently) to 6.35 ¢/kWh, a 19% reduction in COE. SOURCE: NETL (2006)

Although future costs remain highly uncertain, sizeable reductions in CO₂ capture costs are foreseen over the next few decades. Combined with improvements in power plant design, engineering-economic analyses predict reductions of 20–30% for electricity generation with CCS (FIG. 8). Such estimates are consistent with projections from historical “learning curves,” which show technologies become cheaper with maturity (Rubin et al. 2007b). Experience also indicates that reducing cost requires not only sustained R&D but also deployment and adoption of technologies in the marketplace to facilitate learning-by-doing. Policies that promote CCS deployment are thus essential to achieve the cost reductions that are projected.

CONCLUDING REMARKS

Although CO₂ capture and storage holds considerable promise, its acceptance will depend on the nature and pace of government policies to limit CO₂ emissions and/or to provide financial incentives for its use. At present, only the European Union (EU) has CO₂ emission limits in the form of a “cap-and-trade” policy, which requires industrial sources either to reduce emissions or to buy “allowances” to emit CO₂. The price of a CO₂ allowance is established by the European Union in a financial market called the emissions trading system (ETS), the largest existing market for carbon reductions (Ellerman and Joskow 2008). At current ETS carbon prices, CO₂ capture and storage remains prohibitive relative to other measures for meeting emission limits. Although under considerable attention, unresolved legal, regulatory, and public-acceptance issues pose additional barriers to CCS deployment. New post-2012 EU emission limits are under negotiation.

In the US, most cap-and-trade policies proposed in Congress fall short of what is needed to motivate implementation of CCS, although a few proposals include financial incentives for its early adoption (Pena and Rubin 2008). Other proposals would establish power plant performance standards that restrict CO₂ emissions to levels only achievable with CCS. Whatever the method, until there are sufficiently stringent limits on CO₂ emissions, CCS will be used only at a small number of facilities that can exploit government incentives or other economic opportunities such as enhanced oil recovery.

In the absence of strong policy incentives, where do we go from here? There is broad agreement that progress on CCS requires several full-scale demonstrations at fossil fuel power plants, especially coal-based plants. Such projects are needed to establish the true costs and reliability of the various approaches in different settings and to resolve legal and regulatory issues of large-scale geological sequestration (Wilson et al. 2008). Government–industry partnerships in Asia, Europe, and North America are at various stages of planning and financing such projects (TABLE 4). Once funding is in place, it will take several years to design and build each facility, then several years of operation to evaluate its reliability, safety, public acceptance, and performance in reducing CO₂ emissions. If all goes well, a viable CCS industry could be launched in approximately a decade. ■

TABLE 4 A FEW EXAMPLES OF PLANNED AND PROPOSED CO₂ CAPTURE AND STORAGE PROJECTS (BEYOND 2008). Many would proceed in phases beginning with smaller units than shown here. As of mid-2008, approximately 65 projects have been announced worldwide. Several large projects also were cancelled in 2007–2008. SOURCE: MIT (2008)

Project Name	Location	Feedstock	Size MW	Capture	Start-up
Callide-A Oxy Fuel	Australia	Coal	30	Oxy	2009
GreenGen	China	Coal	250	Pre	2009
Williston	USA	Coal	450	Post	2009–2015
Sargas Husnes	Norway	Coal	400	Post	2011
S&S Ferrybridge	UK	Coal	500	Post	2011–2012
Naturkraft Kårstø	Norway	Gas	420	Post	2011–2012
Fort Nelson	Canada	Gas	Process	Pre	2011
Zero Gen	Australia	Coal	100	Pre	2012
UAE Project	UAE	Gas	420	Pre	2012
Appalachian Power	USA	Coal	629	Pre	2012
UK CCS Project	UK	Coal	300–400	Post	2014
Statoil Mongstad	Norway	Gas	630	Post	2014
RWE Zero CO ₂	Germany	Coal	450	Pre	2015
Monash Energy	Australia	Coal	60 k bpd	Pre	2016

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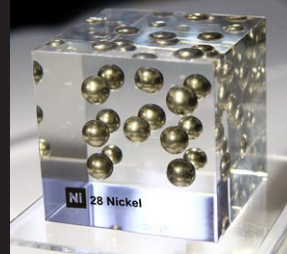
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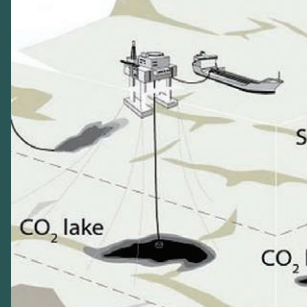
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Ocean Storage of CO₂

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One method for minimizing climate change is to capture CO₂ from power plants and inject it into the deep ocean, thus reducing the magnitude and rate of change of CO₂ concentration in the atmosphere and the surface ocean. Many discharge options are possible, with varied mixing and retention characteristics. The ocean's capacity is vast, and mathematical models suggest that injected CO₂ could remain sequestered for several hundred years. While theoretical and laboratory studies support the viability of ocean storage, field experiments are necessary to realistically evaluate the environmental impact.

KEYWORDS: ocean carbon sequestration, CO₂ ocean storage, environmental impact, climate change

INTRODUCTION

Other articles in this issue discuss the motivation for carbon dioxide (CO₂) capture and storage as a method to help combat global climate change (Oelkers and Cole 2008; Broecker 2008). In particular, storage in underground reservoirs is highlighted (Benson and Cole 2008; Oelkers et al. 2008). Here we describe the possibilities for CO₂ storage in the deep ocean, focusing on direct-injection strategies that could be applied on an industrial scale.

There are several reasons for considering the deep ocean as a sink for anthropogenic CO₂. First, the ocean has a vast uptake capacity. It currently contains an estimated 40,000 Gt C (billion tons of carbon), mostly in the form of dissolved inorganic ions. This compares with about 800 Gt C contained in the atmosphere and 2000 Gt C in the land biosphere. Thus, the amount of carbon that would cause a doubling of the atmospheric concentration would only change the ocean concentration by about 2%. Second, we are already discharging CO₂ indirectly into the surface ocean when we emit it to the atmosphere. Because emissions are large, the atmosphere and ocean are currently out of chemical equilibrium, causing a net flux of about 8 Gt CO₂ per year (2 Gt C per year) to the ocean. Over a period of centuries, 70–80% of present-day emissions will ultimately reside in the ocean. Discharging CO₂ directly into the deep ocean would accelerate this natural process, thus reducing peak atmospheric concentrations and protecting ocean surface waters with a slower rate of CO₂ increase. FIGURE 1 presents the results of simulations for the reduction in atmospheric CO₂ concentration that could be achieved using several release-uptake scenarios in which known fossil fuel reserves are consumed (Kheshgi and Archer 2004). Compared with

releasing all CO₂ to the atmosphere, as happens now, introducing half to the deep ocean would reduce the peak concentration by a factor of about two. However, the ocean and atmosphere systems are closely coupled, so even if all anthropogenic CO₂ were injected directly into the oceans, some would return to the atmosphere through degassing.

Over the past 200 years, oceans have taken up over 500 Gt of

CO₂ from the atmosphere, compared with over 1300 Gt CO₂ emitted to the atmosphere (IPCC 2005). As a result, the pH of the surface ocean (the upper few hundred meters that are in greatest contact with the atmosphere) has dropped by about 0.1 pH units from the preindustrial value of about 8.2. This causes concern for the health of coral reefs and other organisms that use calcium carbonate in their skeletons or shells. FIGURE 2 presents model results for ocean pH if known fossil fuel reserves are burned and CO₂ is released. The atmospheric concentration would increase to ~2000 ppm in 300 years (similar to FIGURE 1), and ocean

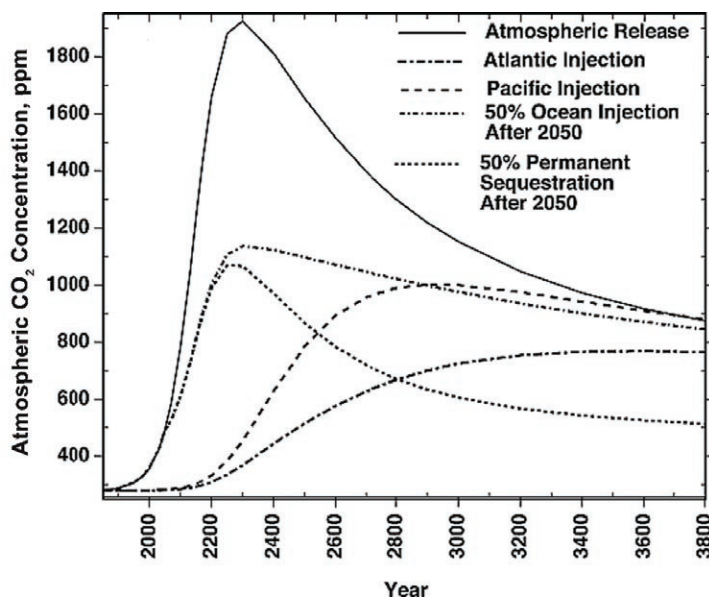


FIGURE 1 Simulated atmospheric CO₂ concentration (ppm) resulting from release of 18,000 Gt CO₂ to the atmosphere, to the ocean at 3000 m below sea level, or to a combination of both. ADAPTED FROM KHESHGI AND ARCHER (2004), WITH PERMISSION FROM THE AMERICAN GEOPHYSICAL UNION

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surface pH would drop by more than 0.7 units (Caldeira and Wickett 2003). By injecting some of the CO₂ into the deep ocean, the time until it disperses to surface water is extended, allowing the change in pH to be distributed more uniformly with depth.

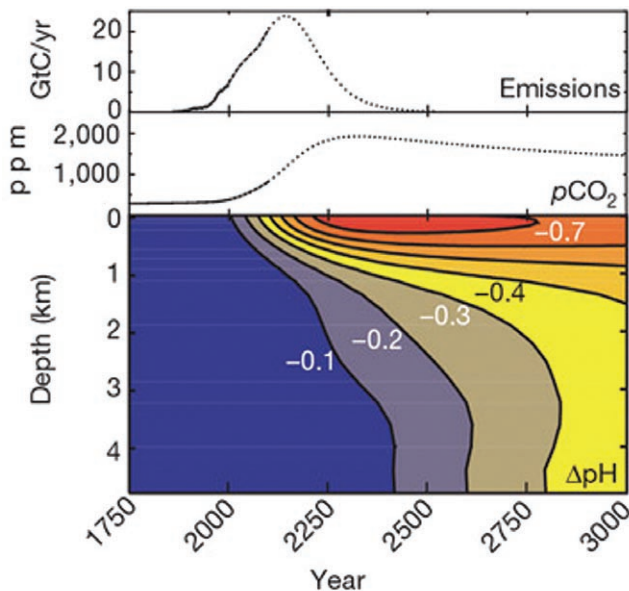
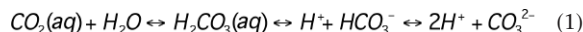


FIGURE 2 Model simulations of long-term changes in ocean pH, averaged horizontally, as a result of the CO₂ emissions shown in the top panel. pCO₂ is the atmospheric concentration of CO₂. REPRINTED FROM CALDEIRA AND WICKETT (2003), WITH PERMISSION FROM MACMILLAN PUBLISHERS LTD.

CAPACITY

Oceans occupy more than 70% of the Earth's surface and have an average depth of about 3.8 km. Considering the saturation concentration of CO₂ in seawater, this storage capacity is orders of magnitude greater than the capacity needed to absorb the CO₂ produced by burning all of the world's fossil fuel resources, equivalent to an estimated 5000 to 10,000 Gt C. However, a more realistic capacity estimate requires understanding ocean biogeochemistry and the expected environmental impact.

CO₂ exists in seawater in various forms as part of the carbonate system:



The relative proportions of these species are defined by the pH of the solution and by equilibrium relationships. Dissolving additional CO₂ increases production of hydrogen ions (decreasing pH), but the change is buffered by conversion of carbonate into bicarbonate. Thus, the principal reactions for CO₂ dissolution in seawater are as follows:



Decreased pH is one of the principal environmental impacts threatening marine organisms; the other is the concentration of CO₂ itself. Near the injection point, changes in pH and CO₂ concentration would be greatest, so injection schemes would have lowest impact if dilution is maximized. Far from the injection point, as CO₂ becomes widely distrib-

uted in the ocean, its impact would be similar to that of anthropogenic CO₂ absorbed from the atmosphere. Adding about 2000 Gt CO₂ to the ocean would reduce the average ocean pH by about 0.1 units, similar to the change already observed in the surface ocean. Adding about 5600 Gt CO₂ (about 200 years of current emissions) would decrease the average ocean pH by about 0.3 units (IPCC 2005).

The impact of such changes is not well known. However, one can examine spatial and temporal variations in ocean pH to understand how much change might be tolerated. The pH variability within latitudinal bands in each of the three major oceans (Pacific, Atlantic, Indian) during the 1990s was roughly 0.1 unit (IPCC 2005). If a change of 0.1 unit is assumed as a threshold tolerance and if the CO₂ is stored in the bottom half of the ocean (to maximize retention), approximately 1000 Gt CO₂ could be stored, enough to stabilize atmospheric concentrations at 500 ppm over the next 50 years, assuming energy consumption follows current trends and no other mitigation measures are put into place (Pacala and Socolow 2004). It should be realized that over the long term (millennia), the change in whole-ocean pH would ultimately be the same, whether CO₂ is released into the atmosphere or injected into the deep ocean, because thermodynamics drives the system to equilibrium. However, in the shorter term (several centuries), injecting into the deep ocean, below 1000 m depth, would limit pH drop in the near-surface, where marine biota are most plentiful, thus decreasing the adverse impact in the surface ocean.

INJECTION METHODS

Injection was first proposed by the Italian physicist Cesare Marchetti, who suggested dissolving CO₂ into the outflow from the Mediterranean Sea. Because this water is saltier than average seawater, the higher density would cause the CO₂ to sink into the depths of the Atlantic Ocean (Marchetti 1977). As illustrated in Figure 3, a number of options have been considered since then, including introducing the CO₂ as a rising or sinking plume, dispersing it from a moving ship, and creating a lake on the deep seafloor.

Before describing these methods in more detail, we first provide some background about the CO₂-seawater system. Figure 4 shows a simple phase diagram for CO₂ in seawater. At typical ocean pressure and temperature, pure CO₂ is in gas form above a depth of 400–500 m and in liquid form below. At a depth of 1000 m, liquid CO₂ is about 6% less dense than seawater. Because liquid CO₂ is more compressible than seawater, at a depth of 3000 m its density is similar to that of seawater. Thus liquid CO₂ would be positively buoyant and rise if it were injected above 3000 m, but it would sink if injected deeper. Below about 400 m depth, if the concentration of dissolved CO₂ is high enough, hydrate phases form. CO₂ hydrate, whose composition is given by CO₂·nH₂O (n ≈ 5.75), is a solid in which each CO₂ molecule sits in a cage-like structure of water molecules held together by hydrogen bonds. Unlike methane hydrates, which have a similar structure but are positively buoyant (Ruppel 2007), pure CO₂ hydrates are about 10% denser than seawater. Unless the surrounding water is saturated with CO₂, the hydrate is unstable, but it dissolves more slowly into seawater than does liquid CO₂.

Methods by which CO₂ is dissolved directly into seawater have received the most attention. The easiest scenario is to discharge it as a buoyant liquid, forming a rising droplet plume (Alendal and Drange 2001; Sato and Sato 2002). The required technology is available now to inject CO₂ from a manifold lying on the seafloor. Effective sequestration could be achieved by locating the manifold below the natural

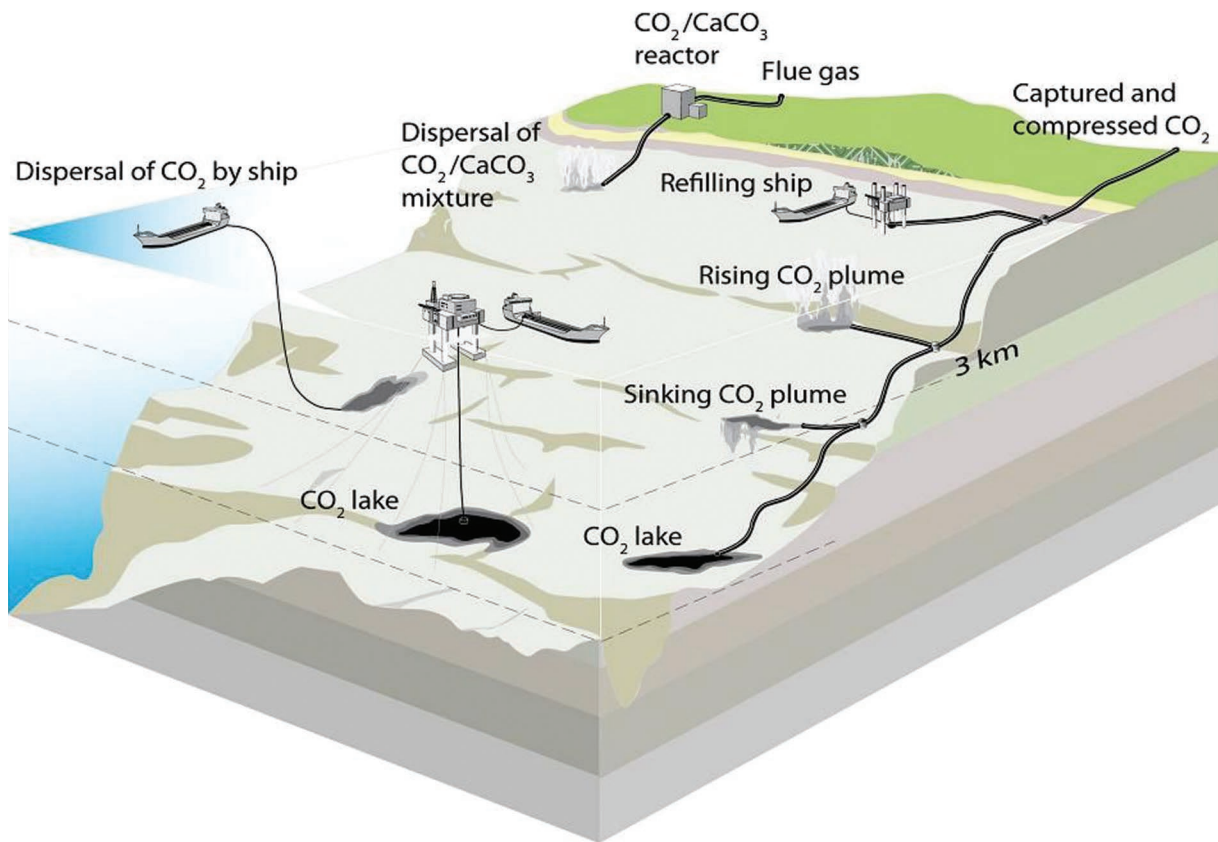


FIGURE 3 Strategies for ocean carbon sequestration. REPRINTED FROM FIGURE TS-9: SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE (IPCC 2005), WITH PERMISSION FROM THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

thermocline (the depth at which vertical temperature gradients in the ocean are strongest), and adequate dilution could be achieved by making the manifold sufficiently long. Even better dilution could be achieved by releasing CO₂ droplets from a ship, where motion provides additional dispersal (Ozaki et al. 2001). Although the delivery methods are different, the resulting plumes would be similar: each would yield a vertical band of CO₂-enriched seawater over a predetermined horizontal region.

Another dissolution option is to inject liquid CO₂ into a vessel where it can react at a controlled rate with seawater to form hydrates. While 100% reaction efficiency is difficult to achieve, laboratory and field experiments indicate that CO₂ sinks with as little as about 15–25% reaction efficiency (Tsouris et al. 2007). Instability leads to dissolution and dispersion during descent. The hydrate reactor could be towed from a moving ship, promoting additional dilution, or attached to a fixed platform, where the large concentration of dense particles and the increased seawater density caused by hydrate dissolution would create a sinking plume (Wannamaker and Adams 2006).

Dissolving high concentrations of CO₂ into seawater and then releasing the solution at the seafloor is another option (Haugan and Drange 1992). Enrichment with CO₂ causes only a slight density increase, but it is sufficient to promote sinking, especially within a submarine canyon. The environmental impact is higher, because the plume is more concentrated and it would come into direct contact with the seafloor, home to an abundance of relatively immobile fauna, bacteria, and algae. Alternatively, creating a CO₂

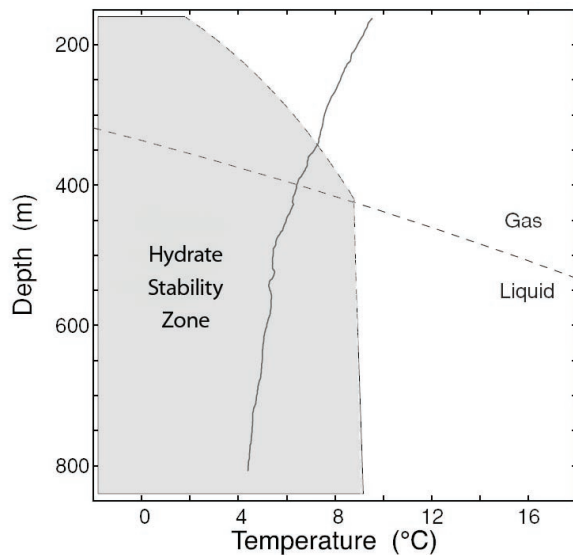


FIGURE 4 CO₂ phase diagram. Pressure is defined by water depth. The solid line indicates a temperature profile measured in Monterey Bay, California, USA. Above the dashed line, CO₂ in equilibrium with seawater is a gas, whereas below the line, it is a liquid. At sufficiently low temperature and high pressure, CO₂ hydrates form (grey region). REPRINTED FROM BREWER ET AL. (2004; FIGURE 1), WITH PERMISSION FROM THE AUTHOR AND SPRINGER SCIENCE AND BUSINESS MEDIA

lake on the seafloor minimizes leakage to the atmosphere and exposure to biota (Ohsumi 1995; Haugan and Alendal 2005). A CO₂ lake would exist partly in the form of solid hydrates, which would slow dispersion to the water column, increasing retention time. Producing a lake would require more advanced technology and perhaps cost more than other options, because the lake must be more than 3000m below the water surface.

Retention could be increased further using the reaction of CO₂ with carbonate minerals. Anthropogenic CO₂ currently transported to the deep ocean will equilibrate with carbonate sediments over a period of about 6000 years (Archer et al. 1998). Technical means could be used to accelerate this reaction, increasing effectiveness and diminishing the environmental impact. Power plant gas could be dissolved in seawater (Eq. 2) and then reacted with crushed limestone, either at the power plant or at the point of release, thus buffering pH change (Caldeira and Rau 2000). Conversely, an emulsion of liquid CO₂ and water could be stabilized by fine particles of pulverized limestone; the emulsion would be sufficiently dense to sink, and pH would be partially buffered by the limestone (Golomb et al. 2007). Drawbacks to these approaches include the cost to mine, crush, and transport large quantities of carbonate rock.

EFFECTIVENESS

Since the time when the oceans and atmosphere formed, they have exchanged CO₂ constantly. Now, about 350 Gt are exchanged each year, with a net ocean uptake of about 8 Gt CO₂ (IPCC 2005). Because of this exchange, one can ask how long it would take before injected CO₂ leaks back to the atmosphere. Long-term experiments with directly injected CO₂ have never been carried out, so effectiveness must be estimated from observations of other oceanic tracers, such as radiocarbon (¹⁴C), and from computer models of ocean circulation and chemistry.

As a result of anthropogenic input, the atmosphere and ocean are currently out of equilibrium, so most emitted CO₂ will ultimately end up in the ocean. The percentage of CO₂ permanently sequestered is defined by thermodynamics and depends on the atmospheric concentration (TABLE 1). At today's atmospheric level of ~380 ppm, nearly 80% of CO₂ emitted *either* to the atmosphere *or* to the ocean would become permanently stored in the ocean, while at a concentration of 750 ppm, 70% would be stored. Of course, even at equilibrium, CO₂ would continue to be exchanged between the atmosphere and the ocean, so the carbon in the ocean on any given day would not be exactly the same carbon present on the previous day, even though the total would be constant. The predictions in TABLE 1 include the possibility of increased carbon storage in the terrestrial biosphere, but do not consider natural or engineered dissolution of carbonate minerals. Over thousands of years, retention would increase somewhat as CO₂ reacts with ocean sediments.

TABLE 1 implies that, for CO₂ injected into the ocean today, the *net quantity stored* ranges from 100% (now) to about 70–80% as the atmosphere approaches equilibrium with the ocean. One can also define retention as the fraction of injected CO₂ that is retained without ever reaching the

surface; this fraction ranges from 100% at the time of injection to zero at equilibrium. The exact time depends on the location and depth of the injection.

Several computer-modeling studies have investigated CO₂ retention time in the world's oceans. The most comprehensive summary is the Global Ocean Storage of Anthropogenic Carbon (GOSAC) intercomparison study of several ocean general circulation models (OGCM). Ten models simulated the fate over 500 years of CO₂ injected at seven locations and three depths (Orr 2004). FIGURE 5 shows the fraction of CO₂ retained as a function of time, averaged over the seven sites. Although there is substantial variability, all models indicate increased retention with injection depth, and most predict over 70% retention after 500 years for injection at 3000 m. Note that these calculations assume CO₂ is dispersed in the water column at the injection depth. Formation of a CO₂ lake or reaction with marine sediments could increase retention time.

The time required for injected carbon from the deep ocean to enter the atmosphere is roughly equal to the time required for carbon from the atmosphere to reach the deep ocean. This can be estimated from observations of ¹⁴C. Correcting for mixing with waters from various sources (polar ice, rivers, other oceans), the age of North Pacific deep water is estimated to be between 700 and 1000 years, while other basins, such as the North Atlantic, have turnover times of 300 years or more. These estimates are consistent with OGCM output and collectively suggest retention times of 300 to 1000 years. It is important to stress that CO₂ leakage to the atmosphere would take place gradually, over large areas of the ocean surface. Thus, unlike sequestration in porous rock, it would not be possible to produce a sudden release that could lead to harmful CO₂ concentrations at the ocean or land surface.

LOCAL ENVIRONMENTAL IMPACT AND PUBLIC PERCEPTION

Environmental impact may be the most significant factor determining the acceptability of ocean storage, because the strategy is grounded on the notion that impact on the deep ocean would be significantly less than the impacts avoided by limiting emission to the atmosphere. Above, we discussed environmental impacts from the global perspective. Here, we focus on the injection point.

A number of studies have summarized the potential impact on a variety of organisms, including adult and developing fish, zooplankton, and benthic fauna (Kikkawa et al. 2003; Ishimatsu et al. 2004; Pörtner et al. 2004; Watanabe et al. 2006). Earlier studies focused on the lethal impact on coastal fauna exposed to strong acids such as HCl (Auerbach et al. 1997), but recent work has examined the impact on deep-water organisms when exposed to CO₂, including sublethal effects (Kurihara et al. 2004). Organisms experience respiratory stress (decreased pH limits oxygen binding and transport of respiratory proteins), acidosis (low pH disrupts acid/base balance), and metabolic depression (elevated CO₂ causes some animals to reach a state of torpor). Data show a number of trends: (1) H₂CO₃ generally causes greater stress on an organism than an equivalent change in pH produced by another acid; (2) there are large differences in tolerance among different species and among different life stages of the same species; and (3) the duration of stress, as well as the level of stress, are important. While some studies suggest that deep organisms would be less tolerant than surface organisms, other studies have shown the opposite. Likewise, some animals are able to avoid regions of high CO₂ concentration (Vetter and Smith 2005), while others are less able (Tamburri et al. 2000). Results generally imply

TABLE 1 CO₂ PREDICTED TO BE PERMANENTLY SEQUESTERED IN THE OCEAN AS A FUNCTION OF ATMOSPHERIC CONCENTRATION

Atmospheric CO ₂ concentration (ppm)	CO ₂ permanently sequestered (%)
350	80
450	77
550	74
650	72
750	70
1000	66

BASED ON DATA IN IPCC (2005) AND REFERENCES THEREIN

that lethal effects can be avoided by achieving high near-field dilution. However, more research is needed, especially at the community level (e.g. studies of reduced lifespan, reproduction effects, and tolerance to other stresses).

The viability of ocean storage as a greenhouse gas mitigation option hinges on social, political, and regulatory considerations. In view of public precaution toward the ocean, which is a common, global resource, the strategy will require that all parties (private, public, non-governmental organizations) be included in ongoing research and debate. But the difficulty in this approach is highlighted by the recent experience of an international research team whose aim was to assess ocean carbon sequestration, as encouraged by the United Nations Framework Convention on Climate Change. A major part of their activity would have been a field test with 5 tons of CO₂ released off the coast of Norway. The plan was to monitor the physical, chemical, and biological effects of the injected CO₂ over a period of about a week. However, lobbying from environmental groups caused the Norwegian minister of the environment to rescind the group's permit (Giles 2002). Such actions unfortunately prevent collection of data that are critical for policy makers to evaluate the prudence of full-scale implementation.

COSTS AND COMPARISON WITH OTHER STORAGE METHODS

The storage media most comparable to the ocean, in terms of size and cost, are depleted or partially depleted hydrocarbon reservoirs and saline aquifers (Friedmann 2007; Benson and Cole 2008). Ocean storage and use of these geological media both require that CO₂ be captured and then compressed and transported to an injection site. Summarizing a number of studies, IPCC (2005) estimates the cost (2002 basis) of capture and compression for a coal- or gas-fired power plant at US\$20–95 per ton CO₂ net captured and the cost of transportation at US\$1–10 per ton CO₂ transported. The cost of geological storage is estimated at US\$0.5–10 per ton CO₂ net injected, while the cost of ocean storage is estimated at US\$5–30 per ton CO₂, making ocean storage somewhat more expensive (more details in Rubin 2008 this issue).

The aim of geological sequestration is to permanently trap the CO₂ within well-defined regions, so that it cannot interact with terrestrial or oceanic ecosystems. Sometimes CO₂ can be used to enhance oil recovery or coalbed methane production. For these reasons, geological storage has been favored. In contrast, most ocean disposal schemes aim to minimize impact by diluting the CO₂ in the vastness of the ocean, and while it may be isolated from the atmosphere for centuries, approximately 20–30% of it will eventually leak back. The ocean storage option that promises the most permanence is mineral carbonation, but this is more expensive—IPCC (2005) estimates the cost at US\$50–100 per ton CO₂. On the other hand, compared with deep underground storage, CO₂ dispersed in the ocean is relatively easy to monitor, and because it is dispersed, the CO₂ that eventually reaches the atmosphere will escape slowly.

In a method that is hybrid between ocean and geologic storage, CO₂ would be injected into marine sediments, deep offshore (House et al. 2006). Because of the relatively high pressure and low temperature in this environment, the CO₂ would be negatively buoyant, perhaps forming solid hydrates, thus minimizing leakage through the sediment-water interface. And any CO₂ that was eventually released to the ocean would be dispersed and diluted.

Another form of ocean sequestration is enhanced production of biomass. Fertilizing portions of the world's oceans with iron would stimulate phytoplankton growth. The

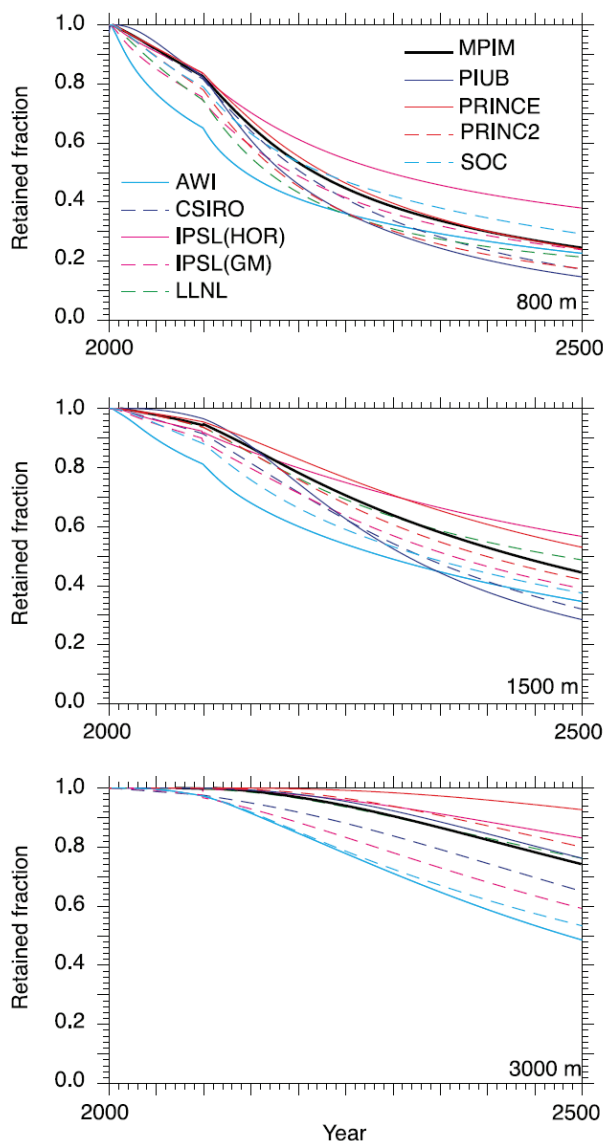


FIGURE 5 Comparison of ten model simulations, denoted by abbreviations (Orr 2004), showing as a function of time the amount of CO₂ that never reaches the ocean surface, for injection events at depths of 800 m, 1500 m, and 3000 m. Results are averaged over seven injection locations. Most of the CO₂ that does reach the surface remains in the ocean (TABLE 1), so the total retained is greater than shown here. REPRINTED FROM ORR (2004), WITH PERMISSION FROM IEA GREENHOUSE GAS R&D PROGRAMME

phytoplankton would increase the rate of biological uptake of CO₂ from the surface water and the atmosphere, and a portion would be transported to the ocean depths when the plankton dies. Iron fertilization is relatively inexpensive, and the organisms do most of the capture and transport, making this process an attractive solution. However, the technique is considered risky because it relies on deliberate manipulation of an ecosystem, with uncertain effects. At least ten international field experiments have been conducted to examine the short-term effects of iron fertilization (Coale et al. 2004). Although these experiments have demonstrated a clear response over the short term, the long-term effectiveness and the potential for detrimental changes to marine ecosystems are uncertain.

CONCLUSIONS

Ocean storage is one method to help mitigate global climate change. Compared to business as usual, ocean storage would reduce the peak CO₂ concentration and slow its rate of increase in both the atmosphere and ocean surface water. A number of injection schemes show promise for effective sequestration for several centuries, while diluting the concentration of CO₂ below levels of environmental concern. While

such strategies appear promising, they require field verification. Reliable data are necessary before responsible decisions can be made about the safety of ocean storage. Because the ocean is common to all, public participation is essential. The ocean is vast but none the less finite, meaning ocean storage should be viewed as a potential interim solution, to be used while society prepares for its transition to more sustainable energy sources. ■

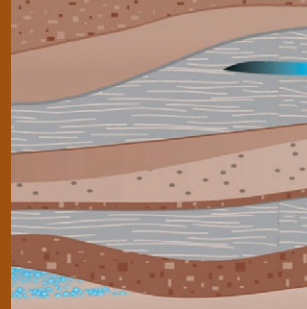
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CO₂ Sequestration in Deep Sedimentary Formations

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Carbon dioxide capture and sequestration (CCS) in deep geological formations has recently emerged as an important option for reducing greenhouse emissions. If CCS is implemented on the scale needed to make noticeable reductions in atmospheric CO₂, a billion metric tons or more must be sequestered annually—a 250 fold increase over the amount sequestered today. Securing such a large volume will require a solid scientific foundation defining the coupled hydrologic–geochemical–geomechanical processes that govern the long-term fate of CO₂ in the subsurface. Also needed are methods to characterize and select sequestration sites, subsurface engineering to optimize performance and cost, approaches to ensure safe operation, monitoring technology, remediation methods, regulatory overview, and an institutional approach for managing long-term liability.

KEYWORDS: sequestration, CO₂ properties, fluid migration, monitoring, risks

INTRODUCTION

Twelve years ago, Statoil began to inject a million metric tons per year of carbon dioxide into an aquifer 800 meters beneath the North Sea (Torp and Gale 2003). The CO₂ was stripped from natural gas to meet specifications for sale in Europe. Statoil could have emitted the CO₂ into the atmosphere and paid a \$50 per ton tax, but they opted instead to inject it into a subseabed aquifer, thus beginning an entirely new approach for reducing emissions: carbon dioxide capture and sequestration (CCS). Since then, two other commercial CCS projects have started, one in Canada and another in Algeria, and today over 20 million tons (Mt) CO₂ have been sequestered (Riddiford et al. 2003; White et al. 2004).

Hailed by some as a silver bullet for meeting the climate-change challenge and by others as ludicrous, CCS is in fact neither. With over 60% of worldwide emissions coming from point sources that are potentially amenable to CO₂ capture, the prospects for CCS to significantly reduce CO₂ emissions are great (IPCC 2005). Technical and economic assessments suggest that over the coming century, CCS may contribute up to 20% of CO₂-emission reductions, equivalent to reductions expected from efficiency improvements and large-scale deployment of renewable energy resources (IPCC 2005). So what is CCS technology? Why have experts concluded that it will work? And why have others expressed concern? Here we address what is known, and what is not known, to answer these questions.

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WHERE COULD CO₂ BE SEQUESTERED?

To significantly reduce global emissions to preindustrial levels, huge volumes of CO₂ must be sequestered. For example, a large coal-fired power plant emits about 8 million tons of CO₂ annually. At the pressures and temperatures expected for sequestration reservoirs, the volume required to sequester CO₂ as a supercritical fluid is about 10 million cubic meters (Mm³) per year. Sequestering the CO₂ emissions from a power plant with a 50-year lifetime would require a volume of about 500 Mm³. Such large volumes make some CCS critics skeptical.

Where could we potentially sequester these large volumes of CO₂? Large sedimentary basins are best suited, because they have tremendous pore volume and connectivity and they are widely distributed (Bachu 2003) (FIG. 1). Vast formations of sedimentary rocks with various textures and compositions provide both the volume to sequester the CO₂ and the seals to trap it underground. Possible repositories include depleted oil and gas reservoirs, saline (salt-water filled) aquifers, and coal beds (FIG. 2).

Suitable formations should be deeper than 800 m, have a thick and extensive seal, have sufficient porosity for large volumes, and be sufficiently permeable to permit injection at high flow rates without requiring overly high pressure. Sequestering CO₂ below depths of 800 meters provides two advantages, both a result of the high pressures encountered at these depths: CO₂ density is high enough to allow efficient pore filling and to decrease the buoyancy difference compared with in situ fluids (FIG. 3). To protect groundwater resources, CO₂ will not be injected into shallow aquifers with total dissolved solid concentrations less than 10,000 ppm. Other important aspects include knowing the condition of active and abandoned wells and whether secondary seals are present in the overburden.

Estimates of worldwide sequestration capacity based on these criteria are large. Depleted oil and gas reservoirs are estimated to have the capacity to sequester between 675 and 900 billion tons of carbon (Gt C), saline aquifers between 1000 and 10,000 Gt C, and deep, unmineable coal beds between 3 and 200 Gt C (IPCC 2005). Sequestration capacity estimates for saline aquifers and coal beds are highly uncertain, although in the past several years, there has been some progress in developing standard methods for capacity estimation and improving regional estimates (Bachu et al. 2007; DOE 2007). In a recent assessment of

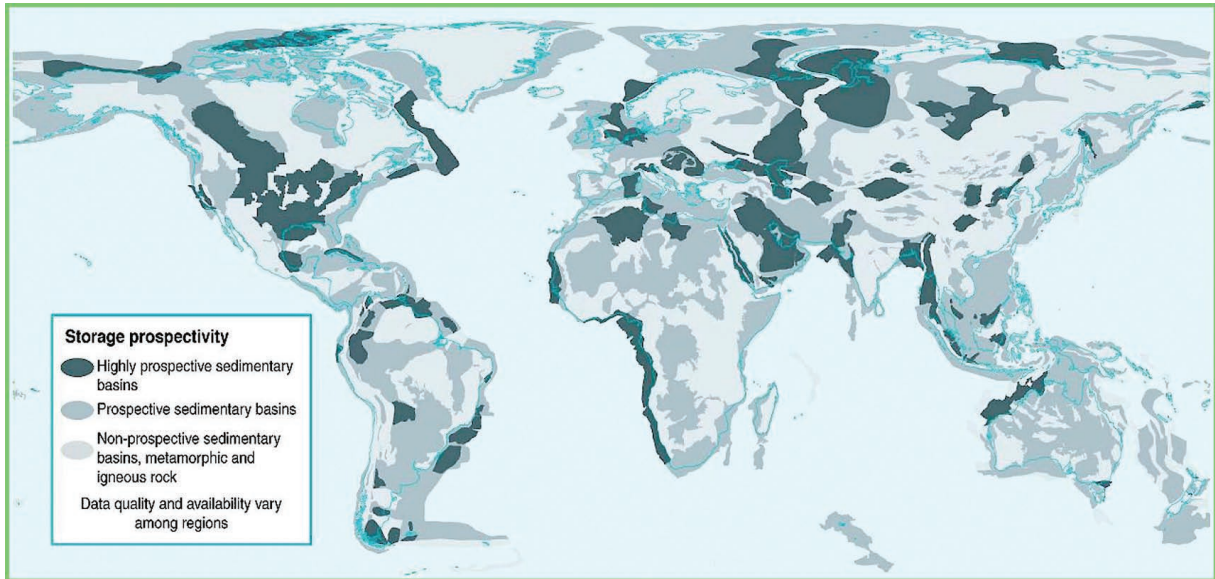


FIGURE 1 Sedimentary basins showing suitability as sequestration sites (IPCC 2005)

North American capacity, oil and gas reservoirs are estimated to be able to contain ~80 Gt C, saline aquifers between 900 and 3300 Gt C, and coal beds about 150 Gt C, for a total of about 1160 to 3500 Gt C (DOE 2007). If these estimates are correct, there is sufficient capacity to sequester several hundreds of years of emissions. Only time and experience will tell whether these estimates are correct.

In the short term, the biggest challenge is to match sequestration sites to CO₂ sources. For example, the large capacity in oil and gas reservoirs will only become available when the operator declares them depleted or implements enhanced oil recovery (EOR) (ARI 2006). A comparison of sequestration capacity and emissions indicates that some of the greatest CO₂ emitters (e.g. in the Ohio River Valley, India, and parts of China) are located in regions without large sequestration capacities. On the other hand, Texas, the US state with the highest CO₂ emissions, has extremely large sequestration capacity. CCS will likely begin in regions with large emission sources, large sequestration capacity, and opportunities for combining CO₂ sequestration and EOR. Beyond that, particularly in the case of saline aquifers and coal beds, the scientific foundations and the potential risks of large-scale injection must be established.

SCIENTIFIC FUNDAMENTALS OF GEOLOGICAL SEQUESTRATION

Physical Properties of CO₂

The physical state of CO₂ varies with temperature and pressure, as shown in FIGURE 4A (Oldenburg 2007). At ambient conditions, CO₂ is a gas, but it becomes liquid at greater depth. At high temperature, CO₂ is a supercritical fluid when pressure is high enough. The transition from one state to another depends on the geothermal gradient. In most sequestration scenarios, CO₂ is injected in liquid form (low T, modest to high P), but it transforms into a supercritical fluid as it is injected and warms to the temperature of the formation. In saline aquifers and oil reservoirs, CO₂ is less dense than the in situ fluids, so it rises to the base of the seal. Clearly, maintaining an impermeable caprock is crucial to containing the buoyant CO₂.

CO₂ Migration Behavior

When CO₂ is injected into deep geological formations, it displaces the pore fluid. Depending on the fluid's properties, CO₂ is either miscible, that is, it can mix completely to form a single liquid phase, or immiscible, so the phases

remain separate. At conditions expected for sequestration, CO₂ and water are immiscible. Oil and CO₂ may or may not be miscible, depending on the composition of the oil and the formation pressure. CO₂ and natural gas are miscible. When the fluids are miscible, the CO₂ eventually displaces nearly all of the original fluid. Injection of an immiscible fluid bypasses some fraction of the pore space, trapping some of the original fluid. With the limited exception of dry-gas reservoirs, most sequestration projects will require immiscible displacement to one degree or another. For example, although oil and CO₂ are miscible, the water that is almost always present in formations is not miscible with oil or CO₂/oil mixtures. Equilibration of CO₂ between oil and water depends on the composition of the oil.

Under conditions where the fluid phases are not miscible, the pressure needed to inject CO₂, the rate at which the leading edge of the CO₂ plume moves, and the fraction of the pore space filled with CO₂ are all governed by multiphase flow relationships (Bear 1972). For CO₂ sequestration, three particularly important consequences arise from multiphase flow behavior. First, the fraction of the pore space that can be filled with CO₂ is limited by the flow dynamics and capillary pressure resulting from interaction of two or more phases. At most, about 30% of the pore space is filled with CO₂ during initial displacement. In practice, CO₂ saturation is likely to be even less because of buoyancy and geological heterogeneity, both of which cause portions of the formation to be bypassed. After injection has stopped, CO₂ continues to move and fluid saturation approaches equilibrium, which is determined by the capillary pressure of the rock and the density difference between CO₂ and the original fluids.

The second important consequence of multiphase flow is that CO₂ mobility is limited during the post-injection period. When CO₂ saturation decreases, such as can occur after injection stops, a certain fraction—the “residual saturation”—remains immobilized in the rock, trapped by capillary forces. Water is imbibed (sucked) back into the pore space (Juanes et al. 2006; Hesse et al. 2008).

The third important consequence in a multiphase flow regime is that seals have two mechanisms for trapping CO₂ in the sequestration volume. Sealing layers are typically

Overview of Geological Storage Options

1. Depleted oil and gas reservoirs
2. Use of CO₂ in enhanced oil and gas recovery
3. Deep saline formations - (a) offshore (b) onshore
4. Use of CO₂ in enhanced coal bed methane recovery

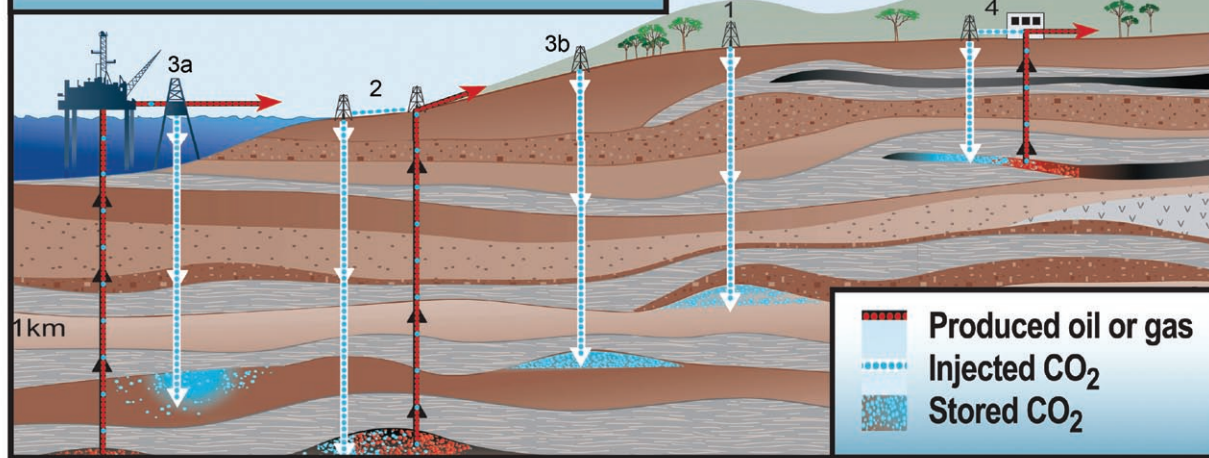


FIGURE 2 Types of geological formations and reservoirs that can be used for sequestration. MODIFIED FROM THE CARBON DIOXIDE COOPERATIVE RESEARCH CENTER (CO₂CRC), [HTTP://WWW.CO2CRC.COM.AU/ABOUT/CO2CRC](http://www.co2crc.com.au/about/co2crc)

fine-textured shales, mudstones, or carbonate rocks, which have low permeability for any fluid. Even at large pressure gradients, flow rates across a seal can be very slow. More important, the small pore spaces have very high capillary entry pressures, which causes the rock to act as a membrane that allows water to pass but blocks CO₂ unless its pressure exceeds the capillary entry pressure (Fig. 5).

Geochemical Interactions among CO₂, Brine, and Formation Rocks

Injecting CO₂ (and other power plant flue gases, such as SO_x and NO_x) promotes geochemical reactions that can alter the mineral assemblage of the host rock and shift thermodynamic equilibria from those that existed prior to injection. During injection, some CO₂ dissolves in the formation brines, decreasing pH typically from near neutral to below 4, and leading to dissolution of some primary phases and precipitation of secondary minerals. These reactions may change formation porosity and permeability (Kharaka et al. 2006a). The nature of the reactions depends on the mineralogical composition of the host rock and associated formation brine. Dissolution of some minerals, especially iron oxyhydroxides, can mobilize toxic trace metals and, where residual oil or other compounds are present, the injected CO₂ can also mobilize toxic organic compounds (e.g. toluene, benzene). Environmental impacts could be significant if these mobilized contaminants migrate into potable groundwater (Kharaka et al. 2006a, b). Furthermore, if SO₂ is coinjected, oxidation near the well bore promotes formation of sulfuric acid, leading to extremely low pH (Knauss et al. 2005).

Reactive chemical transport simulations have been used to study how these reactions evolve over time. In general, the simulations suggest that, initially, carbonate cements dissolve, potentially increasing porosity; later, reactions are dominated by the dissolution of feldspar and the precipitation of carbonate minerals and clays, thus decreasing

porosity and permeability (Gaus et al. 2005). These reactions can also impact the strength and integrity of the rock formation and can modify fluid flow paths, thereby influencing subsequent geochemical reactions. Site-specific assessments of geochemical and hydrological conditions are needed in order to minimize the potential for groundwater contamination resulting from CO₂ sequestration projects.

Trapping Mechanisms and Long-Term Fate of CO₂

Performance standards for sequestration projects have not yet been established, but there is growing agreement that very high retention rates are needed. Hepple and Benson (2005) calculated that retention between 90 and 99% over 1000 years should be the goal, if sequestration is deployed on a large scale. Four trapping mechanisms can contribute

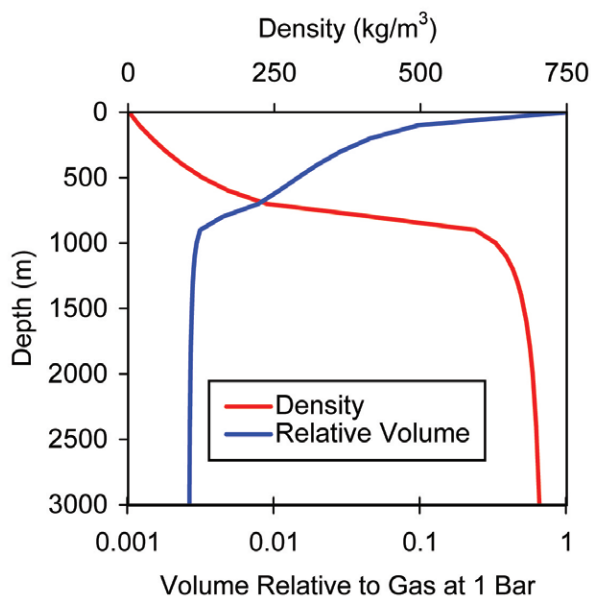


FIGURE 3 Density and change in volume of CO₂ as a function of depth below ground surface for a typical geothermal gradient

to retention over such long periods (IPCC 2005): structural trapping, solubility trapping, capillary trapping, and mineral trapping. The relative importance of these processes is expected to change over time as CO₂ migrates and reacts with the rocks and fluids, as illustrated conceptually in FIGURE 6. Reliance on the primary seal to retain CO₂ decreases as secondary immobilizing processes begin to dominate.

Structural Trapping

The single most important factor for securing CO₂ is the presence of a thick and fine-textured rock that serves as a seal above the sequestration reservoir. The seal should provide an effective permeability and capillary barrier to upward migration.

Capillary Trapping

Sometimes referred to as residual-phase trapping, this process traps CO₂ primarily after injection stops and water begins to imbibe into the CO₂ plume. The trailing edge of the CO₂ is immobilized, slowing up-dip migration. Capillary trapping is particularly important for sequestration in dipping aquifers that do not have structural closure. Studies by Hesse et al. (2008) and Ide et al. (2007) suggest that eventually all the CO₂ in a plume can be immobilized this way.

Solubility Trapping

The dissolution of CO₂ and other flue-gas contaminants into the pore water can lead to trapping by solubility. The amount of gas that can dissolve into the water depends on several factors, most notably pressure, temperature, and salinity of the brine (e.g. Spycher et al. 2003; Lagneau et al. 2005; Koschel et al. 2006; Oldenburg 2007). At the conditions expected for most geological sequestration (ambient to

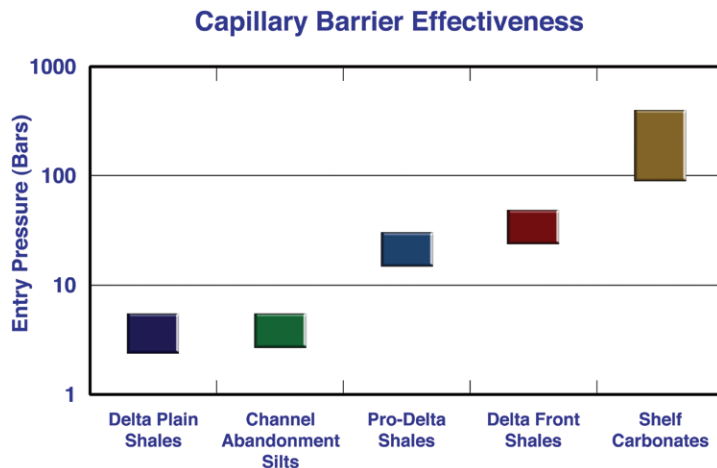


FIGURE 5 Capillary entry pressure for some typical seal rocks

~150°C and a few hundred bars total pressure), CO₂ solubility increases with increasing pressure (i.e. depth) but decreases with increasing temperature and salinity (FIG. 4B). Bench-scale experiments demonstrate that CO₂ dissolution is rapid at high pressure when the water and CO₂ share the same pore space (Czernichowski-Lauriol et al. 1996). However, in a real injection system, CO₂ dissolution may be rate-limited by the magnitude of the contact area between the CO₂ and the fluid phase. The principal benefit of solubility trapping is that once the CO₂ is dissolved, there is less CO₂ subject to the buoyant forces that drive it upwards.

Mineral Trapping

This mechanism occurs when dissolved CO₂ reacts directly or indirectly with minerals in the geologic formation, promoting precipitation of carbonate minerals (Oelkers et al. 2008). Mineral trapping is attractive because it could immobilize CO₂ for very long periods (Gunter et al. 1997). However, the process is thought to be comparatively slow because it depends on dissolution of silicate minerals, so the overall impact may not be realized for tens to hundreds of years or longer.

A COMPREHENSIVE APPROACH FOR SECURE GEOLOGICAL SEQUESTRATION

A fundamental understanding of the geologic, hydrologic, geomechanical, and geochemical processes controlling the fate and migration of CO₂ in the subsurface is necessary to provide a base for developing methods to characterize storage sites and to select sites with minimal leakage risk. However, even at a good storage site, engineering practices must be optimized to ensure reservoir integrity. Monitoring will play a key role in observing CO₂ behavior, in calibrating and validating predictive models, and in providing early warning that leakage may be imminent. In the event of threatened or actual leakage, remediation measures, such as plugging abandoned wells, would be needed. A regulatory infrastructure would be required to ensure due diligence in locating, engineering, operating, monitoring, and remediating CO₂ storage projects. Finally, private- and public-sector frameworks would be needed to ensure financial responsibility for covering short- and long-term liabilities.

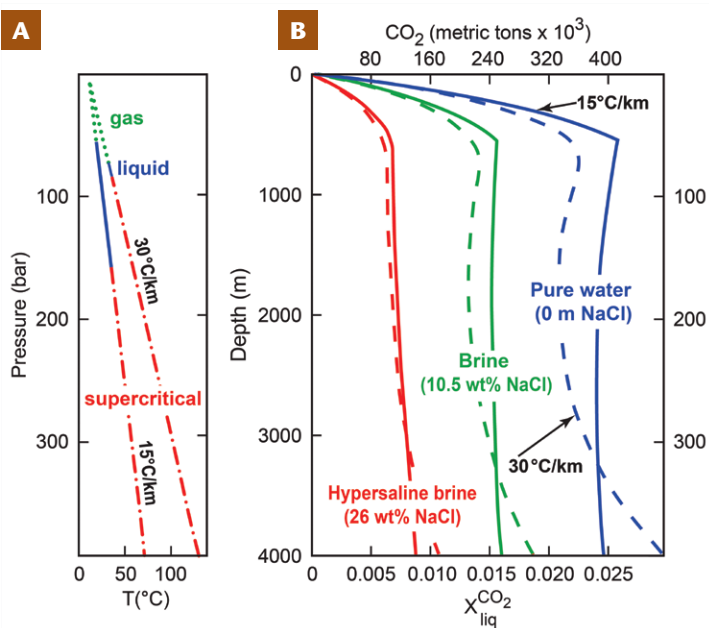


FIGURE 4 (A) Phase behavior of CO₂ as a function of temperature and pressure for two geothermal gradients. (B) Solubility (mole fraction, x) of CO₂ in a NaCl solution as a function of depth and salinity for two geothermal gradients. Model calculations (scaled by the top axis) estimate the mass of injected CO₂ trapped in a 20 m thick formation with 10% of its void space available for CO₂, in a volume extending 1 km out from the well in all directions. A pure-water system can dissolve 5 times more CO₂ than a hypersaline brine. BOTH FIGURES MODIFIED FROM OLDENBURG (2007)

MONITORING THE MIGRATION AND FATE OF INJECTED CO₂

Every sequestration project is likely to use a combination of monitoring techniques to track CO₂-plume migration and assess leakage risk. Technology for monitoring underground sites is available from a variety of other applications, including oil and gas recovery, natural gas storage, liquid and hazardous waste disposal, groundwater monitoring, food and beverage storage, fire suppression, and ecosystem monitoring. Many of these techniques have been tested at the three existing sequestration projects and at many smaller-scale pilot projects around the world (e.g. Arts et al. 2004; Hovorka et al. 2006). Specific regulatory requirements for monitoring have yet to be established. TABLE 1 provides examples of two programs that could be deployed to assure project performance and guard against safety and environmental hazards (Benson et al. 2005).

Geophysical Monitoring

Several methods can be used to observe the migration of the CO₂ plume. Seismic imaging can detect changes in compressional-wave velocity and attenuation caused by the presence of CO₂. Electromagnetic imaging can detect decreases in electrical conductivity when CO₂ is present in rock pores as a separate phase. Gravity measurements are sensitive to the decrease in bulk-rock density when CO₂ is present. To date, seismic imaging has been used most extensively and with great success.

FIGURE 7 shows a sequence of seismic cross sections collected from the Sleipner project. The first image, from 1994, was obtained before injection started. Only two major reflections are evident, correlating with the top and bottom of the Utsira Sand. By the first post-injection survey in 1999, three years after injection began, about 3 million tons of CO₂ had been injected. Several new reflections are present, which are interpreted to represent CO₂ trapped within the pores of the Utsira Sand. The plume is about 1 km wide. Subsequent images show continued plume growth as more CO₂ is injected.

Seismic imaging can also be used in other geometric configurations, such as between two or more wells (cross-well imaging) or with a combination of surface sources and borehole sensors (vertical seismic profiling). These higher-resolution methods have been applied with success at several pilot-scale CO₂ injection tests (Hovorka et al. 2006).

Geochemical Monitoring

Two approaches can be used to monitor CO₂ injection. The first uses fluid samples collected from observation wells where changes in brine composition or the presence of introduced or natural tracers are monitored. The second monitors the near-surface for CO₂ leakage.

By far the most rapid and inexpensive on-site measurement tools available to aid in tracking the injected CO₂ and its breakthrough to observation wells are pH, alkalinity, and gas composition. Of these, pH is probably the most diagnostic indicator of brine-CO₂ interaction. A marked decrease in pH correlates directly with CO₂ breakthrough. The compositions of major, minor, and trace elements can be used to assess the extent of water-CO₂-rock interactions. Enrichment of constituents such as Fe, Mn, and Sr can indicate mineral dissolution at depth during reaction of CO₂-saturated brine with rock (Emberley et al. 2005; Kharaka et al. 2006a, b).

Tracer studies are important for in situ subsurface characterization, monitoring, and validation. Naturally occurring elements, such as the stable isotopes of light elements (¹⁸O, D, ¹³C, ³⁴S, ¹⁵N), noble gases (He, Ne, Ar, Kr, Xe), and

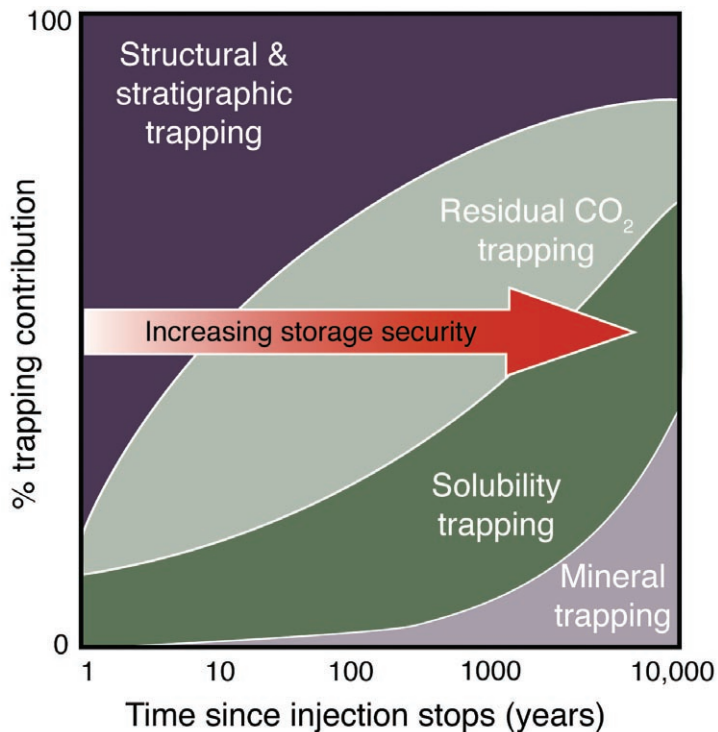


FIGURE 6 A general representation of the evolution of trapping mechanisms over time (IPCC 2005). Actual trapping mechanisms and evolution vary from site to site.

TABLE 1 MONITORING PROGRAMS THAT COULD BE USED OVER THE LIFETIME OF A SEQUESTRATION PROJECT (AFTER BENSON ET AL. 2005)

Basic monitoring program	Enhanced monitoring program
<i>Pre-operational monitoring</i>	<i>Pre-operational monitoring</i>
Well logs Wellhead pressure Formation pressure Injection- and production-rate testing Seismic survey Atmospheric-CO ₂ monitoring	Well logs Wellhead pressure Formation pressure Injection- and production-rate testing Seismic survey Gravity survey Electromagnetic survey Atmospheric-CO ₂ monitoring CO ₂ -flux monitoring Pressure and water quality above the storage formation
<i>Operational monitoring</i>	<i>Operational monitoring</i>
Wellhead pressure Injection and production rates Wellhead atmospheric-CO ₂ monitoring Microseismicity Seismic surveys	Well logs Wellhead pressure Injection and production rates Wellhead atmospheric-CO ₂ monitoring Microseismicity Seismic survey Gravity survey Electromagnetic survey Continuous CO ₂ -flux monitoring Pressure and water quality above the storage formation
<i>Closure monitoring</i>	<i>Closure monitoring</i>
Seismic survey	Seismic survey Gravity survey Electromagnetic survey CO ₂ -flux monitoring Pressure and water quality above the storage formation Wellhead pressure monitoring

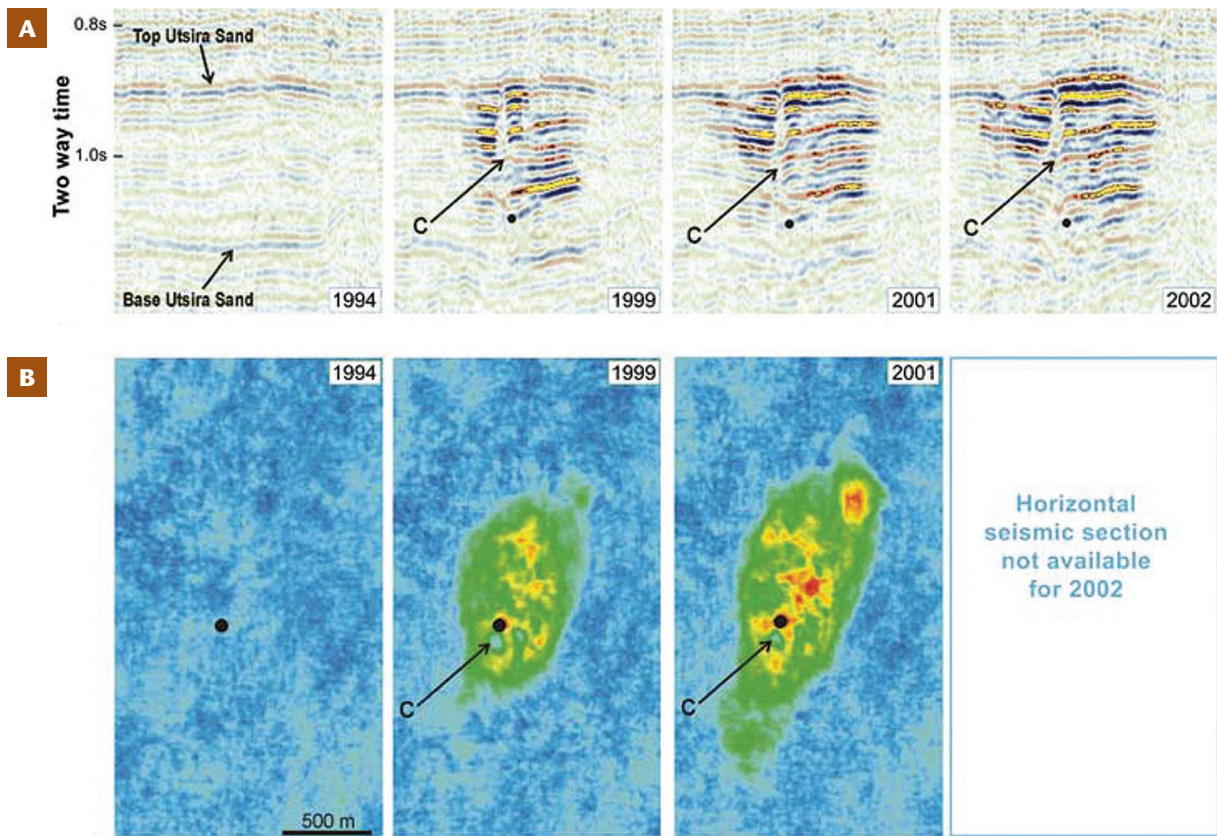


FIGURE 7 (A) Time series of vertical seismic sections through the CO₂ plume in the Utsira Sand at the Sleipner field under the North Sea. CO₂ saturation (c) is high above the injection point (black dot); the bright layers (black) correspond to high acoustic response where CO₂ is present as a separate phase in sandstone beneath thin, low-permeability horizons. (B) Horizontal sections. FROM IPCC (2005)

radioactive isotopes (e.g. tritium, ¹⁴C, ³⁶Cl, ¹²⁵I, ¹²⁹I, ¹³¹I), can be used to complement information from gas and brine composition and to determine the sources of liquid and gas and the processes controlling their migration. This information then allows assessment of the extent of fluid–rock interactions and quantification of fluid residence times in the subsurface (e.g. Kharaka et al. 2006a, b). Although naturally occurring constituents and isotopic composition have the advantage of being available, tracers can be injected for additional insight into subsurface conditions (Wells et al. 2007).

Surface-flux monitoring can directly detect and measure leakage. It may be measured directly with eddy covariance towers, flux accumulation chambers, and instruments such as a field-portable, high-resolution infrared (IR) gas analyzer (Klusman 2003; Miles et al. 2005). Year-round monitoring is needed to distinguish leakage from the highly variable natural biological CO₂ fluxes caused by microbial respiration and photosynthesis at the surface (Klusman 2003; Cortis et al. 2008).

RISKS AND PUBLIC PERCEPTION

Gaining support for CCS will require engaging the interest and building the support of a variety of stakeholders, each with different perspectives and goals. Policy makers want to understand the effects of CCS on the economy. Regulators want to know about the environmental impacts. Commercial developers need confidence in feasibility and financial security. The local community wants to be assured that the process is safe, that groundwater resources are not endangered, and that property values will increase, or at least will not be degraded by proximity to a storage reservoir—and the community perhaps also wants to be informed of other benefits. Public perception will ultimately determine whether or not CCS is implemented on a large scale.

While these perspectives bring a new dimension to large-scale deployment prospects, at the heart of them are four key questions:

- Will geological storage reservoirs leak?
- If leakage occurs, what are the health, safety, and environmental risks?
- Can leakage be predicted, detected, and quantified?
- What can be done to stop or slow a leak, should it occur, and how much would it cost?

Deploying CCS on a large scale will require developing persuasive answers—and effectively communicating them to all stakeholders. Geoscientists from many disciplines are needed to develop the base, test the various aspects, answer the questions, and continue to build a strong scientific foundation. The stakes are high and time is running out.

ACKNOWLEDGMENTS

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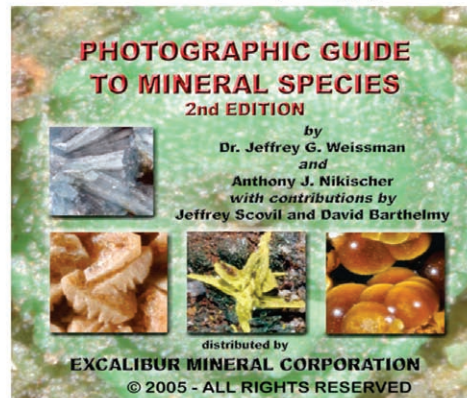
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Mineral Carbonation of CO₂



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A survey of the global carbon reservoirs suggests that the most stable, long-term storage mechanism for atmospheric CO₂ is the formation of carbonate minerals such as calcite, dolomite and magnesite. The feasibility is demonstrated by the proportion of terrestrial carbon bound in these minerals: at least 40,000 times more carbon is present in carbonate rocks than in the atmosphere. Atmospheric carbon can be transformed into carbonate minerals either *ex situ*, as part of an industrial process, or *in situ*, by injection into geological formations where the elements required for carbonate-mineral formation are present. Many challenges in mineral carbonation remain to be resolved. They include overcoming the slow kinetics of mineral–fluid reactions, dealing with the large volume of source material required and reducing the energy needed to hasten the carbonation process. To address these challenges, several pilot studies have been launched, including the CarbFix program in Iceland. The aim of CarbFix is to inject CO₂ into permeable basaltic rocks in an attempt to form carbonate minerals directly through a coupled dissolution–precipitation process.

KEYWORDS: CO₂ sequestration, mineral carbonation, mineralogic storage, basalt carbonation

INTRODUCTION

Mineral carbonation is the fixation of CO₂ as stable carbonate minerals, such as calcite (CaCO₃), dolomite (Ca_{0.5}Mg_{0.5}CO₃), magnesite (MgCO₃) and siderite (FeCO₃) (Metz et al. 2005). Insight into the potential effectiveness of storing atmospheric CO₂ as carbonate minerals is demonstrated by the relative volume of these reservoirs worldwide. The total mass of carbon currently in the atmosphere is approximately 800 gigatons (Gt). In contrast, ~39,000,000 Gt of carbon are currently present in carbonate rocks, such as marble, limestone and chalk, in the Earth's crust (cf. Oelkers and Cole 2008 this issue). In nature, the formation of carbonate minerals from atmospheric CO₂ is one of the major processes in the long-term global carbon cycle (Berner et al. 1983). Gaillardet et al. (1999) stated that about 0.1 Gt of carbon per year is bound by silicate-mineral weathering throughout the world; at this rate, the global atmospheric CO₂ inventory would be consumed after about 8000 years.

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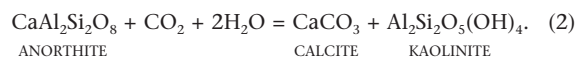
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Mineral carbonation requires combining CO₂ with metals to form carbonate minerals. With few exceptions, the required metals are divalent cations, including Ca²⁺, Mg²⁺ and Fe²⁺. One of the major challenges in the mineral sequestration of CO₂ is, therefore, to obtain these cations. The most abundant cation source is silicate minerals. Carbonate phases are energetically favoured to form from the interaction of CO₂ with such silicate phases as forsterite and anorthite (Seifritz 1990; Lackner et al. 1995; Lackner 2002) in accord with reactions such as:



and



Such reactions have been observed in nature and in the laboratory (e.g. Giammar et al. 2005; McGrail et al. 2006). An alternative to the formation of divalent-cation carbonate minerals, which could eliminate the risk of forming pore-clogging Al-bearing clay minerals, is dawsonite [NaAl(CO₃)(OH)₂], but this compound has high reactivity and relatively low stability, so it is not a good candidate for long-term CO₂ storage (Hellevang et al. 2005; Bénézech et al. 2007).

EX SITU MINERAL CARBONATION

Although the formation of stable carbonate phases by reacting CO₂ with silicate minerals is thermodynamically favourable, it is not straightforward on an industrial scale. There are three major challenges: (1) the mammoth scale of an *ex situ* CO₂ mineralization effort, (2) the need to accelerate the rate of carbonate formation to make it efficient and (3) the large energy costs (cf. Rubin 2008 this issue).

Scale

According to the U.S. Environmental Protection Agency (EPA) E-Grid, an average coal-fired power plant produces 4 million MWh of electricity per year (DOE/EPA 2000). Coal power plants in the US produce approximately one metric

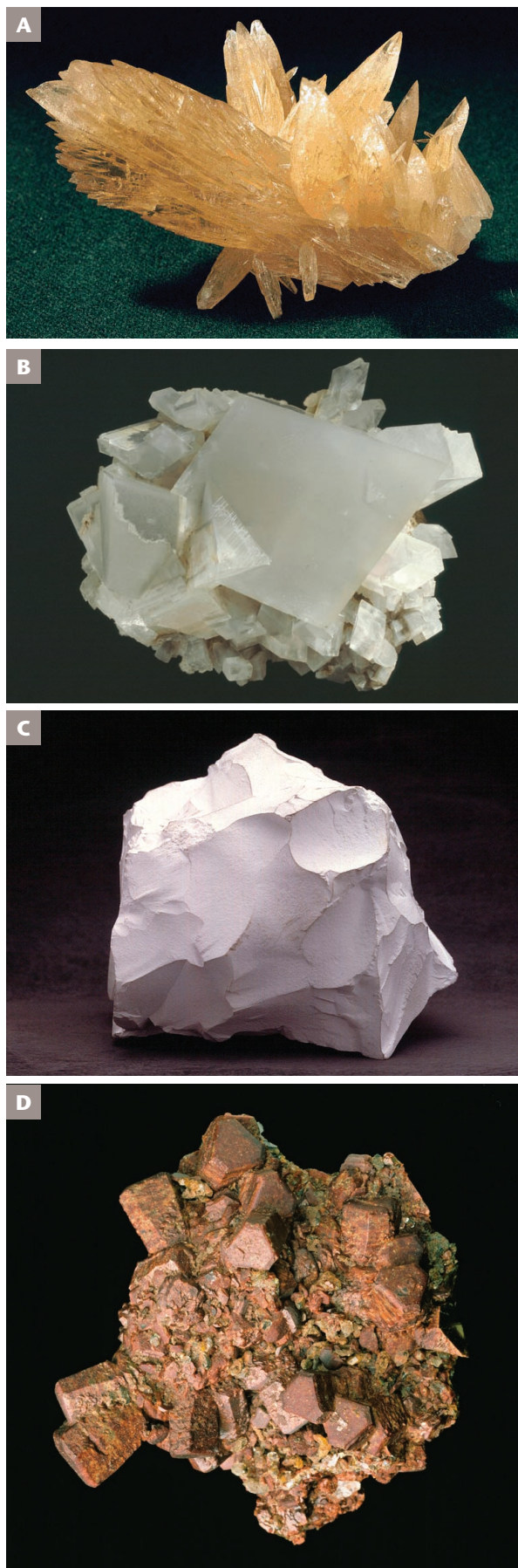


FIGURE 1 Potential mineral hosts of CO₂: (A) calcite, (B) dolomite, (C) magnesite, (D) siderite. COPYRIGHT NHM PICTURE LIBRARY

ton of CO₂ per MWh (DOE/EPA 2000). Based on this emission factor, a 4-million-MWh coal-fired plant emits 4 million tons of CO₂ or 1.1 Mt (1.1×10^3 Gt) of carbon per year.

TABLE 1 lists potential sources of divalent metals required for carbonation; FIGURE 1 and TABLE 2 show the potential CO₂ mineral hosts. The most efficient mineral for sequestering carbon is forsterite, but 6.4 Mt of forsterite would be required to fix the 4 Mt of CO₂ emitted annually from a typical coal-fired power plant. This process would create 2.6 million cubic metres of magnesite, equal to the volume of a cube 140 metres on a side. Note, however, that natural rocks do not contain only the minerals listed in TABLE 1. Numerous other minerals may be present, including those that are poor in divalent cations and those that provoke precipitation of other minerals, such as clays, that compete for the available dissolved metals. As a result, the total mass of rock required to fix CO₂ is usually substantially larger than that listed in this table.

Accelerating Carbonation Rates

In nature, mineral carbonation reactions such as equations 1 and 2 are thermodynamically favoured but proceed slowly. Both in nature and in most mineral carbonation scenarios, the metal-silicate mineral dissolves, and then, through a coupled reaction, a metal carbonate precipitates. In most cases, silicate-phase dissolution rates are slower than the corresponding carbonate precipitation rates, so hastening dissolution is the key to optimization. The dissolution rates of forsterite, wollastonite, serpentine, anorthite and basaltic glass are accelerated by increasing the water-mineral interface area, by increasing temperature and by adding acid or, in some cases, base (cf. Oelkers 2001; Carroll and Knauss 2005). Organic acids have also been observed to accelerate silicate dissolution rates (Golubev and Pokrovsky 2006). A number of studies have attempted to optimize ex situ carbonation methods by increasing temperature, by grinding the silicate source materials and by dissolving them in acidic solutions (e.g. Huijgen et al. 2006).

Energy Penalty and Costs

Ex situ formation of carbonate minerals requires energy and money to transport suitable initial material to a 'carbonation reactor', to grind this material, to heat the reactor system and to store or dispose of the solid CO₂-rich end product. The overall energy costs (or penalty; cf. Rubin 2008) depend on many factors, including the transport distance, the cation content and solubility of the original silicate rock, the degree of grinding required and the quality of the CO₂ stream to be treated. One estimate was reported by Gerdemann et al. (2007), who studied the reaction of Ca-, Fe- and Mg-silicate minerals. Their evaluation of resources, kinetics, process development and costs for each step in the

TABLE 1 SOME POTENTIAL SOURCE MINERALS FOR CARBON MINERALIZATION

SOLID	CHEMICAL FORMULA	Tons required to sequester 1 ton of carbon
Wollastonite	CaSiO ₃	9.68 ^a
Forsterite	Mg ₂ SiO ₄	5.86 ^b
Serpentine/ chrysotile	Mg ₃ Si ₂ O ₅ (OH) ₄	7.69 ^b
Anorthite	CaAl ₂ Si ₂ O ₈	23.1 ^a
Basaltic glass	Na _{0.08} K _{0.008} Fe(II) _{0.17} Mg _{0.28} Ca _{0.26} Al _{0.36} Fe(III) _{0.02} Si _{1.02} O _{3.45}	8.76 ^c

^a as calcite; ^b as magnesite; ^c assuming all Ca, Mg and Fe are converted into calcite, magnesite and siderite

process suggested a total price of ~\$54 per ton of CO₂ sequestered. However, they also concluded that the scale of ex situ mineral carbonation operations needed to immobilize the CO₂ emissions from a 1 GW coal-fired power plant would require moving 55,000 tons of rock per year; the mass of rock that would have to be mined, transported and eventually stored could make such operations impractical.

Another process proposed for ex situ mineral carbonation is to combine CO₂ with fly ash, which is the solid residue generated from coal combustion when lime is used to neutralize the gas stream in the chimney. Further neutralization of the ash with CO₂ produces carbonate minerals (Soong et al. 2005). Fly ash may contain as much as 30% CaO and Fe₂O₃, depending on the impurities in the coal itself and its burning efficiency, making it an effective source of metal cations. However, limited supplies of fly ash make this option unfeasible at a large scale. US coal-fired power plants produced 71.1 Mt of fly ash in 2005, which is less than 5 mass% of the CO₂ emitted annually in the US. Note also that the production of lime, which is the source of much of the CaO present in the fly ash, releases substantial CO₂ to the atmosphere. Nevertheless, although it cannot provide a complete CO₂-sequestration solution, removal by fly ash could aid CO₂ immobilization efforts while removing particulate material and acid gases (CO₂, NO_x, SO_x) from the chimney gas.

IN SITU MINERAL CARBONATION

In situ mineral carbonation overcomes some of the limitations of an ex situ process because in this approach CO₂ is injected directly into porous rocks in the subsurface, where it can react directly with the host rock. In situ carbonation eliminates the need for transport of reactants in and end products out, and may provide heat to accelerate the carbonation process. The choice of host rock, however, is critical. It must contain easily dissolved metal cations and have sufficient permeability and pore volume to store the injected CO₂ and carbonate-mineral products.

A number of reactive-transport calculations has been made to assess the degree to which in situ CO₂ mineralization is possible within sandstones and sandstone-shale sequences (e.g. Xu et al. 2005). Such calculations suggest that both dawsonite and iron-bearing carbonates could precipitate, depending on the composition of the host rock and, in particular, the presence of iron(II)-bearing minerals such as chlorite. Such reactions, however, appear to be relatively slow in response to sluggish silicate dissolution rates; mineral carbonation in such rocks could require 100,000 years or more to produce 90 kg of carbonate minerals per cubic metre of sandstone, if sufficient Al, Na and Fe are present in the rock.

In contrast, in situ mineralization may be far more effective in basalt or ultramafic rock (e.g. McGrail et al. 2006; Matter et al. 2007), which are rich in divalent cations and poor in silica. A typical basalt contains 7–10 wt% Ca, 5–6 wt% Mg and 7–10 wt% Fe, and these metals are readily liberated by reaction with CO₂-rich water.

There is diverse evidence demonstrating the potential of CO₂ sequestration in mafic and ultramafic rocks. First, despite the fact that less than 10% of the Earth's continental surface is covered by basalt, it takes up ~33% of all the CO₂ consumed during natural weathering of Earth's surface silicates (Dessert et al. 2003). Second, the flux of Mg and Ca liberated when CO₂-rich water reacts with basalt is as much as two orders of magnitude larger than when they react with other, more crystalline or silica-rich rocks (Wolff-Boenisch et al. 2006). Third, several well-documented examples of carbonation

of basaltic rocks are known, such as through hydrothermal alteration (Gudmundsson and Arnórsson 2002) and surface weathering (Gislason and Eugster 1987; Gislason et al. 1996; Gislason et al. 2006). Fourth, enormous volumes of mafic and ultramafic rocks are present on the Earth's surface. For example, the Columbia River basalts have a volume in excess of 200,000 km³ and the Siberian basalts, 1,000,000 km³. The locations of some of the major continental basalts are shown in FIGURE 2. These large volumes have a correspondingly large CO₂-sequestration capacity: McGrail et al. (2006) estimated that the Columbia River basalts alone have the capacity to sequester in excess of 100 Gt of CO₂. Many lava flows are porous and permeable and have enormous storage capacity. Basalts also dominate the seafloor, providing vast in situ carbon-mineralization sites throughout the world (Goldberg et al. 2008). Thus, storage in basalts is now considered to be among the best of the options for sequestering CO₂ (O'Connor et al. 2003).

Further insight into in situ mineral carbonation in basalts and ultramafic rocks comes from the results of reactive-transport modeling. Marini (2007) simulated the interaction of injected CO₂ with a number of potential host rocks. Results for CO₂ in a basaltic-glass reservoir are shown in FIGURE 3. Dissolution of basaltic glass by carbonated water promotes the formation of chalcedony (SiO₂), goethite (FeOOH) and the clay mineral kaolinite. The model suggests that after ~1 year, siderite precipitates, followed by dolomite, dawsonite and magnesite. Substantial CO₂ mineralization is evident after 10–100 years of reaction. The volume of these secondary phases is, however, substantially greater than that of the basaltic glass that was dissolved to make them, leading to the potential of these phases to clog the available pore spaces and, in some cases, to substantially decrease the permeability of the host rock (Gysi and Stefánsson 2008).

In situ mineral carbonation in basalt or ultramafic rocks is not without its challenges. These include the availability of water for carbonation, the need for impermeable cap rocks, and the possible mobilization of trace and toxic metals.

TABLE 2 CARBONATE PHASES FOR POTENTIAL MINERAL STORAGE OF CO₂

Mineral	Formula	Mass produced per ton C (ton)	Volume produced per ton C (m ³)
Calcite	CaCO ₃	8.34	3.08
Magnesite	MgCO ₃	7.02	2.36
Dawsonite	NaAl(CO ₃)(OH) ₂	12.00	4.95
Siderite	FeCO ₃	9.65	2.49
Ankerite	Ca(Fe,Mg)(CO ₃) ₂	8.60	2.81

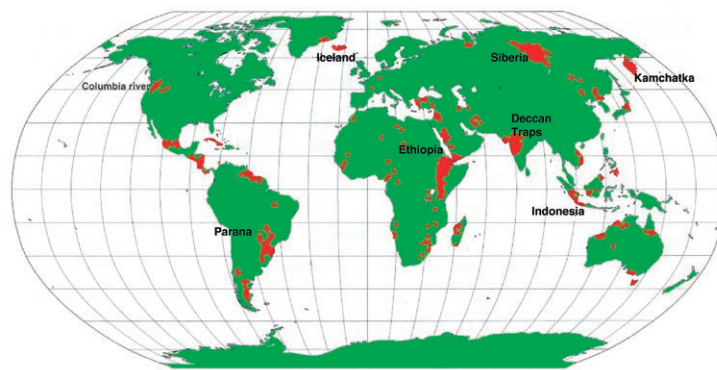


FIGURE 2 Locations of continental basalts that could serve as in situ mineral carbonation sites

AVAILABILITY OF WATER

In situ mineral carbonation requires that the injected CO₂ dissolve into an aqueous solution. CO₂ can be dissolved in water prior to its injection or injected into the target rock formation so that it can dissolve directly into the existing groundwater. Dissolving CO₂ prior to its injection requires large quantities of water. To dissolve one ton of CO₂ at 25 bars partial pressure and 25°C requires ~27 tons of water. This quantity increases to ~341 tons of water at a CO₂ partial pressure of 2 bars. If such large volumes of water are available, CO₂ dissolution can be accomplished at the borehole or during injection. Injecting large quantities of CO₂-rich water requires substantial well-bore permeability at the locality of the bore hole. Injection costs depend on the amount of energy required to pump the CO₂-rich water down the hole. Some of these challenges may be overcome by injecting CO₂ into oceanic basalts. This procedure offers

two advantages: (1) a large volume of water for CO₂ dissolution is readily available (Brady and Gislason 1997) and (2) such basalts may be covered by low-permeability sediments, which serve as a seal to slow water escape, allowing time for reaction (Goldberg et al. 2008).

Direct injection of CO₂ overcomes the difficulty of finding sufficient water, but leads to other problems. If injected as a separate phase, CO₂ must dissolve into the groundwater before carbonation can begin. CO₂ diffusion into groundwater can be a slow process, depending on system hydrology and the chemical composition of the groundwater.

Cap Rock Impermeability

Because both CO₂ dissolution into groundwater and coupled mineral dissolution-precipitation reactions leading to carbon mineralization may be slow, an impermeable cap rock is essential to keep the dissolved CO₂ in contact with the reactive host rock for sufficient time to allow carbonation. Cap rocks are common in oilfield reservoirs but may be missing over a basalt or ultramafic formation. A further complication is that these rock types are commonly fractured. The permeability of the cap rock itself may be altered by its reactions with the injected CO₂, leading to leaks in the originally impermeable barrier (Gaus et al. 2005).

Trace- and Toxic-Metal Mobility

The dissolution of CO₂ into water produces carbonic acid, which reacts with the host rocks to liberate the cations necessary to create carbonate minerals. These reactions may also release trace and toxic metals into solution, allowing them to migrate. The degree to which these metals move with the formation water depends on the hydrology and chemistry of the system. Flaathen and Gislason (2007) reported that trace and toxic metals released from the interaction of basalt and CO₂-charged water are readily immobilized as further reactions increase groundwater pH. The degree to which these metals are immobilized in sandstone, however, remains unclear.

The CarbFix Project

In an attempt to assess the feasibility of in situ CO₂ mineralization in basaltic rocks, a field-scale project, CarbFix, is scheduled to begin during 2009 at Hellisheidi, Iceland (www.carbfix.com). The injection site (FIG. 4) is adjacent to a new geothermal power plant, which will supply up to 30,000 tons of CO₂ per year for injection into subsurface basalts at a depth of 400–700 m and a temperature of ~30°C. The Hellisheidi site was chosen for several reasons, including a local source of CO₂, the availability of several strategically located wells for monitoring the chemical evolution of the groundwater, and the proximity to infrastructure through Reykjavik Energy, a CarbFix partner. CO₂ will be injected at a partial pressure of 25 bars and will be dissolved in water during injection. It is anticipated that the results of this project will be used to optimize the in situ carbon mineralization process, enabling in situ carbonation at sites throughout the world.

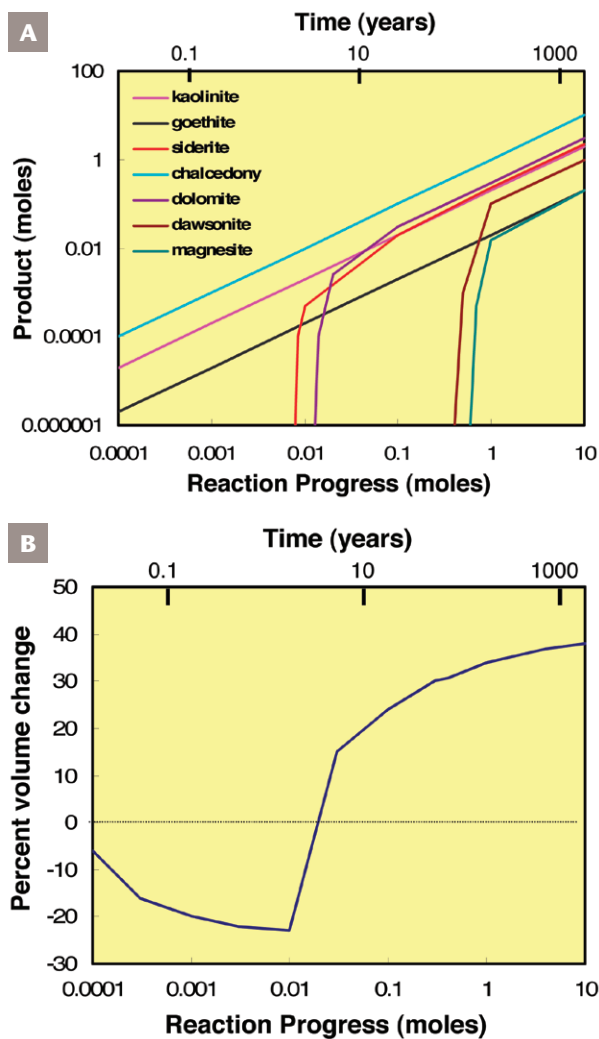


FIGURE 3 Results of reactive-transport calculations for the injection of CO₂ at a pressure of 100 bars into a basaltic-glass reservoir at 60°C (after Marini 2007): (A) mass of secondary minerals formed and (B) change in rock volume as a function of reaction progress and time. Reaction progress is presented as the number of moles of basaltic glass dissolved. For example, after 10 years of the interaction of the CO₂-rich fluid with a basaltic-glass reservoir, one might expect that 0.06 moles of glass had dissolved, leading to the formation of 0.05 moles of chalcedony, 5×10^{-3} moles of kaolinite, 5×10^{-3} moles of dolomite, 4×10^{-3} moles of siderite and 5×10^{-4} moles of goethite. These reactions would increase net volume by 20%, potentially clogging existing pores. Note that these are the results of model calculations, which provide useful predictions, but different minerals could precipitate in the natural systems.

CONCLUSIONS AND PERSPECTIVES

In situ CO₂ mineralization offers the potential for long-term, safe CO₂ storage at a reasonable price. Optimizing this technology, however, will require a multifaceted effort, including field-scale pilot studies, to better characterize the rates of mineral carbonation reactions and the fate and consequences of injecting CO₂ into reactive silicate rocks. Public acceptance and government/industry support will require development of new monitoring techniques to demonstrate that the injected CO₂ has indeed been fixed

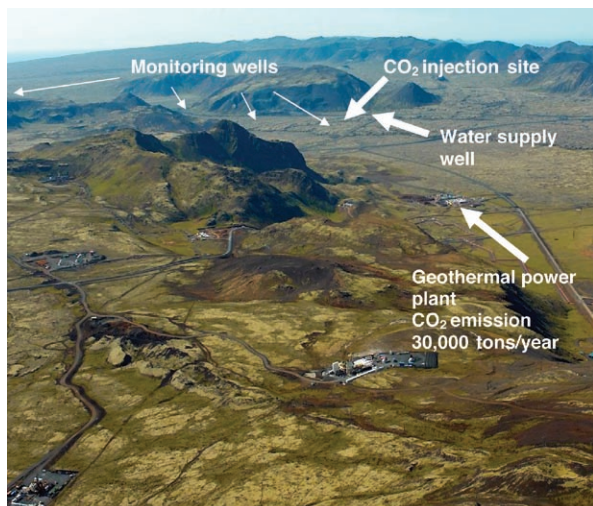


FIGURE 4 The field-scale, in situ basalt-carbonation pilot plant in Hellisheiði, Iceland. PHOTO BY MATS WIBERLUND

in carbonate rocks, with minimal risk that it will leak to the atmosphere. Such monitoring techniques may involve developing chemical or isotopic fingerprinting methods that can characterize subsurface carbonation. They will also require improved techniques to quantitatively define subsurface fluid flow paths and, eventually, sites of blockage. Thus, a large effort by the scientific community is still required to ensure that this sequestration method is economically and technologically viable.

ACKNOWLEDGMENTS

We thank S. Callahan, O. Pokrovsky, J. Schott, D. Wolff-Boenisch, A. Stefánsson, E. Gunnlaugsson, D. Cole H. Sigurðardóttir, G. Björnsson, M. Stute, G. Axelsson and W. Broecker for insightful discussion and encouragement throughout this study. E. Valsami-Jones generously provided the photographs shown in Figure 1. This work was supported by the Centre National de la Recherche Scientifique, the Earth Institute at Columbia University, Carb-Fix and two European Commission Marie Curie Grants (MEST-2005-012210 and MRTN-2006-31482). ■

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A Preview of Goldschmidt 2009

Davos, Switzerland • June 21–26, 2009

The 19th annual V.M. Goldschmidt Conference will take place June 21–26, 2009 at the Congress Centre in Davos, Switzerland. The Organizing Committee invites you to come and discover the unique blend of landscape, architecture, sporting and urban delights.

CHALLENGES TO OUR VOLATILE PLANET

This year the conference focuses on past, contemporary and future challenges to the Earth's resources and environment. The 20 themes and over 100 sessions will be joined by high-profile speakers and compelling panel discussions to highlight the future of geochemistry in its global context.

IMPORTANT DATES

Abstract submission and early registration will be open at the conference website on January 1, 2009, and the deadline for submission of abstracts is February 22, 2009. Early registration, at reduced cost, closes May 22, 2009.

VENUE

Davos is set in the breath-taking mountain landscape of the Grisons Alps, and at 1560m above sea level the town is the highest in Europe. Most famous for hosting the World Economic Forum, Davos is also known as a place for exhilarating summer and winter sports. It was founded in the Middle Ages, and from the middle of the eighteenth century Davos became a popular destination for wealthy visitors and those who sought the clear mountain air for their health.

Today Davos has a plenty of sights and entertainments for visitors and their families including horse-drawn carriages, pony trekking, mountain biking, water-sports, rambling, museums, shopping and the botanical garden. For those who want more science there is the Physical and Meteorological Observatory and the relic Silderberg mines. If you would rather relax, try a visit to the golf course, casino, brewery or spa centre.



Kirchner Museum

DAVOS CONGRESS CENTRE

Goldschmidt2009 will take place at the Congress Centre in Davos Platz. Located within easy reach of accommodation, shops and restaurants, it is also served by excellent bus services to the nearby valleys and sites. Davos has over 35 years of experience in hosting international congresses, including Goldschmidt2002. The Congress Centre offers a selection of modern and comfortable theatres, equipped with hi-tech presentation technology. The entire Centre has wireless network access.

TRAVEL

Reliable public transportation connects Davos to key places in Switzerland and Europe, making your journey through the scenic landscape a relaxing start to the conference. By car, the journey from Zurich International Airport takes just 2 hours, and by train, 2.5 hours. Detailed information on how to reach Davos can be found on the official Davos website: www.davos.ch

ACCOMMODATION AND FOOD

Davos has 20-30,000 beds in accommodation to suit every budget, from self-catering to 5* hotels. There are also nearly 100 restaurants and bars in which to enjoy a wide range of international cuisine. Detailed accommodation, travel and amenities information will become available on the conference website.

SOCIAL EVENTS AND FIELD TRIPS

The conference ice-breaker, banquet and other social events will be held in the Congress Centre. A number of short Field Trips are planned to take a look at the varied geology of the Alps. Details of the excursions will be posted on the conference website.

CONFERENCE WEBSITE

See the conference website for the list of themes, all the latest news and information, and to sign up for the mailing list.

www.goldschmidt2009.org



The Grisons Alps



Family hiking



Congress Centre



Alpine dining

www.goldschmidt2009.org



NOTES FROM ST. LOUIS

Nicholas Wigginton Named GN Editor



Dr. Nicholas Wigginton (Ecole Polytechnique Fédérale de Lausanne) has been appointed as the editor of *Geochemical News*. He succeeds Carla Koretsky and Johnson Haas, who had held the position since 2001. Nick is a recent PhD graduate of Virginia Tech and was endorsed by Carla and Johnson for his innovative ideas and enthusiasm.

Be sure to visit the Geochemical Society website for the latest issue of *Geochemical News*.

Melbourne Goldschmidt Receives Meeting of the Year Award



In May 2008, it was announced that the 2006 V.M. Goldschmidt Conference™ was awarded the prestigious Meetings and Events Industry's 2007 Meeting of the Year Award for meetings with more than 500 delegates. The 2006 conference was held from August 27 to September 1, 2006, at the Melbourne Exhibition and Convention Centre in Melbourne, Australia. It was the 16th annual V.M. Goldschmidt Conference and the first one held in the southern hemisphere. A total of 1515 abstracts were submitted, and 1283 delegates from 37 countries attended.

The Executive Organizing Committee included Simon Turner (pictured with the award), Janet Hergt, John Foden, Hugh O'Neil, and Greg Yaxley. The Scientific Program Committee included Mark Harrison, Jon Woodhead, Marc Norman, Vickie Bennett, Andy Barnicoat, Andy Gleadow, Kurt Knesel, and Bruce Schaefer. The conference was managed by Tour Hosts Pty. Limited of Sidney, Australia.

Goldschmidt2009 – Challenges to Our Volatile Planet

The 19th annual V.M. Goldschmidt Conference will take place June 21–26, 2009, at the Congress Centre in Davos, Switzerland. This year the conference focuses on past, contemporary, and future challenges to the Earth's resources and environment. The 20 themes and over 100 sessions will feature high-profile speakers and compelling panel discussions to highlight the future of geochemistry in its global context.

Davos is set in the breathtaking mountain landscape of the Grisons Alps, and at 1560 m above sea level, the city is the highest in Europe. Most famous for hosting the World Economic Forum, Davos is also known as a place for exhilarating summer and winter sports. Other entertainment includes numerous restaurants and bars, museums, shopping, golf course, casino, brewery, spa center, and even horse-drawn carriages. Located within easy reach of accommodation, shops, and restaurants, the Congress Centre has over 35 years of experience in hosting international conferences, including Goldschmidt2002. It offers a selection of modern and comfortable theaters equipped with hi-tech presentation technology, including wireless network access. Reliable public transportation connects Davos to key places in Switzerland and Europe, and with some 20,000–30,000 beds, there is accommodation to suit every budget, from self-catering to five-star hotels.

JANUARY 1, 2009: Abstract submission and online registration open

FEBRUARY 22, 2009: Abstract submission deadline

MAY 22, 2009: Early-registration deadline

See the conference website for a list of themes and the latest news and information, and to enter your name on the mailing list. www.goldschmidt2009.org (See also ad on page 338.)

2009 Fellows Nominations Deadline is December 15, 2008

Every year we ask that you please take the time to consider the accomplishments of your valued friends and colleagues by nominating them for a Geochemical Society award. With your help, we can ensure that all of geochemistry is recognized and all deserving geochemists are considered. **The GS/EAG Geochemical Fellows Award** is bestowed upon outstanding scientists who have, over some years, made a major contribution to the field of geochemistry. **December 15, 2008**, is the deadline for nominations to be considered for these awards. For information on nomination requirements, visit the Geochemical Society website at www.geochemsoc.org/awards.2009.

Membership Drive

Join online at www.geochemsoc.org

- 25% off Elsevier book orders
- 20% off Wiley/Jossey-Bass publications

2009 MEMBER RATES

(ALL RATES IN US\$)

- Professional: \$30
- Student: \$10
- Senior: \$12 (retired, 65+)

2009 SUBSCRIPTION RATES

Subscription rates (in US\$) are at cost. GS does not make money from member subscriptions.

Elements – Free! (included with membership)

GCA HARDCOPY + ONLINE ACCESS (1995 TO PRESENT)

- Professional: \$147
- Student or senior: \$81

GCA ONLINE ACCESS ONLY (1995 TO PRESENT)

- Professional: \$84
- Student or senior: \$42

G-CUBED ONLINE ACCESS

- Professional or senior: \$80
- Student: \$40

MEMBER DISCOUNTS

Publication Discounts

- 40% off GS special publications
- 25% off most MSA publications including RIMG

REGISTRATION DISCOUNTS

AGU Joint Assembly

24–27 May 2009: Toronto, Ontario, Canada
www.agu.org/meeting/ja09/

V.M. Goldschmidt Conference™

21–26 June, 2009: Davos, Switzerland
www.goldschmidt2009.org

GSA Annual Meeting & Exposition

18–21 October 2009: Portland, Oregon, USA
www.geosociety.org/meetings/2009/

AGU Fall Meeting

14–18 December 2009: San Francisco, California, USA
www.agu.org/meetings/

COMMUNITY

- Access our website's members-only content
- Vote for Board of Director officers
- Receive important announcements and updates
- Participate in member surveys
- Discover volunteer opportunities

For a full report on the Goldschmidt Conference, go to pages 352 and 353 in the Meeting Reports Section

How Are We Doing?

We want to hear from you about our programs and services.

Send comments and/or suggestions to Seth Davis at:

seth.davis@geochemsoc.org



Mineralogical Society of America

www.minsocam.org

PRESIDENT'S LETTER



Moving to a Paperless World

Last December, I closed my President's Letter with a promise that I would report on a transition that is looming on MSA's horizon—the changeover to a paperless version of our flagship journal, *American Mineralogist*. In my conversations with previous leaders of MSA, this topic arose repeatedly as the most perilous challenge that our society faces, and

I asked Vice-President Nancy Ross to convene an ad hoc committee to explore the problem and to report at the spring council meeting in late May. The bottom line from Nancy's committee was this: there is no need to panic.

It will not surprise any members who are familiar with the personnel in our business and publications office that Alex Speer, Rachel Russell, and the editors have been on top of this problem for some time. They have evaluated the mechanisms and the timeline for the transition, and they have developed a stepped pathway to virtual publication that is financially sound and responsive to the needs of our members.

As Rachel emphasized to Council, some of the details that lie behind the publication of *American Mineralogist* are surprising. The largest costs associated with printing eight issues each year (~\$350,000) are incurred not by the production of the physical volumes but by the human components: salaries, rental of office space, peer review, and use of the AllenTrack database. The cost of printing and mailing a year's worth of volumes is \$100,000, mostly reflecting the outlay for paper. In other words, the switch from paper to paperless will diminish our publication expenses, but only by about 25%.

The primary source of income for *American Mineralogist* is the institutional subscribers. That number has been dropping consistently for the past decade. In 1998 it was 978, and today it is 603. As most of you know, libraries have been eliminating subscriptions for many science magazines because the costs of the "elite" journals have increased substantially and university libraries around the world have faced budget cuts. With each institutional subscription set at around \$800, that decrease represents a loss to MSA of many hundreds of thousands of dollars. To counter this trend, MSA served as a founding member of GeoScienceWorld (GSW), which offers electronic access to *American Mineralogist* and over 40 other Earth science journals. GSW offers a deal that few libraries can turn down, and GSW now boasts 308 subscribers. Every time someone downloads an *American Mineralogist* article through GSW, MSA receives compensation. Last year, MSA collected \$85,000 from GSW, and we hope to see that number soar even higher.

As GSW grows in popularity, the demand for hardcopies of *Am Min* will continue to diminish. Among individual members, the number of journal subscribers who have selected electronic access is approaching 25%. The publications office at MSA has developed a two-step system to address this trend. When the number of printed copies of *American Mineralogist* falls below 500 copies, Rachel will move to a digital printing process that becomes cost-effective for smaller runs. This transition

should not be apparent to the readership. When the number of printed copies approaches an even smaller number, perhaps 200, then MSA will generate those hardcopies through "print-on-demand" (PoD) services. With PoD, it always will be possible for members to receive a hardcopy for a reasonable subscription price, even if only one person desires it. In addition, PoD will provide physical volumes for archival preservation.

The ad hoc committee raised some questions that can only be answered as that final changeover draws nearer. Future officers will have to set a date for the switch from the hardcopy to the virtual version of *American Mineralogist* as the "journal of record." For example, electronic papers are more amenable to colored figures and dynamic graphics, and those enhancements become "official" components of the article once the electronic version is recognized as the journal of record. Second, MSA will continually analyze the business model for the virtual *American Mineralogist* to ensure that income balances expenses.

It is reasonable for members to greet this new frontier with some degree of unease. On the other hand, it is a transition that all science journals are confronting. Indeed, the American Geophysical Union recently announced that it will no longer produce print versions of any journals after 2008. We all should feel some assurance that MSA is in the hands of the most capable people, with the expertise to navigate this next stretch of the ongoing publications revolution.

With this final letter, I move into the realm of virtual presidents. Many thanks to the dedicated councilors and office staff who have made this job such a pleasure, and welcome to Nancy Ross.

Peter J. Heaney, MSA President
Pennsylvania State University

AMERICAN MINERALOGIST UNDERGRADUATE AWARDS FOR OUTSTANDING STUDENTS

The Society welcomes the following exceptional students to the program's honor roll and wishes to thank the sponsors for enabling the Mineralogical Society of America to join in recognizing them. MSA's American Mineralogist Undergraduate (AMU) Award is for students who have shown an outstanding interest and ability in mineralogy, petrology, crystallography, or geochemistry. Each student is presented a certificate at an awards ceremony at his or her university or college and receives an MSA student membership with electronic access to *American Mineralogist* and an MSA publication chosen by the sponsor, student, or both. Past AMU awardees are listed on the MSA website. Instructions on how MSA members can nominate their students for the award are also provided on the site.

Kathryn M. Albright

Acadia University – Sponsored by Dr. Sandra Barr

Seela H. Lahti

University of New Brunswick – Sponsored by Dr. Cliff Shaw

Merilie Reynolds

Smith College – Sponsored by Dr. John Brady



EVEN IF YOUR INTERESTS ARE DIFFERENT THAN THOSE AROUND YOU, THERE IS A PLACE FOR YOU IN MSA.
JOIN MSA ONLINE AT WWW.MINSOCAM.ORG

NOTES FROM CHANTILLY

• MSA members were contacted electronically in September to renew their membership for 2009. Members who renewed and paid online before October 31, 2008, received a \$5 dues discount; the discount reflects cost savings to MSA from members who renew early online. After several electronic reminders, a paper copy will be sent during November to those who did not renew online by the end of October.

• Members and Fellows who are in the senior, honorary, and life categories are sent renewal notices. They need not pay dues, but are sent notices as the best way to prompt an update of membership information, particularly mail and e-mail addresses.

Members qualify for Senior Member or Senior Fellow status if they have reached the age of 65, have retired from fulltime professional employment, and have been a member of the Society for at least 30 years. Senior Members and Fellows

retain all benefits of MSA membership (receiving *Elements*, voting rights, reduced rates on MSA products, etc.), but need not pay dues. They can subscribe to the paper or electronic version of *American Mineralogist* or other journals, purchase Society publications, and attend short courses all at member rates. If you are interested in senior status, select Senior Member or Fellow dues on your next renewal and write in the text box that you would like to become a Senior Member.

• If you subscribe to other journals through MSA—*Journal of Petrology*, *Physics and Chemistry of Minerals*, *Mineralogical Abstracts*, *Mineralogical Record*, *Rocks & Minerals*, *Gems & Gemology*—please renew early. MSA needs to forward your renewal to the publishers before your subscription runs out.

• The results of the 2008 election are in: the new president of the Society is Nancy L. Ross, the new vice-president John B. Brady, and the new treasurer Darrell J. Henry. Secretary Mickey Gunter

remains in office. The new councilors are Marc M. Hirschmann and Penelope L. King. They join continuing councilors Jean Morrison, Klaus Mezger, Peter C. Burns, and Carol D. Frost.

• Accepting the recommendations of the respective award committees, MSA Council selected Alexandra Navrotsky of the University of California–Davis as the 2009 Roebling Medalist. Robert M. Hazen of the Carnegie Institution of Washington is the 2009 Distinguished Public Service Medalist. Jillian F. Banfield of the University of California–Berkeley is the 2010 Dana Medalist, and Thomas Patrick Trainor of the University of Alaska–Fairbanks is the 2009 MSA Awardee

• The 2009 Kraus Crystallographic Research Grant recipient is Andrew J. Wall, Pennsylvania State University, for his study “Assessing Cu isotopic fractionation in Cu-(Fe)-S minerals using time-resolved synchrotron X-ray diffraction.” The 2009 Mineralogy/Petrology Research Grant recipients are: Christopher M. Fisher,

Memorial University of Newfoundland, for his study “Testing the Use of Synthetic Minerals as Isotopic Reference Materials: An Example Using Hafnium in Zircon” and Dongbo Wang, Virginia Tech, for the study “Investigating a New Pathway to Carbonate Mineralization and Implications for Mg:Ca Paleoenvironmental Signatures.”

• New Fellows of the Society are Daniele Cherniak, Patrick Cordier, Herta Effenberger, Kiyoshi Fujino, Robert W. Luth, Masanori Matsui, A. Mottana, Enver Murad, Philip Peter Nabelek, and Lidunka Vočadlo.

• Reports by the MSA secretary and the MSA treasurer containing more details on these and many other society events of the past year can be obtained on the MSA website by selecting “Officer Reports” under “The Society”.

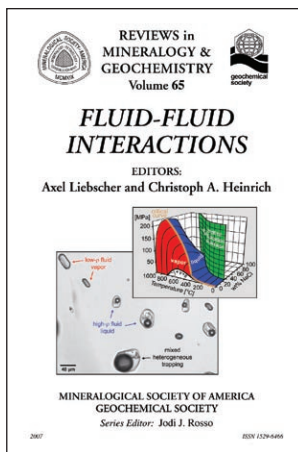
J. Alex Speer

MSA Executive Director
j_a_speer@minsocam.org

FLUID-FLUID INTERACTIONS

REVIEWS IN MINERALOGY & GEOCHEMISTRY VOL. 65

Mineralogical Society of America and Geochemical Society



Fluid-Fluid Interactions explores the role that co-existing mixing and unmixing fluids play in the diverse geologic environments. Fluid interactions in continental, volcanic, submarine, and subduction zone environments are examined.

Volume 65, 2007, Axel Liescher and Christoph A. Heinrich, eds. i-xii and 430 pp. ISBN 978-0-939950-77-5. US\$40

For a more detailed 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, Tel: +1 (703) 652-9950, Fax: +1 (703) 652-9951, e-mail: business@minsocam.org

2008–2009 MSA DISTINGUISHED LECTURERS

The Mineralogical Society of America is pleased to announce its Distinguished Lecturers and their lectures for 2008–2009

Donald Dingwell

University of Munich, Munich, Germany
Explosive Volcanism: A Materials Catastrophe
and
Flow of Magma: Solving a Rheological Puzzle

Jennifer Jackson

California Institute of Technology, Pasadena, California, USA
Diamonds, Iron, and X-rays: Views into Earth's Interior
and
The Behavior of Iron-Bearing Mineral Assemblages in Earth's Lower Mantle

Bruce Marsh

The Johns Hopkins University, Baltimore, Maryland, USA
History of Geologic Exploration of Antarctica, Magma in the Proposed Yucca Mountain Nuclear Repository,
and
Magmatic Mush Column Magmatism: McMurdo Dry Valleys, Antarctica

The schedules of the Lecturers' tours are given on the MSA website (www.minsocam.org/MSA/Lecture_Prog.html). Check to see if they will be at a location near you. MSA expresses its appreciation to these individuals for undertaking such a service to our science.



IN MEMORIAM

EDWARD J. MARCIN (Life Fellow – 1947)
AKHIO MIYASHIRO (Life Fellow – 1962)
EDUARD WOERMANN (Fellow – 1965)



Mineralogical Society of Great Britain and Ireland

www.minersoc.org

EXCITING LINE-UP OF MEETINGS

In recent months the Society has been busy planning for several meetings, which will all happen in the next 18 months. Details of these are given below.

Nature's Treasures: Minerals and Gems

Natural History Museum, London – Sunday, 7 December 2008



This is a one-day meeting, co-organized by Gem-A (the Gemmological Association and Gem-testing Laboratory of Great Britain), the Russell Society and the Mineralogical Society. It will provide a day of short talks of interest to an audience comprising members of all three organizations and to others who have not previously had an association with any mineral/gem society. Students from schools and universities will be welcome. A morning of short talks will be followed by lunch and, in the afternoon, by a series of mineral displays.

An exciting group of talks is planned:

- **ROY GILL**, University of Edinburgh: 'Minerals and their growth, shapes and colours'
- **JACK OGDEN**, Gem-A: 'Minerals to gems, and ancient uses'
- **JEFF HARRIS**, Glasgow: 'Smashing diamonds'
- **ANDY RANKIN**, Kingston: 'Fluid and solid inclusions in minerals and gems; guides to their origin'
- **KATHRYN GOODENOUGH**, British Geological Survey, Edinburgh: 'Mapping and mineral exploration in Africa'
- **KAREN HUDSON-EDWARDS**, Birkbeck College, London: 'Environmental mineralogy'
- **CHRIS STANLEY**, Natural History Museum, London: 'Industrial applications of minerals'
- **BOB SYMES**, Devon: 'Minerals in the field: where to find them, and how to collect responsibly'
- **BRIAN JACKSON**, Edinburgh: 'Agates'
- **ADRIAN FINCH**, St. Andrews University: 'Mineral luminescence: the brilliance of imperfections'

Register online at

www.minersoc.org/pages/meetings/nature/nature.html

New Views of the Earth's Interior

Burlington House, London – 12–13 February 2009

This is a cross-disciplinary meeting organized jointly by the British Geophysical Association and the Mineral Physics Group of the Mineralogical Society. The aim is to present new developments on the structure, composition, dynamics and evolution of all parts of the Earth's interior. This includes subduction zones, the transition zone, the lower mantle and D'', and the Earth's inner and outer cores. Scientists who have agreed to give presentations are: Dr Arwen Deuss (Cambridge, UK), Dr Dan Frost (BGI), Prof. Alex Halliday (Oxford, UK), Prof. Thorne Lay (University of California Santa Cruz, USA), Dr Carolina Lithgow-Bertelloni (UCL, UK), Prof. Graham Pearson (Durham, UK), Prof. Andreas Rietbrock (Liverpool, UK), Prof. Paul Tackley (ETH, Switzerland), Dr Lidunka Vočadlo (UCL, UK), Prof. Don Weidner (SUNY-Stony Brook, USA).

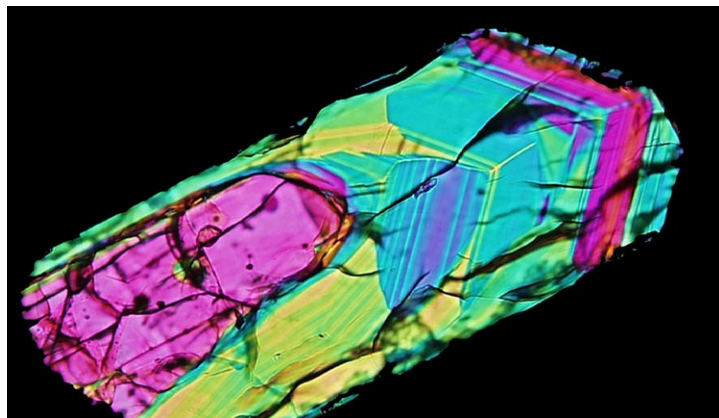
Dr Sebastian Rost will also present the Bullerwell Lecture of the British Geophysical Association at the meeting.

Go to www.minersoc.org/pages/groups/minphys/minphys.html#views for more information or to register; contact the convenor, Prof. J. Brodholt, University College London, at j.brodholt@ucl.ac.uk for information.

Micro-Analysis, Processes, Time (MAPT)

Edinburgh, 31 August to 2 September 2009

Numerous updates to the proposed sessions for this meeting have been published on the MAPT website. Please visit www.minersoc.org/pages/meetings/MAPT/MAPT.html for details about this exciting meeting.



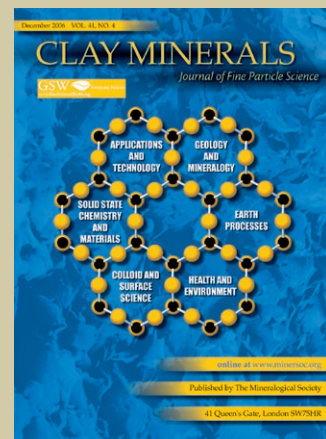
PUBLICATIONS NEWS



Mineralogical Magazine

The editors of *MinMag* have been working hard to catch up on the delay in publication of the journal. At the time of writing, the June 2008 issue is in press. The February 2008 issue comprises extended abstracts from the Geochemistry of the Earth's Surface 8 conference held in London in August 2007. This is available on an open-access basis at

www.ingentaconnect.com/content/minsocmag/2008/00000072/00000001. Feel free to visit and download copies of the abstracts free of charge!



Clay Minerals

We are delighted to announce that Prof. D. Bish (University of Indiana) has become an Associate Editor of *Clay Minerals*. Welcome Dave.

MINERALOGICAL ABSTRACTS TO CEASE PUBLICATION AFTER 88 YEARS

Minabs Online, formerly *Mineralogical Abstracts*, will cease publication at the end of 2008 after nearly 90 years of operation. At its peak in the late 1980s, *Mineralogical Abstracts* had a circulation of some 600 library subscribers, as well as many more individual subscribers who were members of the joint publishers, the Mineralogical Society of Great Britain and Ireland and the Mineralogical Society of America. From the outset, part of the *Mineralogical Abstracts* ethos was to make geochemical, mineralogical and petrological data available worldwide and, in particular, to help those who could not afford to subscribe to the growing number of published journals. This ethos was continued in recent years when *Minabs Online* was made available at nominal cost, or free in many cases, to colleagues in more than 100 developing nations. A feature of both *Mineralogical Abstracts* and *Minabs Online* has been to list the more important data and the conclusions along with the abstract. Also the original title has always been quoted exactly as in the original paper (inclusive of any spelling variants), but the correct or IMA-approved spelling of mineral names was used in the text of the abstracts. This feature has been particularly appreciated by students completing their theses and by authors of papers for publication.

Mineralogical Abstracts first appeared in March 1920 as a supplement in *Mineralogical Magazine*. Its first editor was L.J. Spencer, Keeper of Mineralogy at what is now the Natural History Museum, and he continued as Editor for 36 years. It started with just a few abstracts in each issue, but by the time Spencer's reign as Editor ended in 1956 and he was succeeded by Norman Henry, the number of abstracts had increased considerably. To cope with the increasing output, Spencer recruited colleagues from all over the world to act as abstractors, and he appointed sub-editors to take charge of the editing and arrangement of 18 sub-sections.

The steady increase in the number of abstracts necessitated a change in page size, leading to *Mineralogical Abstracts* being published as a separate journal from the *Mineralogical Magazine* in 1958, when James Phemister took over as Editor. Over the next few years, the growing number of abstracts reflected the upsurge in research papers resulting from innovations such as the electron microprobe, X-ray spectrometry, X-ray fluorescence, etc. Around this time more abstractors were recruited from universities, museums, and geological surveys around the world. Individuals who assisted valiantly include such people as P. Bayliss, A.C. Bishop, R.I. Gait, R.K. Harrison, C.M.B. Henderson, R.A. Howie, B. Lindqvist, B. Mason, D.J. Morgan, R.F. Nafziger, A. Pabst, I. Parsons, G.W. Robinson, N.C.N. Stephenson, I. Sunagawa, M. Weibel and J. Zeeman.



Robert Howie

The initials R.A.H. (representing Prof. R.A. Howie) first appeared beneath an abstract in 1958; the number of RAH abstracts increased steadily year by year, and during the last year of publication, there will be more than 1700 RAH abstracts. Bob Howie was appointed Editor in 1966 (designated as Principal Editor in 1971) and served on the Mineralogical Society Council continuously for more than 40 years. During that time, he has contributed some 60,000 abstracts to *Mineralogical Abstracts* and *Minabs Online*. In 1999 Jim MacDonald was appointed as Deputy Principal Editor, and in

2002 he became Joint Principal Editor with the specific remit of overseeing the creation of the online version of *Mineralogical Abstracts*. Bob Howie retired as Principal Editor in 2003.

January 2004 saw the launch of *Minabs Online*, whose database included all the abstracts published in *Mineralogical Abstracts* since 1982, and during that year the print version was phased out. Due to ill health, Jim MacDonald stood down as Principal Editor in 2007 and was succeeded by Harry Shaw. A key member of the editorial staff whose contribution to *Mineralogical Abstracts* and *Minabs Online* also needs to be acknowledged is Robert Preston. Robert provided expertise in the areas of printing and scientific publishing as well as helping editorially in many, many abstracts.

Although the creation of *Minabs Online* achieved very significant savings in production costs, the institutional subscription base continued to shrink with increased competition from both subscription-based and free searchable databases. In addition, increasing pressure on academics and others worldwide has made it increasingly difficult to recruit volunteer abstractors to provide the quality of abstracts required, and the problem could not be rectified by employing paid abstractors because of the need to minimise production costs. Most significantly, perhaps, the recent disappointing usage of the database has made it difficult to justify the very considerable effort made by the editors and our worldwide team of volunteer abstract writers. The combination of these factors has led us to the decision to discontinue publication at the end of 2008. The Mineralogical Society intends to retain the 132,000 abstracts (1981–2008) as a 'free-to-all' resource, as long as demand exists.

The Mineralogical Society Council and membership say a very big 'Thank you' to all those who have worked on *Mineralogical Abstracts* and *Minabs Online* over the years. Your enormous contribution has helped many generations of scientists deal with the increasingly huge volume of literature available to them. We hope that you will be able to continue to serve the Society in other ways.

NOW AVAILABLE
FOR PURCHASE FROM THE MINERALOGICAL SOCIETY


Landmark Papers

Metamorphic Petrology

} NUMBER

The key benefit in the Landmark series is the commentaries by guest editors. Bernard Evans, in this case, places in context the chosen works and describes how they contributed to the advancement of the science. He weaves a fascinating tale. "Many metamorphic rocks are attractive in appearance, in hand specimen and in thin section under the microscope. Their aesthetic appeal touches senses beyond the merely scientific, a pleasure that most geochemists forego. Added to this is the satisfaction we derive as they reveal each new instance of nature's fidelity to scientific laws. But the aesthetic appeal comes at a cost. Metamorphic petrologists need to be adept in very many things: crystal chemistry, physical chemistry, phase equilibria, microscopy, textural analysis, regional geology, structural geology, geodynamics and geochronology."

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www.minersoc.org

AND FINALLY

It's coming close to annual subscription time again. We have introduced a small increase in the membership fee for this year. Members and fellows will be asked to pay £32, i.e. an increase of £1. Students are still entitled to one year's free membership. Students renewing will be billed at the bargain rate of £10. Optional extras include paper journals and/or e-journals. Please visit www.minersoc.org/pages/msinfo/membership.html for details about the charges for these. This year, for the first time, members will be able to pay their dues online. A message will be sent to all members in early November, inviting them to do so.

Kevin Murphy, Executive Director Mineralogical Society
Kevin@minersoc.org



Société Française de Minéralogie et de Cristallographie

www.sfmc-fr.org

GENERAL ASSEMBLY AND COUNCIL MEETING

The SFMC held its general assembly at the Museum d'Histoire Naturelle, Paris, on 10 June 2008. During the meeting, the Society awarded the Prix Haüy-Lacroix to Mélanie Auffan (see *Elements*, August 2008).



FROM LEFT TO RIGHT, Dominique DeLigny, Anne Marie Boulrier, Michel Maquet, Catherine Mével, Stéphanie Rossano, Marc Blanchard, Patrick Cordier, Mélanie Auffan, Martine Lagache, Anne Marie Karpoff, François Farges

FORTHCOMING WORKSHOPS AND MEETINGS

Transmission Electron Microscopy Workshop

A workshop on new developments in TEM techniques and applications will be organized by Patrick Cordier and held in Lille in January 2009 (patrick.cordier@univ-lille1.fr).

Micro-Analysis, Processes, Time Conference (MAPT)

The Society, as co-convenor, is involved in sessions of the 2009 annual meeting of the Mineralogical Society of Great Britain and Ireland. The program is still being developed. The conference will be held in Edinburgh, from 31 August to 2 September 2009. The SFMC is involved in the following sessions:

- New advances in transmission electron microscopy characterisation and preparation of minerals (patrick.cordier@univ-lille1.fr)
- Environmental mineralogy: from science to solutions (farges@mnhn.fr)

For more information, visit

www.minersoc.org/pages/meetings/MAPT/MAPT.html.

XIV International Clay Conference

Society members are co-convenors of the following sessions at the AIPEA meeting, which will be held in beautiful Castellaneta Marina, Italy, June 14–20, 2009.

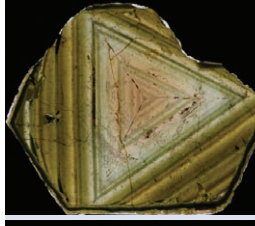
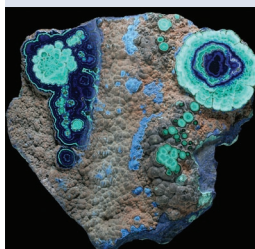
- Clays in geological processes (amk@illite.u-strasbg.fr)
- Serpentine as hot clays (baronnet@crmcn.univ-mrs.fr)
- Structural characterisation of lamellar compounds (Bruno.Lanson@obs.ujf-grenoble.fr)
- Crystal chemistry and structure of clays (alain.meunier@univ-poitiers.fr)

For more information, visit www.14icc.org/index.html.



For all SFMC and FFG joint activities visit the website
<http://e.geologie.free.fr>

A VIRTUAL GALLERY OF MINERALOGY IN PARIS



The Muséum National d'Histoire Naturelle in Paris has opened its virtual gallery of mineralogy and gemology. Funded thanks to the corporate philanthropy of the French oil company TOTAL, the website currently displays 300 samples from the museum collection. Historical samples that cannot yet be exposed to the public, like the Great Sapphire of Louis XIV of France, and recent acquisitions from the Himalayas are among the items shown in the gallery. Texts explain how minerals are formed and give scientific information on each mineral species presented. Some minerals can be visualized in 3D using QuickTime® VirtualReality technology. One can zoom into each sample to see details. The site is bilingual in French and English. The gallery is now in its first version, and further developments are underway to increase the number of displayed samples. A very new type of marketing was associated with the opening of the gallery, involving bloggers and journalists from the virtual world.

A blog (address below) gives details on recent acquisitions, donations, trips, exhibits and much more. The bilingual blog aims to provide recent information in a few clicks. Notes are classified according to the year (currently 2007 and 2008). Among the information given is a mention of the fabulous Rosenthal donation, recently obtained, which comprises many very rare gems (painite, red beryl and many more) and an exquisite fire opal from Mexico. The blog also highlights the instruments recently obtained by the Museum, including a Gandolfi-type micro-diffraction instrument and a variable-pressure scanning electron microprobe. Including its SIM and nanoSIMS capacities, the laboratory is one of the world's best, if not the best, laboratory for research centered around a major mineral and gem collection.

François Farges

Professor MNHN/Stanford, Curator in Charge

Website at:

www.museum-mineral.com/home.php

Video announcement in English (HD format) at: www.vimeo.com/1189820

Blog at:

www.mnhn.fr/blogmineralogie



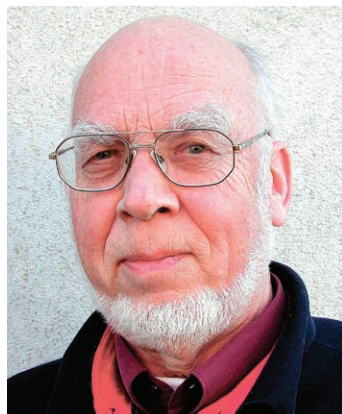
International Association of GeoChemistry

www.iagc.ca

IAGC AWARDS FOR 2008

Vernadsky Medal

The IAGC Vernadsky Medal is awarded to Bjørn Bølviken (Norwegian Geological Survey, Norway – retired) for a distinguished record of scientific accomplishment in geochemistry over the course of his career.



Bjørn Bølviken, recipient of the IAGC Vernadsky Medal

Bjørn Bølviken, born in 1928, is a Norwegian citizen. He obtained the title Siv.ing. in chemistry in 1953 at the Technical University of Norway (NTH). He worked for a short period as a professor's assistant at NTH. Since 1954 he has been employed by the Geological Survey of Norway (NGU) in various positions within its Chemical Division, ranging from researcher to division director. He has also been an associate professor at NTH, a visiting professor at Purdue University, Indiana, and a UN expert in geochemical exploration in Ecuador while on leave of absence from NGU. He has published a number of papers in applied geochemistry, in particular

in geochemical exploration for ores, geomedicine (medical geology), natural heavy-metal poisoning of soils, electrogeochemistry, regional geochemical mapping, and the statistical treatment of data.

Other Awards

- The honorary title of IAGC Fellow is bestowed on Gunter Faure (Ohio State University, USA) and Thure E. Cerling (University of Utah, USA) for outstanding contributions to the field of geochemistry.
- The Hitchon Award goes to Ralph Seiler, Ken Stollenwerk, and John Garbarino of the U.S. Geological Survey for their 2005 paper "Factors Controlling Tungsten Concentrations in Ground Water, Carson Desert, Nevada," which appeared in volume 20 of *Applied Geochemistry*.
- IAGC Certificates of Recognition are awarded to Rosa Cidu (University of Cagliari, Italy), John Gray (U.S. Geological Survey, USA), David Long (Michigan State University, USA), Jodie Miller (University of Stellenbosch, South Africa), and LeeAnn Munk (University of Alaska–Anchorage, USA) for scientific accomplishment in a particular area of geochemistry, for excellence in teaching or public service, or for meritorious service to IAGC.

Further details about these awards and profiles of the award recipients will be provided in the next IAGC Newsletter and posted on the IAGC website (www.iagc.ca).

IAGC WELCOMES NEW COUNCIL MEMBERS

Four members will join the IAGC Council for the 2008–2012 term. Rona Donahoe is an aqueous geochemist in the Department of Geological Sciences at the University of Alabama, USA. Nancy Hinman is a hydrochemist in the Department of Geology at the University of Montana, USA. Harue Masuda is a geochemist in the Department of Geosciences at Osaka City University, Japan. Zhonghe Pang is a geochemist in the Chinese Academy of Sciences.

IAGC SPONSORS MAJOR GEOSCIENCES SYMPOSIUM AT IGC 33

Since the era of modern geochemical analysis began in the 1960s, geochemistry has played an increasingly important role in the study of planet Earth. Today highly sophisticated analytical techniques are utilized to determine the major- and trace-element inorganic and organic compositions of the Earth's cosmological sphere, its atmosphere and surficial skin, and shallow and deep interiors across a wide range of spatial scales. With this in mind, IAGC sponsored a two-day symposium entitled "Contribution of Geochemistry to the Study of the Planet" during the 33rd International Geological Congress. The symposium consisted of a "Historical Perspectives" session, which comprised a historical review of geochemistry and its contributions to the study of the Earth, and a "Today and Tomorrow" session, which considered current and future developments in geochemistry and how the rapidly evolving analytical tools and approaches used by geochemists can be used to solve emerging environmental and other societal problems.

IAGC FOCUS ON CANADA IN 2009

IAGC is looking northward to Canada for its two major events in 2009. IAGC will join the Association of Applied Geochemists in the sponsorship and organization of the 2009 International Applied Geochemistry Symposium. IAGS2009 will take place on 1–4 June 2009 at the University of New Brunswick in Fredericton, New Brunswick, Canada. Keynote speakers include Kurt Kyser of Queen's University (Canada), Matt Leybourne of GNS Science (New Zealand), and William Chávez, Jr. of New

Mexico Tech (USA). Information is available at the website www.unb.ca/conferences/IAGS2009/.

The 8th Applied Isotope Geochemistry Symposium will take place just three months later. Organized by the IAGC Applied Isotope Geochemistry Working Group, this meeting will take place from 30 August to 4 September at the Manoir Richelieu, located near La Malbaie in a rural area about 1.5 hours by car from Quebec City. Further information can be obtained from Martine Savard (msavard@nrcan.gc.ca).

STUDENT RESEARCH GRANT AWARDS FOR 2009

To recognize and promote the work of young scientists in the field of geochemistry, the IAGC announced a Student Research Grant program in 2007. The objective of this initiative was to support the dissertation research of PhD students in geochemistry by helping them to undertake and acquire geochemical analyses.

An IAGC Student Research Grant award consists of a grant of up to US\$3000, a certificate, and an article profiling the recipient in the IAGC Newsletter and posted on the IAGC website. Each recipient of an IAGC Student Research Grant will also receive a complementary one-year membership in IAGC for the year following receipt of the award, if the student is not already a member.

More details on the grant program and how to apply can be found on the IAGC website, www.iagc.ca.



International Association of Geoanalysts

<http://geoanalyst.org>

REPORT ON THE 31ST ISO/REMCO MEETING



Jacinta Enzweiler

Users of geochemical data and geoanalysts share the need to know the closeness between analytical results and the real values of the measurands of their samples. Reference materials (RMs), which can be either certified or quality-control materials, play an essential role in achieving this objective. The vast majority of available geochemical RMs are non-certified because they were produced at a time when this issue was not so clear. Regardless of metrological category, all aspects related to RM production, use, terminology and certification should be subject to the guidelines developed by the Reference Materials Committee of the International Organization for Standardization (ISO/REMCO). The benefits of applying strict

metrological standards and the need for harmonization of results are reasons why the International Association of Geoanalysts has a Certification Committee and is an observing member within ISO/REMCO.

The 31st ISO/REMCO annual meeting, held in Rio de Janeiro from 10 to 13 June, 2008, was attended by 32 delegates representing the majority of the 31 participating countries and the 20 liaising international organizations, including the IAG. ISO/REMCO has several working groups, and at the meeting each presented the progress of its efforts, which are aimed mainly at the development of new ISO Guides or the revision of those already in use.

For instance, ISO Guide 80, "Production of RMs for Metrological Quality Control," which is still under development, will establish a common basis for the production of RMs intended for use in quality assessment, for the purpose of demonstrating that a measurement system is under statistical control, performs as expected and provides reliable results. It can be expected that this future guide will be of great interest to both the geochemical community and to the IAG, which already markets, for quality-control applications, materials that were part of previous rounds of the GeoPT™ International Proficiency Test programme.

Jacinta Enzweiler

IAG Representative at 2008 ISO/REMCO meeting

SECOND QUALITY ASSURANCE IN ANALYTICAL GEOCHEMISTRY WORKSHOP

The Goldschmidt Conference provides a great forum to present, discuss and review the latest advances in analytical geochemistry. The International Association of Geoanalysts took this opportunity to hold its second Quality Assurance in Analytical Geochemistry workshop, immediately before the 2008 Goldschmidt Conference in Vancouver. The goal of this year's one-day workshop was to foster discussion and highlight important aspects of good data

quality (e.g. measurement uncertainty, metrological traceability, proficiency tests, etc.).

The workshop was characterized by lively discussion and the expression of many concerns about the unawareness of how to properly report data. The 19 participants from governmental, academic and corporate backgrounds contributed much input from their own experiences, and all agreed that more needs to be done in the field of geochemistry to shift from the current notion of accuracy and precision

to the more universal measurement uncertainty concept. Such a change in paradigm will greatly facilitate comparison of data produced in different labs or between independent analytical methods or procedures.

At the Vancouver workshop the IAG emphasized its commitment to support the analytical geochemist by organizing collaborative trials, including the highly successful GeoPT proficiency test programme (www.geoanalyst.org), and by producing and distributing certified reference

materials (www.iageo.com) in accordance with ISO/REMCO guidelines. The success of these workshops has encouraged us to hold further such events at important regional meetings (DMG Conference, September 2008 in Berlin; MAPT meeting, September 2009 in Edinburgh), and of course at the 2009 Geoanalysis (South Africa) and Goldschmidt (Switzerland) conferences.

Thomas Meisel

Chairperson, IAG Certification Committee

OSMIUM ISOTOPE REFERENCE MATERIAL IAG-4 DROsS NOW AVAILABLE



A new reference solution, prepared collaboratively by the University of Durham and the IAG's Certification Committee, has been distributed to leading laboratories in the field of Os isotope research. IAG-4 DROsS exists as a 2000 µg/mL solution, of which roughly 10 litres remain in stock. In contrast to other solutions used for in-house quality control, this new solution is recommended for researchers planning to set up new Os isotope programmes, for method validation and for quality control in osmium isotope analysis, for example, for the radiogenic isotope ratios ¹⁸⁶Os/¹⁸⁸Os and

¹⁸⁷Os/¹⁸⁸Os and for cosmogenic induced changes in the isotope abundances of Os. In view of the current state of the art, it is not possible to certify this solution's absolute composition at an acceptable uncertainty level. An earlier solution (LOsST), distributed by Thomas Meisel, demonstrated that slight but significant biases exist among labs. The source of such bias has yet to be resolved to the extent that the total uncertainty of an absolute Os isotope determination can be reduced to a level that is significantly below the uncertainties reported for routine measurements. This issue is particular true for the ¹⁸⁶Os/¹⁸⁸Os ratio in the long-lived Pt-Os isotope system.

It is thus suggested to use IAG-4 DROsS as a "delta zero" solution for reporting variations of the ¹⁸⁶Os/¹⁸⁸Os ratio and variations of the stable isotope ratios. Such a strategy, if adopted by many researchers, will rapidly lead to an improved situation regarding the traceability of measurement data among various labs. Significantly, there is sufficient supply of DROsS in stock to last for perhaps two decades even if the MC-ICP-MS technique turns out to be the determination method of choice in the near future. The hope is that DROsS can be certified for its absolute Os isotope composition at some future date with an acceptable level of uncertainty, once methods have improved significantly.

Inquiries about IAG-4 DROsS can be addressed to the chair of the IAG's Certification Committee: thomas.meisel@unileoben.ac.at.



Association of Applied Geochemists

www.appliedgeochemists.org

PRESIDENT'S MESSAGE

IAGS 2009

We look forward to the AAG's 24th International Applied Geochemistry Symposium (IAGS), to be held in Fredericton, New Brunswick, Canada, on 1–4 June 2009. The technical program has been finalized; details and a first call for papers are available at www.unb.ca/conferences/IAGS2009. The symposium will feature 17 thematic sessions, with topics ranging from deep-search geochemical exploration methods to the application of geochemistry in CO₂ sequestration. There will be a plenary session in honor of Prof. Gerry Govett. A number of associated field excursions will run throughout the region before and after the symposium. This biennial meeting will be cosponsored for the first time by the AAG, the IAGC and the IAG, providing opportunity for members of the three societies to meet and discuss recent advances in areas of applied, pure and analytical geochemistry, on top of attending social gatherings.

AAG Distinguished Lecturer

On the educational front, Dr. Kurt Kyser from Queen's University will deliver a number of talks, in various locations worldwide, as the AAG Distinguished Lecturer for 2007–2009. Organizations interested in hosting talks by Kurt should contact the AAG. Details are on the AAG website (www.appliedgeochemists.org). The AAG is also increasing its commitment to the general educational side of the discipline through support of various short courses and workshops during the year, as well as by providing programs of training offered by individual AAG members to industry and the tertiary educational sector.

Supporting Students

The component of university Earth science programs that invariably attracts the strongest positive responses from students is fieldwork and related practical experiences – the opportunity to put theory into practice. Many science students decide to major in the geosciences after first-year field trips, and this decision is then reinforced by subsequent excursions arranged by their institutions or student societies. The logistics and costs of such ventures are substantial, and AAG will be renewing its efforts to secure additional funding from industry to support associated student chapters.

On the topic of students, all members of the geochemistry community are invited to submit nominations for the 2008 AAG Student Paper Competition, sponsored by SGS Mineral Services. The paper must have been published in the society's journal, *GEEA*, with the student as the principal author. All that is required is a copy of the paper and a brief letter setting out the grounds for nomination. Supervisors can nominate their students. Details are available at www.appliedgeochemists.org.

David Cohen
AAG President

University of New South Wales, Australia



Field excursion to examine acid mine drainage at the historic Sunny Corner Ag mine for staff and students from the University of New South Wales

INTRODUCING THE PRESIDENT



David Cohen

Prof. David Cohen is currently the departmental head at the School of Biological, Earth, and Environmental Sciences at the University of New South Wales (UNSW). He has over 20 years of experience in applied geochemistry and is a longstanding member of the AAG. Dave attended the University of Sydney, Queen's University (Canada), and UNSW, always with a focus on applied geochemical research. His teaching and research interests are exploration and environmental geochemistry, biogeochemistry, regional geochemical mapping, selective geochemical extractions, and statistical data analysis. Dave is a well-received keynote speaker and regularly publishes in the journals *Geochemistry: Exploration, Environment and Analysis (GEEA)* and *Journal of Geochemical Exploration*. Dave has been a key contributor to the Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME) in Australia, which is renowned for applying regolith science to the challenges facing Australia in natural resource management and mineral exploration.



CALL FOR PAPERS (Oral and Poster)

24th International Applied Geochemistry Symposium • Monday June 1st to Thursday June 4th, 2009
hosted by the University of New Brunswick – Fredericton, New Brunswick (Canada)
www.unb.ca/conferences/IAGS2009/

The extended-abstract volume will have a format of two to four pages in *GEEA* format, with a short 200-word abstract. These extended abstracts will be printed and reproduced on CD, as well as made available on the AAG website. The final deadline for submitting extended abstracts is February 15, 2009. For details on the abstract format, check out the website.



Mineralogical Association of Canada

www.mineralogicalassociation.ca

FROM THE PRESIDENT

The Role of MAC in the Mineralogical Sciences Today



Peter C. Burns

Upon becoming president of the Mineralogical Association of Canada (MAC) in May, I reflected on the history of our Association, seeking an informed approach to shaping its future. MAC was incorporated on August 5, 1955, by letters patent under the Canadian Corporations Act for the purpose of advancing knowledge in crystallography, geochemistry, mineralogy, petrology, mineral deposits, and allied sciences.

I am happy to report that MAC remains committed to the vision of the founding members and to affirm that this mission remains vital to the future of the mineralogical sciences. MAC has advanced knowledge in many ways, some highly visible to our membership, others less apparent. The most visible of MAC activities is publication of *The Canadian Mineralogist*, one of the premier mineral sciences journals in the world today. The journal has certainly evolved over the past 50 years, and now publishes six times a year papers with a broad international authorship and a similarly broad international readership. Over all these years, the journal has remained consistent with the original mission of MAC: publishing papers over the entire breadth of crystallography, geochemistry, mineralogy, petrology, mineral deposits, and allied sciences. Many of our members will also be aware that MAC was a founding organization in the highly successful publication *Elements*, which is enhancing recognition of important research by mineralogists (broadly defined). Another highly visible activity is our cosponsorship of the annual GAC-MAC meeting.

Less visible activities of MAC are also having an impact. Every year MAC sponsors one or more **short courses** and publishes corresponding volumes, thus providing professionals and students with an opportunity to broaden their scientific horizons. MAC sponsors **Berry Schools**, again providing unique opportunities for the continued intellectual growth of our membership (and others). In a similar vein, MAC sponsors special sessions at scientific meetings, both in Canada and abroad, which stimulate learning and debate in some of the most important areas of our science. MAC's highly successful **Special Publications** series—the envy of other mineralogical societies—includes spectacular volumes such as the recent ones concerning pegmatites and migmatites.

MAC also invests significantly in **people**. Each year the Association provides a scholarship to a deserving graduate student in mineralogy who is either working in Canada or is a Canadian citizen working anywhere in the world. Outstanding undergraduates are encouraged, through our annual undergraduate awards and travel grants, to attend scientific meetings. MAC recognizes scholarship of professionals with the **Young Scientist Award** and the **Peacock** and **Hawley** medals, which are highly regarded in academic circles.

Finally, MAC is actively engaged with other mineralogical societies and associations internationally. These collaborations result in informed policy, better meetings, and a sense of common goals.

I hope you agree that MAC continues to be consistent with the mission defined more than 50 years ago, and that this mission is still timely and important. The support of our membership is essential to achieving our goals. MAC has a modest business office in Quebec City, with fantastic employees who keep the day-to-day operations running smoothly. Nothing would be possible without the tremendous time invested by our volunteers, including members of the Executive (the president, vice president, secretary, treasurer, past president); editors of the journal, special publications, and short course volumes; members of

Council; organizers and speakers at short courses and special sessions; reviewers of papers in our journal; organizers of our annual meetings; and the many others who contribute.

Peter C. Burns, University of Notre Dame, USA
President, Mineralogical Association of Canada

2007-2008 UNDERGRADUATE STUDENTS AWARDS

The MAC Undergraduate Awards are given annually to undergraduate students for excellence in one of the fields covered by MAC (mineralogy, crystallography, petrology, geochemistry, and economic geology). The award consists of one free publication and one-year subscriptions to *Elements* and to the online version of *The Canadian Mineralogist*. We congratulate the 2007-2008 awardees.

Donnelly B. Archibald,
St. Francis Xavier
University

Eleanor J. Berryman,
McGill University

Natasha L. Bumstead,
The University of
Western Ontario

Ania Danigier,
University of Windsor

David Dirisio,
Brock University

Chelcy J. Fougere,
Acadia University

Sean P. Funk,
University of Alberta

Devon C. Griffiths,
University of Calgary

Monika Haring,
Laurentian University

Kayla M. Helt, Queen's
University

Luke J. Hilchie,
Dalhousie University

**Maude Lévesque
Michaud**, Université
Laval

Kevin J. MacKenzie,
UBC Okanagan

Seamus J. Magnus,
Lakehead University

Laura Malone,
University of New
Brunswick

Shawn O'Connor,
Carleton University

Christopher R. Rawluk,
University of Manitoba

Ryan Ruthart,
University of Waterloo

Eric E.S. Street,
Simon Fraser University

Jolene Styan,
University of Victoria

Ryan Szilagyi,
University of Regina

CALL FOR NOMINATIONS FOR THE 2009 MINERALOGICAL ASSOCIATION OF CANADA AWARDS

YOUNG SCIENTIST AWARD

This award is given to a young scientist who has made a significant international research contribution in a promising start to a scientific career. The scientist must be 40 or younger at the time of the award. He or she must be a Canadian working anywhere in the world or a scientist of any nationality working in Canada. The research areas include mineralogy, crystallography, petrology, geochemistry, mineral deposits, and related fields of study.

PEACOCK MEDAL

The Peacock Medal (formerly known as the Past-Presidents' Medal) is awarded to a scientist who has made outstanding contributions to the mineralogical sciences in Canada. There is no restriction regarding nationality or residency. The medal is intended to recognize the breadth and universality of these contributions in mineralogy, applied mineralogy, petrology, crystallography, geochemistry, or the study of mineral deposits, rather than in a narrow area of expertise.

BERRY MEDAL

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

PLEASE SUBMIT YOUR NOMINATIONS BY DECEMBER 31, 2008.

Check our website for additional details.

WWW.MINERALOGICALASSOCIATION.CA

MAC FOUNDATION SCHOLARSHIP TO ERNESTO PECOITS

The Mineralogical Association of Canada awarded its 2008-2009 Foundation Scholarship to Ernesto Pecoits, a PhD student at the University of Alberta. Starting next year, two scholarships will be awarded, one to a PhD student and one to an MSc student.

Ernesto Pecoits was born in Montevideo, Uruguay. He graduated in geology (BSc Hons) from the Universidad de la República in 2003. While studying he became the curator of the mineral collection of the Institute of Geology and Paleontology and a teaching assistant in mineralogy, geotectonics, structural geology, paleontology, sedimentology, and economic geology. After graduating, he served as staff geologist in the Department of Geology and acted as secretary of the Commission on Precambrian Stratigraphy of Uruguay. He has conducted numerous field studies on the geology of Uruguay, including studies on late Proterozoic tectonomagmatic events, the (bio)stratigraphy and geochemistry of Ediacaran successions, and the paleomagnetism and sedimentology of Paleozoic-Mesozoic rocks. As a principal investigator for a research project on the correlation between Proterozoic volcanosedimentary successions of Uruguay and similar units in South America and South Africa, and as an active participant in three IGCP projects, he had the opportunity to expand his field research to other countries, such as Argentina, Brazil, South Africa, and Canada. He has presented more than 30 research communications, including abstracts, field trip guides, book chapters, and research papers, and he was an invited guest coeditor for a special issue on the Precambrian geology of Uruguay.

Ernesto began his PhD studies at the University of Alberta in the fall of 2006 under the supervision of Prof. Kurt O. Konhauser and Dr. Murray K. Gingras. His PhD thesis research focuses on the Ediacaran banded iron formation (BIF) and carbonates of Uruguay and their paleo-oceanographic, paleoclimatic, and paleobiologic implications. This research project is based on the good preservation of well-exposed and poorly known Ediacaran units in Uruguay, including glacial deposits, BIF, thick chert successions, pre- and post-glacial carbonates, and black shales, and on the presence of organic-walled microfossils and shelly fauna, stromatolites, ichnofossils, etc. These rocks offer an ideal opportunity for determining the paleoenvironmental conditions in the Ediacaran oceans. The initial stages of this multifaceted work required strong field-based research, including mapping, construction of detailed cross-sections, and collection of samples. Of particular importance are BIF and carbonates, which are well-preserved chemical sediments nearly devoid of detrital input. Thus, these rocks provide a unique opportunity to assess the distribution of elements between the original iron oxide and carbonate precipitates and ancient seawater.

Despite the broad implications of this project, the main goal is to provide a better understanding of the partitioning of various trace elements in BIF and carbonates by performing microscale geochemical analyses, coupled with high-resolution petrography. Over the last two years, a new research direction focusing on rare earth element (REE) and yttrium (Y) data has been developed in order to test, first, the compatibility of a marine-precipitate origin for BIF and carbonates and, second, the involvement of microbes in iron oxide and dolomite precipitation. Accordingly, the identification of genuine marine chemical sediments through insight gained from REE+Y patterns combined with



mineralogical, trace element and isotope attributes will permit more robust interpretations about the origin and conditions surrounding these deposits and will lead to a better understanding of the origin and significance of BIFs and dolomite formation.

Mineralogical Association of Canada

STUDENT TRAVEL/RESEARCH GRANTS

The Mineralogical Association of Canada awards travel and research grants to assist honors undergraduate and graduate students in the mineral sciences to:

- Present their research at a conference
- Attend a short course or a field trip relevant to their field of study
- Visit a facility, laboratory, or field area to gather data for their research
- Pay for analyses or equipment for their research

The maximum grant value is CDN\$1200 per student. Grants will fund up to 50% of costs incurred for registration, travel, and subsistence, and up to 100% of other research costs (e.g. equipment, analyses). Quotations and receipts may be requested for any equipment purchased.

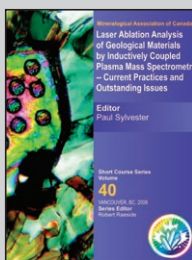
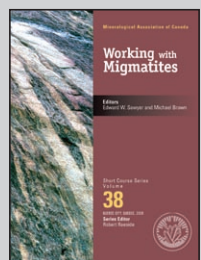
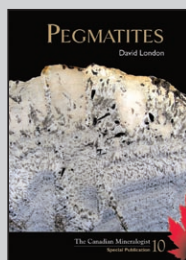
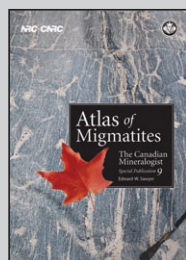
Eligibility

- Graduate students and honors students at the undergraduate level in one of the fields covered in *The Canadian Mineralogist* (mineralogy, crystallography, petrology, economic geology, geochemistry)
- Grant recipients must submit a report on their travel or research for possible publication by MAC.

For more information, see www.mineralogicalassociation.ca

Deadline to apply: January 15, 2009

WE HAVE NEW PUBLICATIONS FOR YOU!



- SP 9 Atlas of Migmatites – EDWARD W. SAWYER (2008)
ISBN 978-0-66019-787-6, 386 pp
- SP 10 Pegmatites – DAVID LONDON (2008)
ISBN 978-0-921294-47-4, 368 pp
- SC 38 Working with Migmatites
– EDITORS: EDWARD W. SAWYER AND MICHAEL BROWN (2008)
ISBN 978-0-92129-446-7, 168 pp
- SC 40 Laser Ablation ICP-MS in the Earth Sciences
– EDITOR: PAUL SYLVESTER (2008)
ISBN 978-0-921294-49-8, 348 pages

Order online at www.mineralogicalassociation.ca



The Clay Minerals Society

www.clays.org

PRESIDENT'S CORNER



El Presidente

The Clay Minerals Society is now into another fall season: committees are busy at their tasks, and dues renewal notices have just gone out. You may have a notice sitting on your desk right now. Each time I get my renewal notice, I feel good about supporting the CMS for another year. For me the feeling comes from the camaraderie that I associate with the CMS. We are a bit unusual in that we have always been a smaller society, and this smallness brings familiarity to the Society's meetings and journal. When I think of the Society, I usually think of certain people that I believe embody the friendly curiosity and creativity of a CMS member. I try to emulate these people, and am sometimes successful.

In recent years, as new international members have become prominent within the CMS, we are disappointed to see that a small number of our members decide not to renew. The CMS thrives on your ideas, your goodwill, and your membership. I once met a volunteer fireman and was surprised to see how similar our attitudes were regarding volunteerism and membership. He said, "We are having trouble putting out fires because some volunteers decide with each alarm whether they will participate that day. I made my decision once, and I choose to fight a fire with each alarm, no matter when it occurs...it is a part of me." This is the way good members think, and the way good small societies run. I made my decision to join the CMS once, and that was in 1980. I never had to make that decision again.

Choose to renew, and then tell me about your ideas.

Andrew Thomas

President, The Clay Minerals Society
Chevron Energy Technology Company, Houston, Texas, USA
andrew.thomas@chevron.com

STUDENT NEWS AND RECOGNITION

The Clay Minerals Society congratulates the following student grant awardees and contest winners for 2008:

Research Grants

TOP AWARD: Robert C. Reynolds Jr. Research Award – Jie Wang, University of Florida, USA

SECOND AWARD: Ashley Williams, University of Montana–Missoula, USA

2008 Paper Contest

FIRST PLACE: Ali Hooshidar Fard, University of Alberta, Canada

RUNNER-UP: Daria Kibanova, Universidad Nacional Autonoma de Mexico, Mexico

HONORABLE MENTION: Liming Zhu, Indiana University, USA

2008 Poster Contest

FIRST PLACE: Joyce Lok, Purdue University, USA

RUNNER-UP: Tanya Borchardt, Arizona State University, USA

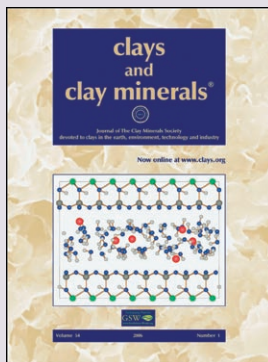
HONORABLE MENTION: Eric C. Johnson, Purdue University, USA

We hope that you continue to strive for excellence in your field of clay science.

MEMBER ALERTS

The membership and subscription renewal season for 2009 is upon us. Please take note of your e-mails for early-renewal discounts. New features this fall will be online membership applications (so tell a friend or colleague), online publication orders with renewals or stand-alone orders, and of course online renewals for existing members.

AUGUST 2008 ISSUE OF CLAYS AND CLAY MINERALS



INFLUENCE OF Mn(III) AVAILABILITY ON THE PHASE TRANSFORMATION FROM LAYERED BUSERITE TO TUNNEL-STRUCTURED TODOROKITE – Haojie Cui, Xiangwen Liu, Wenfeng Tan, Fan Liu, and Huada Daniel Ruan

PREFERRED ORIENTATION OF MINERAL GRAINS IN SAMPLE MOUNTS FOR QUANTITATIVE XRD MEASUREMENTS: HOW RANDOM ARE POWDER SAMPLES? – Reinhard Kleeberg, Thomas Monecke, and Stephen Hillier

ROLE OF MICROBIAL Fe(III) REDUCTION AND SOLUTION CHEMISTRY IN AGGREGATION AND SETTLING OF SUSPENDED PARTICLES IN THE MISSISSIPPI RIVER DELTA PLAIN, LOUISIANA, USA – Deb P. Jaisi, Shanshan Ji, Hailing Dong, Ruth E. Blake, Dennis D. Eberl, and Jinwook Kim

KAOLINITE FORMATION FROM Palygorskite and Sepiolite in Rhizosphere Soils – H. Khademi and J.M. Arocena

CHEMICAL AND MINERALOGICAL CHARACTERISTICS OF FRENCH GREEN CLAYS USED FOR HEALING – Lynda B. Williams, Shelley E. Haydel, Rossman F. Giese Jr., and Dennis D. Eberl

THE TRAPPING OF B FROM WATER BY EXPOLIATED AND FUNCTIONALIZED VERMICULITE – Mohamed Kehal, Laurence Reinhert, David Maurin, Fumihiko Ohashi, Jean-Louis Bantignies, Ammar Mennour, and Laurent Duclaux

XRD, FTIR, AND THERMAL ANALYSIS OF BAUXITE ORE-PROCESSING WASTE (RED MUD) EXCHANGED WITH HEAVY METALS – Paola Castaldi, Margherita Silveti, Laura Santona, Stefano Enzo, and Pietro Melis

LOW-TEMPERATURE FTIR STUDY OF KAOLIN-GROUP MINERALS – Cliff T. Johnston, Jessica Elzea Kogel, David L. Bish, Toshihiro Kogure, and Haydn H. Murray



The 46th annual meeting of the Clay Minerals Society, "Clays of the Big Sky," will be held June 6–11, 2009, in Billings, Montana, USA. The scientific meeting will be preceded, on June 6, by a field trip to "Bentonite Country" in the Big Horn Basin of northwestern Wyoming to see and discuss the geological setting, mining, and processing of Wyoming sodium bentonite. General and technical sessions will run on June 7–9, followed by a workshop on June 10 and 11. The workshop, "Clays of Yellowstone National Park," takes a new format this year and will be held in the field. So mark your agenda now for what promises to be a fantastic meeting. For further information and updates, see the CMS website, www.clays.org/home/HomeAnnualMeeting.html.

SPECIAL SESSION IN HONOR OF DANA MEDALIST THOMAS ARMBRUSTER

The Dana Medal is awarded by the Mineralogical Society of America in recognition of contributions through original research by a mineralogist "in the midst of their career," that is, within 25 years of receiving the PhD degree. Thomas Armbruster was honored for his crystallographic studies in mineral groups as diverse as epidotes, zeolites, and triplite-wagnerite. The medal was formally presented to Thomas (SEE PHOTO) at an award ceremony on July 16, 2008, during the 18th V.M. Goldschmidt Conference in Vancouver, Canada. A fuller citation by Martin Kunz and an acceptance speech by Thomas were given on July 18 during the oral portion of the session "Crystallography of Petrologically Significant Minerals: Symposium in Honor of Thomas Armbruster," which we organized to accompany the award ceremony.

In reviewing Thomas Armbruster's accomplishments, Martin Kunz emphasized his scientific productivity as well as the diversity of minerals on which Thomas has become the leading authority. Thomas is the first mineralogist from outside the U.S. to receive the Dana Medal since it was first awarded in 2001. During his acceptance speech, Thomas entertained the audience with his excellent storytelling skills, while thanking those who made the occasion possible.

Thomas devoted his scientific presentation for the medal to the triplite-wagnerite group, which comprises phosphates with the general formula $(\text{Mn,Fe,Mg})_2[\text{PO}_4](\text{F,OH})$. Thomas was the first to recognize that there is more than one polytype of wagnerite, and his systematic studies with Christian Chopin, Edward Grew, and Alain Baronnet led to the realization that the triplite-wagnerite group constitutes a modulated series.

The session comprised 9 poster presentations on July 17 and 13 oral presentations on July 18, including Thomas's medal talk. Participants covered topics as broad as Thomas's own interests. Frank Hawthorne gave the keynote address, which considered the important role played by local charge balance in constraining variations in amphibole compositions. Joel Brugger began the session with an invited talk describing how he successfully reproduced replacement of pentlandite by



Presentation of the Dana Medal to Thomas Armbruster at the Goldschmidt Conference, July 16, 2008. MSA President Peter Heaney and Citationist Martin Kunz are on Thomas Armbruster's right and left, respectively. PHOTOGRAPH COURTESY OF BARB DUTROW

violarite in the laboratory, a process involving dissolution and reprecipitation. Darrell Henry gave the second invited talk, which was on variations in metapelitic mineral composition with metamorphic grade. The subjects of volunteered talks on crystal chemistry ranged from beryllium silicates (Joel Grice) and the borosilicate holtite (Lee Groat) to the fillowite group of phosphates (Frédéric Hatert). Talks with petrological themes concerned the occurrence of the recently discovered phosphate chopinite in a meteorite (Edward Grew) and mushroom garnet from high-pressure rocks in the Alps (Bastien Darbellay). Experimental and theoretical themes (Guy Hovis, Nancy Ross, Anke Watenphul, Giuseppe Cruciani) rounded out the oral presentations. Poster presentations also covered crystal chemistry (tourmaline, by E. Tillmanns; Ba-mica, by Callum Hetherington; bournemanite, by F. Cámara; unnamed arsenate, by U. Kolitsch), as well as quartz deformation (Martin Kunz), crystal growth (Peter Heaney), and Te-Sb-W mineralization (Stuart Mills).

Edward Grew (University of Maine) and
Lee Groat (University of British Columbia)

GEOCHEMISTRY OF THE EARTH'S SURFACE 8

The Geochemistry of the Earth's Surface 8 (GES8) meeting was held at the Natural History Museum, London, from 18 to 22 August 2008. The meeting was funded by the Mineralogical Society, the International Association of Geochemistry and the Natural History Museum, with additional support from the European Association for Geochemistry, the Diamond Light Source and the following special interest groups of the Mineralogical Society: Environmental Mineralogy Group, Applied Mineralogy Group, Geochemistry Group and Mineral Physics Group.

About 150 mineralogists and geochemists attended the meeting, which featured 25 lectures from invited speakers as well as poster presentations. Sessions at the meeting were: Mineral Weathering; Synchrotrons in Environmental Science; Biomineralisation; Global Geochemical Cycles; and Contaminated Environments, Toxicology and Human Health. In addition Professor Julian Gale from Curtin University of Technology gave the Hallimond Lecture on controls on the mineralisation of barite and calcite. A feature of many of the lectures was the mention of the vital importance of the role of biological processes in natural geochemical and mineralogical phenomena.



The format of the meeting provided much time for animated discussion around the posters. This gave delegates a greater opportunity to discuss science than is often the case at larger meetings.

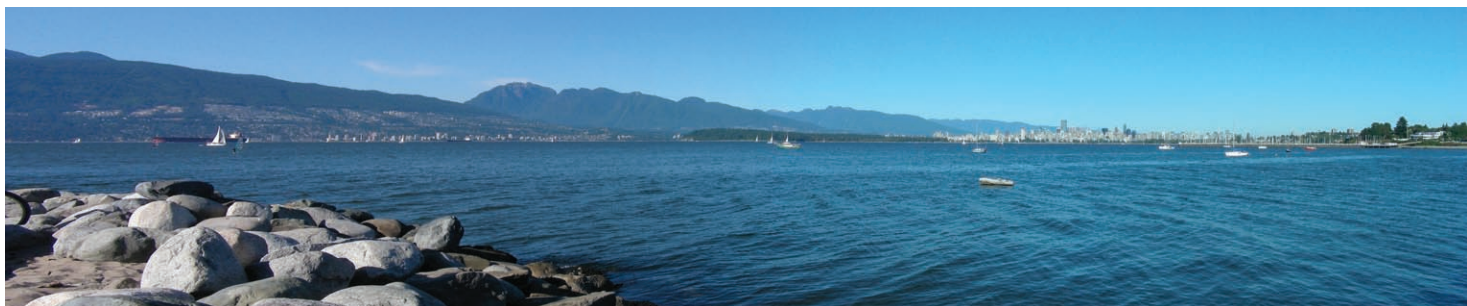
The conference dinner took the form of a cruise down the river Thames from central London to beyond the Thames barrier. During the dinner the Mineralogical Society's Max Hey Medal was awarded to Dr. Diego Gatta and the Schlumberger Medal to Professor David Rubie.

For those of you who missed the conference, extended, four-page abstracts of the majority of the presentations are available as a special issue of *Mineralogical Magazine*, which is freely available on the Internet at www.ingentaconnect.com/content/minsoc/mag/2008/00000072/00000001. Many of the invited presentations are available for viewing on the Mineralogical Society's website at www.minersoc.org/GES8.htm.

I would like to thank the sponsors of the meeting and the staff of the MinSoc (Kevin Murphy, Russell Rajendra, Martin Hughes and David Mole) for helping to make the meeting such a great success.

Mark Hodson
(University of Reading)

GOLDSCHMIDT 2008



The 18th Annual V.M. Goldschmidt Conference took place at the University of British Columbia, in Vancouver, Canada, on July 13–18, 2008. It was the first Goldschmidt Conference held in Canada and the largest ever in North America. More than 2000 participants from 47 countries made the trip to Vancouver. Student participation was impressive: 488 students represented nearly one-quarter of the total number of participants.

The International Program Committee (chairs: R. Carlson, B. Sherwood-Lollar, D. Weis) crafted a stimulating scientific program covering a breadth of research interests from “Sea to Sky.” The meeting comprised 120 symposia, 1211 oral presentations in 15 concurrent sessions, and 991 posters.

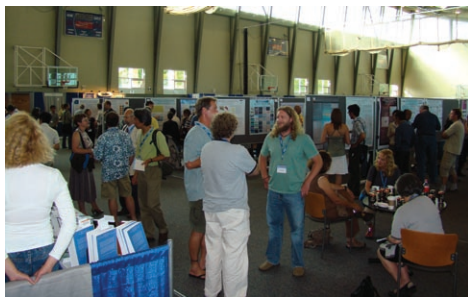
Award ceremonies were distributed over three days, just after the plenary lectures, and included the presentation of the Goldschmidt Medal to Francis Albarède, the Dana Medal to Thomas Armbruster, and the Shackleton Medal to Larry Edwards.



Goldschmidt Medal winner Francis Albarède (center) with Marty Goldhaber (left) and Marc Chaussidon



The Museum of Anthropology provided a stunning backdrop for the conference BBQ.



Beer attracted good attendance to the Students Recreation Center during the poster sessions

The conference began with a well-attended welcoming party under the tent and on the surrounding lawn of MacInnes Field. Discussions were lively as participants were happy to see their friends and colleagues.

On Wednesday evening, the conference barbecue was held behind the Museum of Anthropology. In this magical setting, a capacity crowd of 1200 people, including many students, enjoyed barbecued salmon. The Paperboys, a local folk music group, per-

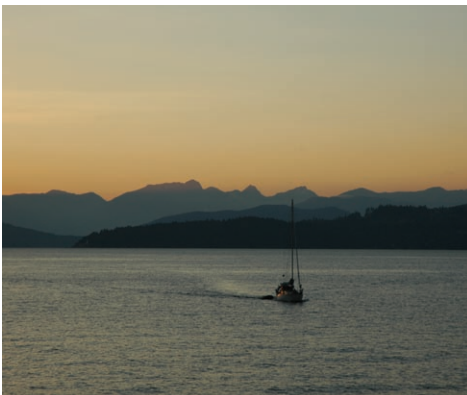


Student helpers gearing up for on-site registration

formed in the later part of the evening and closed the night on a cheerful note. Friday evening featured a well-attended dinner cruise (Harbour Cruises) in the beautiful Vancouver Harbour and surrounding waters.



Participants enjoying the refreshments at the opening reception



Sunset over Georgia Strait

The organizers of Goldschmidt2008 wanted to encourage student involvement. The student travel-support program had a total of about CDN\$80,000 generously contributed by the National Science Foundation, the Geochemical Society, the conference itself, the Mineralogical Association of Canada, the European Association for Geochemistry, the European Science Foundation, and the Geochemical Society of Japan. The program was very effective and provided a great incentive for students. Out of about 130 applications, 70 students and 10 low-income-country researchers from 20 nations were selected.

Forty-six student helpers from the universities of British Columbia, Simon Fraser, and Victoria, as well as from the University of Porto and ENS Lyon, did a fine job ensuring that all oral presentations ran smoothly. At the end of the conference, the 20 Mac computers purchased for the meeting were given away to these students in a draw.

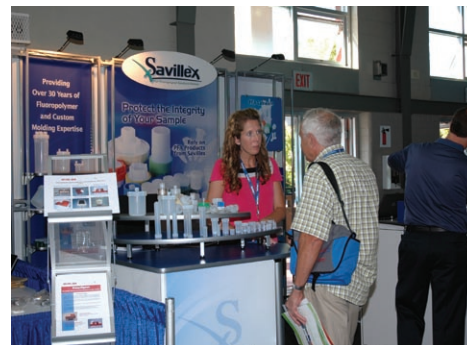


Rising excitement and noise during the computer draw



"Wrangellia Flood Basalt" field-trip participants at Myra Falls on Vancouver Island

Ecological, social, and economic factors entered strongly into the planning and execution of the conference. All conference and delegate items were made of recycled (notepads, pens, bags, lanyards, beverage cups, etc.), recyclable (program volume), or eco-friendly (USB drive) materials. They were designed to be reusable for other purposes, and as much as possible were locally produced.



Delegates interacting with exhibitors

The conference benefited from the sponsorship of four analytical companies (Nu Instruments, Thermo Fisher Scientific, IsotopX, and Savillex) and from the participation of 29 exhibitors (22 commercial and 7 scientific societies).

For a full report on Goldschmidt2008, check out *Geochemical News* online at www.Geochemsoc.org

Dominique Weis and **Diane Hanano**
on behalf of the Local Organizing Committee
and Cambridge Publications



CARLETON UNIVERSITY
DEPARTMENT OF EARTH SCIENCES

Applications are invited for a **tenure-track appointment in the field of mineralogy** at the rank of Assistant Professor, commencing July 1, 2009. This position is subject to budgetary approval.

Candidates should have a Ph.D. in Earth Sciences, demonstrable expertise and experience in the field of mineralogy, and demonstrated excellence in teaching. We are especially interested in candidates with field-oriented research programs. The successful candidate will be expected to teach both undergraduate and graduate courses to a culturally diverse student body, to develop an externally funded research program, and to contribute effectively to academic life in the department. Proficiency in English is a requirement.

The Department's historical strength lies in offering a field-based comprehensive education. At the undergraduate level this includes B.Sc. programs (Honours, Major and General) in Earth Sciences and in Computational Geophysics (Honours), as well as a Concentration in Vertebrate Paleontology and Paleoecology (Honours). Other programs include Combined Honours with Biology, Chemistry or Physical Geography. At the graduate level, we offer M.Sc. and Ph.D. programs, and, together with Earth Sciences at the University of Ottawa, we form the core of the Ottawa-Carleton Geoscience Centre (OCGC), a research and graduate institution. Available research facilities include stable and radiogenic isotope laboratories, XRF, XRD, a SEM – electron microprobe laboratory, and ICP-OES, as well as fluid inclusion, cathodoluminescence, and fluorescence microscopy. Further information on the Department can be obtained from the Web site, www.earthsci.carleton.ca.

Carleton University is located on a beautiful campus in the central portion of Ottawa, bounded by the Rideau River on one side, and the Rideau Canal on the other. Its prime location -- minutes from downtown, an international airport, and the Gatineau Hills -- enhances quality of life, and allows for

recreational opportunities for individuals and families. The City of Ottawa is Canada's capital and reflects the country's bilingual and multicultural character. Carleton's location in the capital also provides many opportunities for research with groups and institutions that focus on earth sciences, notably the Geological Survey of Canada, part of Natural Resources Canada. The Department of Earth Sciences benefits from collaborative research opportunities with federal government agencies and scientists. More information on the University and the city of Ottawa can be obtained at the Faculty Recruitment and Support Web site www.carleton.ca/facultyrecruitment.

Carleton University is strongly committed to fostering diversity within its community as a source of excellence, cultural enrichment and social strength. We welcome those who would contribute to the further diversification of our faculty and its scholarship, including but not limited to women, visible minorities, Aboriginal peoples, persons with disabilities, and persons of any sexual orientation or gender identity. In accordance with Canadian immigration requirements, priority will be given to Canadian citizens and permanent residents.

Applicants are to include a curriculum vitae, a cover letter, a teaching dossier, a statement of teaching and research interests, and the names and addresses (including e-mail addresses) of three referees. Applications should be sent to:

Dr. John Blenkinsop, Chair, Department of Earth Sciences
Carleton University, 1125 Colonel By Drive, Ottawa
Ontario, K1S 5B6, Canada
Fax: 1.613.520.5613
Email: chair@earthsci.carleton.ca

The closing date for receipt of applications is **January 12, 2009**.

JOYS AND HARDSHIPS OF ANTARCTIC FIELDWORK



Conor J. Ryan*

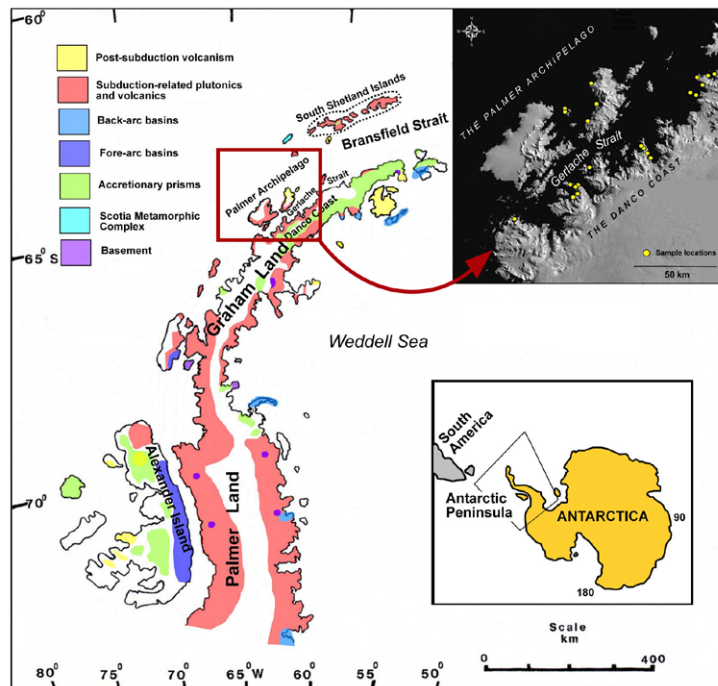
Icebergs off the Antarctic Peninsula. PHOTO BY CONOR RYAN

Being rudely awakened in my coffin-sized bunk at 4 a.m. by a flash-light; trying to stay upright while getting into cold, damp clothes and boots; emerging onto a freezing deck to be greeted by the cold spray of the heaving Southern Ocean; struggling to change the sails with numb hands – this was fieldwork...but not as I knew it!

As part of the British Army Antarctic Expedition (BAAE) 2007–2008, led by Antarctic veteran Major Richard Pattison (Royal Anglian Regiment), I was asked to lead, design and implement a geological sciences fieldwork program. This was in keeping with previous collaboration on fieldwork in the Antarctic, from which I earned my PhD, through BAAE 2001–2002. We were to spend several weeks exploring the Danco Coast and Palmer Archipelago area of the Antarctic Peninsula with the aim of mapping the geology of this poorly accessible region and collecting samples for analysis back home (see map). The results of previous work had already shed light on the geological history of this region over the last 100 million years. Our goal for this expedition was to collect samples to further our understanding of the tectonic evolution of Antarctica. But first we had to get there.

We chose to travel to the Antarctic on a 22 m yacht named *Discoverer* – a very different undertaking to a previous voyage on HMS *Endurance*, a 100 m ice-breaker. We set sail from Mare Harbour in the Falkland Islands in mid-December 2007, with the daunting task of crossing the notorious Drake Passage ahead of us. As this was my introduction to sailing, I was concerned I might have bitten off more than I could chew. The routine for the next six days on that great, grey, heaving sea involved getting used to a watch system that allowed little time for sleep or relaxation. The crossing of the Drake Passage was a test of the stomach for many of the crew...thankfully I found my sea legs fairly quickly, but others were not so fortunate! Changing sails on the fore-deck as the boat pitched and rolled in rough seas, with freezing waves crashing over us, was invigorating work to say the least! The problem with life on the boat was that once something got wet, the cold air ensured that it stayed that way. Life in the galley was also a challenge – we took turns cooking, wrestling with pots and pans in the heavily swaying, tiny kitchen! During the ocean crossing, we got a taste of the wildlife that awaited us further south: huge Mincke whales followed the boat for hours, and we were constantly under the watchful eye of the graceful albatross. It was with some relief that, on Christmas Eve, we reached the calmer waters between the Antarctic Peninsula and the Palmer Archipelago. We were greeted by spectacular scenes as the Antarctic midnight sun hung low on the horizon, casting an orange glow upon the snow-clad peaks, some of which soared to over 2000 m straight out of the sea. Mulled wine took the chill out of the air that evening, while we rang in Christmas Day with the bagpipes.

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Simplified geological map and location map



Working on the deck of *Discoverer* while crossing the Drake Passage. PHOTO BY STEVE AYRES



Sampling by boat off the Antarctic Peninsula. PHOTO BY MARTIN CAREY

On Christmas morning, we moored alongside the wreck of an old whaling vessel – now it was time to get on with the business of geology. A long day was spent visiting islands in Wilhelmina Bay via our motorized inflatable boats, sampling volcanic and plutonic rocks. The sedimentary rocks of the Trinity Peninsula Group eluded us that day, as the only exposure of these interbedded sandstones and siltstones was guarded

by huge ice cliffs, pieces of which plunged into the sea at regular intervals. A memorable moment that day was speeding through a natural arch in an iceberg! We pulled up alongside *Discoverer* that evening, tired, cold and wet, but the fine meal (relatively speaking of course!) that greeted us soon warmed us up.



Skiing on Anvers Island. PHOTO BY ROB HADFIELD

During the next few weeks, we explored various areas along the Danco and Graham coasts of the Antarctic Peninsula, places such as Waddington Bay, Paradise Harbour, the Reclus Peninsula and Anvers Island in the Palmer Archipelago. The awe-inspiring scenery of these places must be seen to be believed; photos cannot do them justice. Our usual tactic was to establish a camp from which we would explore the area by ski. Moving camp required using the pulk, a canvas-covered sledge that served for man-hauling gear ...and rocks! The pulk had the advantage of reducing the amount of gear on your shoulders, but was an absolute beast to traverse over steep ground; many expletives were uttered during those trying times. We also used pulks to transport snow-coring equipment across the ice. The glaciological work involved using a hollow drill to take cores of snow, up to 10 m below the surface, in order to examine snow-accumulation rates over time.

Pitching a tent in the Antarctic is an art that takes a while to perfect. The routine involves leveling the site, excavating pits for cookers, digging the tent in to improve its stability should the wind pick up, and somehow squeezing three fully grown men into a space that is cozy enough for one! The less said about the palatability of dehydrated rations, the better. The daily effort required to rouse oneself from the warmth of one's sleeping bag to get the cooker going was considerable. A freezing tent is not a nice thing to wake up to! In the evening, after a hard day man-hauling, there was a balance to be struck between re-hydrating properly and avoiding the need to answer the call of nature in the middle of the night, as this necessitated a chilly trip outside.

The wildlife in the Antarctic is magnificent. The comedic behaviour of the various species of penguin is well known; these creatures are completely unfazed by humans and will

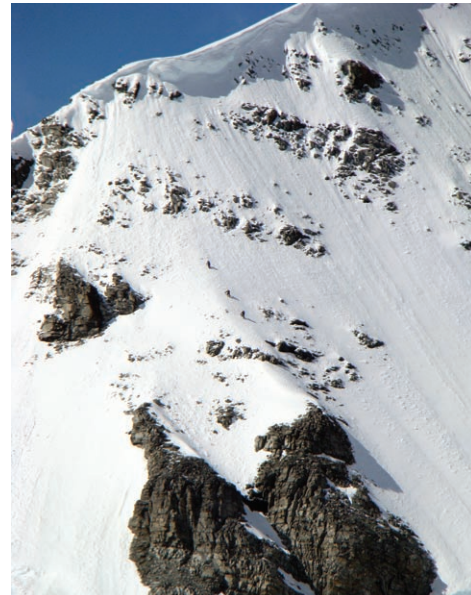
gladly walk up to you to peck at your boot laces. Humpback whales regularly came alongside the yacht, announcing their presence by jetting seawater from their blow-holes. These gentle giants would usually circle the boat for several minutes before diving to the depths, with their characteristic tails breaching the surface. Orcas (killer whales) were also seen from time to time, and seals were everywhere, often warming themselves on icebergs in the Antarctic sun.

Towards the end of the expedition, we finally succeeded in sampling the sedimentary rocks of the Trinity Peninsula Group at Paradise Harbour. In addition, we carried out a vertical traverse on Mount Heogh, collecting samples of granitic rocks for thermochronological studies. We later learned that our exploits on the side of Mount Heogh generated considerable interest at the local Chilean base! Although climbing on the side of Mount Heogh was exciting, collecting in the Trinity Peninsula Group sedimentary rocks was arguably a much more dangerous exercise due to our infringing on the territory of the local leopard seal, who watched our activities at too close a range for comfort. A leopard seal was responsible for the tragic death of a marine biologist in this region a few years ago. We treated its presence seriously.

With our final two sampling goals completed, it was time for the expedition to head north. With mixed feelings of relief and sadness, I stood on deck as we made our way home through the spectacular scenery of the Antarctic Peninsula. The previous month had been the adventure of a lifetime, but the prospect of home comforts, like a hot shower (or indeed any shower!), cheered me.



Cross-cutting mafic dykes (sampling target) at Waddington Bay, Antarctic Peninsula. PHOTO BY CONOR RYAN



Geological party (small figures in the centre of photo) collecting samples on Mount Heogh. PHOTO BY MARTIN CAREY

Life in the Antarctic is tough. The physicality involved in the everyday grind of sailing, man-hauling sledges, ski-touring with heavy packs, and establishing camps takes its toll on the body. However, more than physical fitness, it is mental toughness that allows one to thrive in this environment. The stress of operating in such an unforgiving wilderness places huge demands on the individual, and only those with the mental capacity to endure constant stress and discomfort will leave the Antarctic with a sense of accomplishment. The Antarctic is a place where you stand to lose much more than you could ever hope to gain ...perhaps that is one of its allures. The constant courtship with danger and adversity keeps the Antarctic explorer coming back for more. People often ask me why I would choose to put myself through needless hardship, and I am often left with no answer to give them – I think it is probably a case of the old adage that 'if you have to ask, you will never understand'. Antarctica is a world away from the comfortable lives most of us enjoy in the civilized world. But I found that when times were at their hardest down south, thoughts of home and loved ones kept me positive, and that sentiment was common to all my polar companions.

The rock samples that we collected have now arrived in the UK. They will be curated at the University of Brighton and will be studied at various British and Irish institutions over the coming years.

I would like to thank the Geological Society of London and the Mineralogical Society of Great Britain and Ireland for supporting my participation in this expedition through fieldwork grants. I would also like to thank my fellow expedition members, in particular Major Richard Pattison and Colonel Richard Clements, for their assistance with the geological fieldwork.

PEGMATITES*

Pegmatites are remarkable rocks, and this is a remarkable book. Almost everything one could wish to know about pegmatites, their characteristics and their origin is contained in its pages. Thus, it provides readers from a very wide range of backgrounds and interests with an entry-level, a catch-up, or a state-of-the-art review about these fascinating rocks. It would also look good on a coffee table, with its large format and beautiful photographic illustrations.

David London, of the University of Oklahoma, has written a tour de force – a reflective analysis based on his over 30 years of experience working with pegmatites. The book combines and explains in depth field observations, mineralogy, geochemistry, experimental petrology and silicate science in the context of pegmatite science. Using this integrated approach and on the basis of substantial arguments, London proposes a new model for the formation of pegmatites, challenging the well-established Jahns and Burnham model. Hence the book is much more than a textbook; it is provocative and intends to stimulate future work on pegmatites.

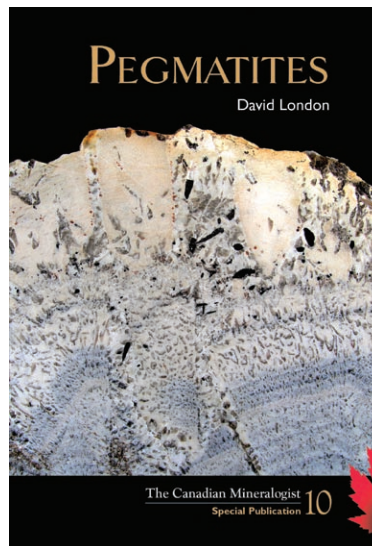
The first half of the book is a primer on pegmatites, in which their field occurrence and mineralogy are described. The minerals in pegmatites are beautifully illustrated with the author's photographs of his mineral specimens. There are 24 full pages of photographs of minerals (three of feldspars alone), almost 10% of the book. For each mineral group, there is a useful systematic presentation of their occurrence, properties and uses.

The second half of the book covers the origin of pegmatites. It reviews the extensive experimental work that relates to pegmatite genesis, and it challenges the 50-year-old Jahns and Burnham model, which states that pegmatites form from an exsolved aqueous phase derived once late-stage granitic melts become water saturated. Instead, pegmatitic textures are proposed to originate from the very rapid crystallization, between 350 and 450°C, of late-stage melts enriched in fluxes and incompatible elements. The evidence to support this hypothesis (including the origin of graphic quartz–feldspar intergrowths through magmatic crystallization from highly viscous melts) is carefully and thoroughly discussed. Again challenging accepted wisdom, according to which large crystals grow slowly, the author presents strong evidence from many sources to demonstrate that pegmatite intrusions crystallize in days to a few years, even pegmatites with crystals tens of metres in length.

David London's authority to reflect upon pegmatites comes from his career at the forefront of research into the phenomena that characterize volatile-enriched granitic melts. Based on fundamental principles of mineral equilibria and melt–vapour–mineral interactions, his thesis takes shape in a logical and structured way. The discussion of how theories concerning the origin of pegmatites have developed is interwoven with the human dimension, addressing the characteristics and human failings (as well as the strengths) of influential individuals. Readers with an interest in the history of science will find these aspects of the book most rewarding.

When starting to review this book, I began at the back. Here, 800 references, mostly from peer-reviewed journals, are listed in 38 pages. At the front of the book, the author notes that he has included only reference to papers that he has actually read. Returning to the back, one of the most interesting chapters concerns what we know and don't know about pegmatites. London is keen to recruit disciples to the pegmatite faith, and in this chapter he highlights some of the key research that still needs to be done.

* London D (2008) *Pegmatites*. The Canadian Mineralogist Special Publication 10, 347 pp, ISBN 978-0-921294-47-4, US\$125, 20% discount for MAC members



The book is easy to pick up and read on a selective basis. Each chapter starts with a short summary, which helps to make the book more easily accessible. Readers can embed themselves in the book with ease and, as long as they read the summaries, they can skip chapters that they consider low priority. The quality of the illustrations is one of the book's strengths, as is the provision of a CD-ROM that contains not only the figures (for teaching, research, outreach, etc.), but also a pdf of the chapters of the original Mineralogical Association of Canada Short Course Handbook on Granitic Pegmatites, edited by Peter Černý and published in 1982.

The reader is drawn into the book. The photographs in the first half are seductive, and the second half exercises the reader intellectually through its use of phase diagrams, discussion of the kinetics of crystal growth, thermal modeling, etc. The wide range of techniques discussed in the context of pegmatite evolution makes this book ideal for teaching petrogenesis. The textures that are described are easily visible in the photographs (and can be scrutinised in more detail using the CD-ROM). Concepts that many students find difficult, such as phase diagrams, are explained clearly. By using this book, a student will become familiar with a range of transferable interpretative skills that can be used in the investigation of many igneous rock types. The pedagogic value of pegmatites for teaching and engagement is an important aspect of the book.

What is there to criticize? A number of minor points arise. The description of pegmatites in rocks that are not granitic is very limited, despite a substantial literature. The coverage of the book very much focuses on North American examples, and this means that the 'known knowns' section of the last chapter, which identifies pegmatites that are well studied, omits work on pegmatites in Europe and descriptions that are written in languages other than English. Also, it is disappointing that the book lacks an index (but it is so clearly structured that this is not a major problem). Perhaps the most irritating deficiency of the book is the way in which captions for the photographs of the mineral specimens overflow from one page to the next. It is hard to link the photograph with the caption in some cases.

The criticisms are minor and do not detract from the value of the book for anyone interested, in whatever way, in pegmatites. It is a 'must-buy' book for any igneous petrologist, challenging as it does much accepted wisdom in that field of geoscience.

David Manning
Newcastle University

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2008

December 3–6 9th European Meeting on Environmental Chemistry, Girona, Spain. E-mail: emec9@eps.udg.edu; web page: www.udg.edu/tabid/10391/Default.aspx

December 3–12, 2008 Modular Course in Exploration Geochemistry, Laurentian University, Sudbury, Ontario, Canada. Information: Steve Piercey; e-mail: spiercey@laurentian.ca; website: http://earthsciences.laurentian.ca

December 7 Joint meeting of the Mineralogical Society, the Gemmological Association of Great Britain and the Russell Society. Details: Kevin Murphy; e-mail: Kevin@minersoc.org; web page: www.minersoc.org/pages/meetings/nature/nature.html

December 13–14 MSA Short Course: Minerals, Inclusions and Volcanic Processes, San Francisco, CA, USA. Details: Keith Putirka; e-mail: kputirka@csufresno.edu; web page: www.minsocam.org/MSA/SC/#volprocess

December 15–19 2008 AGU Fall Meeting, San Francisco, CA, USA. E-mail: meetinginfo@agu.org; web page: www.agu.org/meetings

2009

January 5–7 Fifth International Conference on Environmental, Cultural, Economic and Social Sustainability, Mauritius. E-mail: support@sustainabilityconference.com; web page: www.SustainabilityConference.com

January 11–16 Gordon Research Conference: Hydrocarbon Resources, Ventura, California, USA. Web page: www.grc.org/programs.aspx?year=2009&program=hydrocarb

January 18–23 33rd International Conference & Exposition on Advanced Ceramics & Composites, Daytona Beach, Florida, USA. Web page: www.ceramics.org/daytona2009

February 2–9 XI International Meeting "VOLCÁN DE COLIMA", Colima, Mexico. E-mail: reunion2009@ucol.mx; web page: www.ucol.mx/volcan/reunion2009

February 12–13 New Views on the Earth's Interior, London, UK. Details: J. Brodholt; e-mail: j.brodholt@ucl.ac.uk; web page: www.minersoc.org/pages/groups/minphys/minphys.html

February 14–21 Hydrothermal Ore Deposits Joint Modular Short Course, Ottawa, ON, Canada. E-mail: icsr@uottawa.ca

February 16–20 High-Pressure Experimental Techniques and Applications to the Earth's Interior, University of Bayreuth, Germany. E-mail: bayerisches.geoinstitut@uni-bayreuth.de; web page: www.bgi.uni-bayreuth.de

February 21–24 GRMENA Conferences: Oil and Gas Exploration, Water - Resources Management, Mineral - Resources, Environment and Geosciences, and Remote Sensing & GIS, Cairo, Egypt. E-mail: grmena2009@yahoo.com; web page: www.grmena.com.eg

March 2–6 Non-Destructive Analysis of Gemstones and Other Geo-Materials Short Course and Workshop, University of Vienna, Austria. E-mail: lutz.nasdale@univie.ac.at; web page: www.univie.ac.at/Mineralogie/MINSPEC/aktuelles_e.htm

March 9–12 17th Annual Meeting of the German Society of Crystallography, Hannover, Germany. Web page: conventus.de/dgk2009

March 22–26 American Chemical Society 237th ACS National Meeting & Exposition, Salt Lake City, UT, USA. Web page: www.chemistry.org

March 23–27 40th Lunar and Planetary Science Conference (LPSC 2009), The Woodlands, Texas, USA. Web page: www.lpi.usra.edu/meetings/lpsc2009

March 24–27 Chapman Conference on Arsenic in Groundwater of Southern Asia, Siem Reap, Cambodia. Web page: www.agu.org/meetings/chapman/2009/acall

April 2–4 Conference on Micro-Raman Spectroscopy and Luminescence Studies in the Earth and Planetary Sciences, Mainz, Germany. Details: Arnold Gucsik; e-mail: gucsik@mpch-mainz.mpg.de; web page: www.lpi.usra.edu/meetings/spectroscopy2009

April 13–17 2009 MRS Spring Meeting, San Francisco, CA, USA. Web page: www.mrs.org/s_mrs/index.asp

April 14–17 3rd International Maar Conference, Malargue, Argentina. E-mail: info@3imc.org or secretary@3imc.org; web page: www.3imc.org

April 20–23 Microanalysis of Particles II, Westmont, IL, USA. Web page: www.microbeamanalysis.org/meetings/topical/Particles2009/index.htm

April 23–24 Magmatism, Metamorphism and Associated Mineralizations (3MA), Beni Mellal, Morocco. Web page: www.fstbm.ac.ma/3MA/EN/Home.htm

May 9–13 Global Uranium Symposium (U2009), Keystone, Colorado, USA. Website: www.U2009.org

May 10–14 11th European Workshop on Modern Developments and Applications in Microbeam Analysis (EMAS 2009), Gdansk, Poland. E-mail: Luc.Vantdack@ua.ac.be; web page: www.emas-web.net/index.htm

May 11–15 Penrose Conference: Plumes and Their Role in Whole Mantle Convection and Recycling, Pico, the Azores. Web page: www.geosociety.org/penrose/09azores.htm

May 24–27 AGU Joint Assembly and Geological Association of Canada/Mineralogical Association of Canada Annual Meeting, Toronto, ON, Canada. E-mail: meetinginfo@agu.org; web page: www.agu.org/meetings

June 1–4 IAGS 2009 – 24th International Applied Geochemistry Symposium, Fredericton, NB, Canada. E-mail: lodge@unb.ca; Web page: www.unb.ca/conferences/IAGS2009

June EURISPET: High-Pressure Metamorphism and Subduction Zones, Granada, Spain. Details: Maria Teresa Gómez-Pugnaire; e-mail: teresa@ugr.es or eurispet@eurispet.eu; web page: www.eurispet.eu

June 6–11 46th Annual Meeting of the Clay Minerals Society, Billings, Montana, USA. Details: Richard Brown; e-mail: rbrown@wyoben.com; web page: www.clays.org/home/HomeAnnualMeeting.html

June 7–10 AAPG Annual Convention and Exhibition, Denver, CO, USA. Web page: www.aapg.org/meetings/misc_mtgs.cfm

June 14–19 Gordon Research Conference: Interior of the Earth, Mount Holyoke College, South Hadley, MA, USA. Web page: www.grc.org/programs.aspx?year=2009&program=interior

June 14–20 14th International Clay Conference, Castellana Marina, Italy. Details: Saverio Fiore; e-mail: chair@14icc.org or info@14icc.org; webpage: www.14icc.org/index.html

June 16–18 2009 Xi'an Ni-Cu Symposium Research Progress on Magmatic Ni-Cu Sulfide Deposits: Mineralization in Small Intrusions and Conduits, Xi'an, China. Dr. Yan Wang; e-mail: wang_yan@gig.ac.cn

June 21–29 Crystallography Online: International School on the Use and Application of the Bilbao Crystallographic Server, Lekeitio, Spain. Web page: www.crystallography.fr/mathcryst/bilbao2009.php

June 22–26 Goldschmidt 2009, Davos, Switzerland. E-mail: info@goldschmidt2009.org; website: www.goldschmidt2009.org

June 29–July 3 6th International Symposium on Ecosystem Behavior (BIOGEMOM 2009), Helsinki, Finland. Web page: www.environment.fi/default.asp?contentid=266595&lan=EN

July 5–10 Gordon Research Conference: Origin of Solar Systems, Mount Holyoke College, South Hadley, MA, USA. Web page: www.grc.org/programs.aspx?year=2009&program=origins

July 7–10 American Association of Petroleum Geologists (AAPG) Annual Meeting, Denver, CO, USA. Web page: www.aapg.org/meetings/misc_mtgs.cfm

July 10–20 Industrial Mineralogy, Chania, Greece. Details: George Christidis; web page: www.univie.ac.at/Mineralogie/EMU/events.htm

July 12–17 Gordon Research Conference: Catchment Science: Interactions of Hydrology, Biology & Geochemistry, Proctor Academy, Andover, NH, USA. Web page: www.grc.org/programs.aspx?year=2009&program=catch

July 12–17 Gordon Research Conference: Thin Film and Crystal Growth Mechanisms, Colby-Sawyer College, New London, NH, USA. Web page: www.grc.org/programs.aspx?year=2009&program=thinfilm

July 13–15 Granulites & Granulites 2009, Hrubá Skála, Czech Republic. Web page: www.petrolog.natur.cuni.cz/conference

July 13–18 71st Annual Meeting of the Meteoritical Society, Nancy, France. Web page: www.metsoc2009.org

July 19–24 Gordon Research Conference: Clusters, Nanocrystals and Nanostructures, Mount Holyoke College, South Hadley, MA, USA. Web page: www.grc.org/programs.aspx?year=2009&program=clusters

July 25–30 American Crystallographic Association (ACA) Annual Meeting, Toronto, Ontario, Canada. Details: James F. Britten; e-mail: britten@mcmaster.ca; web page: aca.hwi.buffalo.edu/meetingspg_list/futuremeetings.html

August 3–7 International Symposium on Zeolites and Microporous Crystals 2009 (ZMPC 2009), Tokyo, Japan. E-mail: zmpc2009@list.waseda.jp; web page: wwwsoc.nii.ac.jp/zeolite/event/zmpc-e.html

August 14–16 Symmetry and Crystallography in Turkish Art and Culture, Istanbul, Turkey. Web page: www.crystallography.fr/mathcryst/istanbul2009.php

August 16–20 American Chemical Society 238th ACS National Meeting & Exposition, Washington, DC, USA. Web page: www.acs.org

August 16–21 25th European Crystallographic Meeting (ECM25), Istanbul, Turkey. E-mail: ecm@ecm25.org; web page: ecm25.ecanews.org

August 17–20 Society for Geology Applied to Mineral Deposits 10th Biennial Meeting, Townsville, Qld, Australia. E-mail: SGA2009@jcu.edu.au

August 21–23 Gemological Research Conference 2009, San Diego, CA, USA. E-mail: grc2009@gia.edu; web page: www.grc2009.gia.edu

August 30–September 6 PEG 2009 – 4th International Symposium on Granitic Pegmatites, Recife, Brazil. Web page: www.ufpe.br/geologia/peg2009brazil

September 1–3 The Mineralogical Society's Annual Meeting, in conjunction with the German and French Mineralogical Societies: MAPT – Micro-Analysis, Processes, Time, Edinburgh, Scotland. Details: Simon Harley, e-mail: s.harley@ed.ac.uk; web page: www.minersoc.org/pages/meetings/meetings.html

September 7–11 Geoanalysis 2009, Drakensburg Region, South Africa. E-mail: maggi.loubser@up.ac.za; web page: geoanalysis2009.org.za

September 13–19 8th International Carbon Dioxide Conference, Jena, Germany. Details: Mr Felix Angermüller; e-mail: felix.angermueller@conventus.de; web page: http://www.conventus.de/icdc8/

September 14–18 13th International IUPAC Conference on High Temperature Materials Chemistry, Davis, CA, USA. Details: Alexandra Navrotsky; e-mail: navea@UCDavis.edu; web page: neat.ucdavis.edu/HTMC%2D13

October 18–21 Geological Society of America Annual Meeting, Portland, OR, USA. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings/2009

October 25–30 Materials Science & Technology 2009 Conference and Exhibition – MS&T '09 combined with the American Ceramic Society (ACerS) 111th Annual Meeting, Pittsburgh, PA, USA. Web page: www.matscitech.org/2008/pastmtgts.html

November 16–20 Cities on Volcanoes 6 - Tenerife 2009, Canary Islands, Spain. Details: Dr. Nemesio M. Pérez; e-mail: nperez@iter.es

November 30–December 4 2009 MRS Fall Meeting, Boston, MA, USA. Web page: www.mrs.org/s_mrs/index.asp

December 7–11 2009 AGU Fall Meeting, San Francisco, CA, USA. E-mail: meetinginfo@agu.org; web page: www.agu.org/meetings.

2010

January 24–29 34th International Conference and Exposition on Advanced Ceramics and Composites, Daytona Beach, FL, USA. Web page: www.ceramics.org/meetings/index.aspx

March 21–25 239th ACS National Meeting & Exposition, San Francisco, CA, USA. Web page: www.acs.org

April 5–9 MRS Spring Meeting, San Francisco, CA, USA. Web page: www.mrs.org/s_mrs/sec.asp?CID=2073&DID=92005

June EURISPET: High-Temperature Metamorphism and Crustal Melting, Padova, Italy. Details: Bernardo Cesare; e-mail: bernardo.cesare@unipd.it; web page: www.eurispet.eu

June 14–18 Goldschmidt 2010, Knoxville, TN, USA. Web page: www.geochemsoc.org/news/conferencelinks

June 21–24 11th International Platinum Symposium, Sudbury, Canada. Details: Prof. Michael Leshner; e-mail: 11ips@laurentian.ca; web page: www.11IPS.laurentian.ca

June 22–25 The Mineralogical Society's Annual Meeting: Environmental Mineralogy, University of Aberystwyth, Wales, UK. Details: N. Pearce; e-mail: pearce@aber.ac.uk; web page: www.minersoc.org/pages/meetings/meetings.html

July 72nd Annual Meeting of the Meteoritical Society, Toronto, Canada. Details: Dr. G. Srinivasan, e-mail srini@geology.utoronto.ca.

July 4–9 16th International Zeolite Conference, Sorrento, Italy. Details forthcoming; web page: www.iza-online.org/ConfSched.htm

July 10 EMU School: High-Resolution Electron Microscopy of Minerals, Nancy, France. Web page: www.univie.ac.at/Mineralogie/EMU/events.htm

July 22–31 American Crystallographic Association (ACA) Annual Meeting,

Chicago, IL, USA. Webpage: www.AmerCrystalAssn.org

August 22–26 240th ACS National Meeting & Exposition, Boston, MA, USA. Web page: www.acs.org

August 22–27 20th General Meeting of the International Mineralogical Association, Budapest, Hungary. Website: www.univie.ac.at/Mineralogie/IMA_2010

September 29–October 5 European Crystallographic Meeting ECM-26 and EPDIC XII, Darmstadt, Germany. Webpage: www.lcm3b.uhp-nancy.fr/ecasig5/Activity.php

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

October 17–21 Materials Science & Technology 2010 Conference and Exhibition - MS&T '10 combined with the ACerS 112th Annual Meeting, Houston, TX, USA. Web page: www.ceramics.org/meetings/index.aspx

October 31–November 3 Geological Society of America Annual Meeting, Denver, CO, USA. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings/index.htm

November EURISPET: Experimental Petrology and Rock Deformation,

Zürich, Switzerland. Details: Peter Ulmer, Swiss Federal Institute of Technology (ETH) Zürich; e-mail: peter.ulmer@erdw.ethz.ch; web page: www.eurispet.eu

November 14–18 Third International Congress on Ceramics, Osaka, Japan. Web page: www.ceramics.org/meetings/index.aspx

2011

May 19–28 American Crystallographic Association (ACA) Annual Meeting, New Orleans, LA, USA. Web page: www.AmerCrystalAssn.org

June 27–July 8 XXVth IUGG General Assembly, Melbourne, Australia. Web page: www.iugg2011.com

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

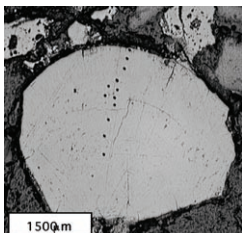
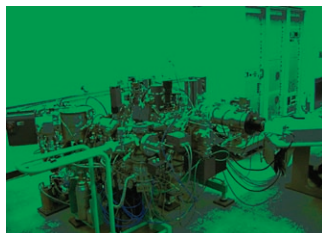
The meetings convened by the societies participating in *Elements* are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol. To get meeting information listed, please contact Andrea at Andrea.Koziol@notes.udayton.edu

Secondary Ion Mass Spectrometry in the Earth and Planetary Sciences: Gleaning the Big Picture from a Small Spot

Toronto, May 22–23, 2009, prior to the Joint Assembly 2009

ORGANIZER: Mostafa Fayek, University of Manitoba (fayek@cc.umanitoba.ca)

Obtaining a quantitative and predictive understanding of geological systems, including exploitable energy sources, requires knowledge of the age of origin and subsequent thermal history of the system over geological time. While analysis of milligram- and microgram-sized materials is routine, important geologic information preserved in features such as zoned minerals and cemented intergranular regions requires in situ measurements at the micron scale. An important breakthrough in this regard was the development of the secondary ion mass spectrometer (SIMS). SIMS is capable of performing precise and accurate (i.e. ‰ to sub-‰) in situ measurements of most elements and their isotopes with ca. 10 µm resolution.



This course will introduce SIMS analytical techniques and assess their applications in the Earth and planetary sciences, as well as in biogeochemistry. Topics include light stable and non-traditional isotope analysis, radiogenic isotope analysis and geochronology, and cosmochemistry.

- Registration fee: \$475 for professionals and \$295 for students (\$420/\$250 for MAC members)

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VANDERBILT UNIVERSITY

DEPARTMENT OF EARTH AND ENVIRONMENTAL SCIENCES

Tenure-Track Position in Biogeoscience

The Department of Earth and Environmental Sciences at Vanderbilt University invites applications for a tenure-track faculty position in the general area of Biogeoscience. This position, effective the Fall 2009 semester, is at the Assistant Professor level.

We seek an individual who is aimed at the highest standards of scholarship in research and teaching at both the undergraduate and graduate (MS, PhD) levels, and who will be attracted by opportunities at Vanderbilt for interaction with a diverse, enthusiastic faculty and student body in the Earth and environmental sciences and related fields. We welcome applications from candidates pursuing theoretical, experimental, and/or field-based work. The specific research specialty is open. Examples of fields of interest include, but are not limited to, climate change and paleoclimate; origin and evolution of the biosphere; critical zone processes; biogeochemical cycling; ecological processes (floral and/or faunal); and extinction patterns and processes. We seek an individual with interest in both ancient and modern biological systems.

Applications should include a vita, a statement of research and teaching interests, and names of at least three references (including mail and e-mail addresses and phone numbers). Select applicants will be later asked to provide student evaluations of teaching (if available). Applications should be submitted by e-mail in PDF or MS-Word format to: EESposition@vanderbilt.edu; up to three representative papers may be attached. Address questions to Molly F. Miller, Interim Chair, at the e-mail address above. Review of applications will begin 22 December 2008. Vanderbilt is an equal opportunity/affirmative action employer. Women and minorities are especially encouraged to apply.

MOST IMPORTANT INSTRUMENT OF THE 20th CENTURY?

When I was a teenager I went to school in southeast London. One of the perks was to be able to attend, with a small group of scientifically orientated youngsters, the Schools Lectures and Christmas Lectures at the Royal Institution. Teenagers, it is fair to say, have a limited sense of history, but I remember being impressed by being addressed in a lecture theatre in which the Christmas Lecture series had been instigated by Michael Faraday in 1825. They are broadcast, on BBC television, to this day. When the camera pans round the eager young faces in the audience, I strongly remember sitting there, with my friends, thrilled by the experiments we were shown, just as Faraday intended.

Some of the Schools Lectures were given by one Lawrence Bragg, who in the 1950s was Resident Professor. I had no idea I was in the presence of such a famous scientist, who, in 1915, when he was only 25, had won the Nobel Prize, with his father, for showing how X-rays could be used to work out the arrangement of atoms in crystals. Nor did I know that little more than 10 years later I would be standing in front of a class explaining the equation that bears his name. Lawrence Bragg was a wonderful lecturer, with an affable manner and a beautifully clear use of words. He pitched his talks just right, neither confusing nor patronising his young audience. There was no hint of arrogance or that he was aware of his personal brilliance. With the high-quality experimental props that the institution provided, the lectures were events that I really enjoyed.

Bragg's work entered my career during my PhD, in Durham, England, when using the instrument shown here – a Unicam single-crystal rotation and oscillation X-ray camera. I bought the one in the picture when another department auctioned some of its old equipment, and I have the unfulfilled intention of cleaning it up. The string is attached to a lead weight at the left and to an arm at the right guided by a heart-shaped cam, causing the sample to oscillate. During tutorial sessions I would tell students that it was the most important small scientific instrument of the twentieth century. I used it to study complex alkali feldspar crystals using a method invented by J. V. Smith and W. S. MacKenzie in 1955. At that time there were the first inklings that sub-millimetre 'single crystals' could in fact be composed of intergrown discrete phases and twins in a variety of orientations at a sub-optical scale. Joe and Mac's paper contains a memorable line, an early example of the 'hard sell' of a new technique: 'The procedure for obtaining the X-ray photograph is hardly more difficult than the operation of the universal stage on a petrographic microscope, and the photograph may be interpreted at a glance.' After struggling for several days to get the *b*-axis of a 0.5 mm cleavage fragment perfectly vertical, by taking successions of photographs, each with an exposure time of several hours, until the layer lines became straight, and then have the fragment fall off the glass fibre to which it was attached, I was prone to repeat their sentence in a creatively enhanced form!



So, why might this be one of the most important scientific instruments ever? In 1950, in King's College in London, Maurice Wilkins received some gelatinous DNA from the thymus of a calf. He was able to draw thin fibres from this material and make them into a bundle. He and Raymond Gosling mounted the fibres in a Unicam cylindrical camera very similar, if not identical, to the one in my picture. Wilkins and Gosling realized that it was necessary to keep the DNA fibres moist, so they passed damp hydrogen (to reduce scattering) through the camera body, sealing it imaginatively with a condom stretched around the camera collimator. With this set-up they took the first X-ray pictures showing that DNA could be obtained in crystalline form, and Alec Stokes, also at King's, deduced that it had a helical structure. Much better pictures of DNA were subsequently taken by Rosalind Franklin, using a miniature, flat-film Norelco micro-camera with a very finely focussed beam, and her photographs led to the discovery of the structure of DNA published by Watson and Crick in 1953. But the honour of first demonstrating the crystallinity of DNA, and its helical character, goes to the old Unicam. I rest my case.

Ian Parsons

University of Edinburgh

NON-DESTRUCTIVE ANALYSIS OF GEMSTONES AND OTHER GEOMATERIALS

This short course and workshop will be held 2–6 March 2009 at the Universität Wien, Vienna, Austria. Participation of student members is supported by the Deutsche Mineralogische Gesellschaft (DMG) and the Österreichische Mineralogische Gesellschaft (ÖMG).

Gemstones are geomaterials whose analysis is particularly challenging. First, analytical tasks reach far beyond simple phase identification; they include the distinction of natural and synthetic materials and the unravelling of different sorts of treatment. Second, analyses need to be done non-destructively, and typical preparation procedures cannot be applied in most cases. This five-day short course will give an introduction to "advanced" analytical techniques that allow one to analyse gemstones and other materials non-destructively and without the need to prepare samples. These include X-ray techniques (single-crystal and powder analysis of unprepared samples) and spectroscopic techniques (main focus Raman and luminescence; also IR and optical absorption spectroscopy). An introduction to gemstones and other geomaterials used in gemology will also be given.



Gem zircon M257 (width 19 mm), a recently proposed SHRIMP reference

The course will include both the theoretical basis and practical training in the use of analytical systems, in data reduction, and in the interpretation of results. It is targeted at diploma and PhD students who are interested in applying modern, non-destructive analytical techniques; however, the participation of postdocs and other colleagues is also welcome. Organizers aim at making participants able to use the above techniques in their own research. In addition, an overview of modern analytical applications in gemology will be given through a number of lectures presented by invited experts and also via short talks given by course participants.

The course will be held in English. For more detailed information please see www.univie.ac.at/Mineralogie/MINSPEC/aktuelles_e.htm or contact the organizer via e-mail at mineralogie@univie.ac.at.

TEXAS A&M UNIVERSITY
Department of Geology & Geophysics

Sedimentary Geology

Two Faculty Positions

The Department of Geology and Geophysics at Texas A&M University invites applications for two tenure-track faculty positions in sedimentary geology, broadly defined. Areas of interest include but are not limited to fundamental and applied problems in sedimentary processes ranging from pore to basin scale, depositional environments, sequence stratigraphy, basin architecture, sea level change and coastal evolution, and energy and natural resource science. At least one position will be offered to an individual working at the basin scale. We will consider applicants at all academic ranks. Successful applicants will be expected to develop and maintain vigorous, externally funded research programs and contribute to undergraduate and graduate teaching. We are a collaborative broad-based department within the College of Geosciences, which includes the Departments of Oceanography, Atmospheric Science, Geography, and the Integrated Ocean Drilling Program. Opportunities for collaboration also exist within the Department of Petroleum Engineering.

Interested candidates should submit electronic versions of a curriculum vita, statement of research interests and teaching philosophy, the names and email addresses of at least three references, and up to four reprints by email attachments, to the Chair of the Sedimentary Geology Search Committee, sedsearch@geo.tamu.edu. Screening of applications will begin October 31, 2008 and will continue until positions are filled. A Ph.D. is required at the time of employment.

The Department of Geology and Geophysics (geoweb.tamu.edu) is part of the College of Geosciences, which also includes the Departments of Geography, Oceanography, and Atmospheric Sciences, Sea Grant, the Geochemical and Environmental Research Group (GERG), and the Integrated Ocean Drilling Program (IODP). Texas A&M University, a land-, sea-, and space-grant university, is located in a metropolitan area with a dynamic and international community of 152,000 people. Texas A&M University is an affirmative action/equal opportunity employer committed to excellence through the recruitment and retention of a diverse faculty and student body and compliance with the Americans with Disabilities Act. We encourage applications from minorities, women, veterans, and persons with disabilities. Texas A&M University also has a policy of being responsive to the needs of dual-career partners (hr.tamu.edu/employment/dual-career.html).

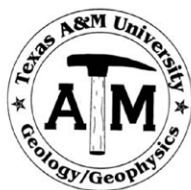
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R. BUCKMINSTER FULLER (1895-1983)

Pacific Northwest National Laboratory GEOCHEMISTRY POSITIONS

Pacific Northwest National Laboratory (PNNL) in Richland, Washington, operated by Battelle for the U.S. Department of Energy, is seeking highly motivated individuals to join its Geochemistry Group within the Chemical and Materials Sciences Division.

For the position of **Research Scientist in Biogeochemistry** (Reference #116124), the successful candidate will have a background in experimental geochemistry or biogeochemistry with expertise in the application of surface and bulk analytical spectroscopies and/or microscopies toward an understanding of fundamental molecular-scale structure and reactivity at environmental interfaces, such as at mineral/water and microbe/mineral interfaces. Initial research opportunities include application of a sophisticated multi-method suite of experimental tools to probe mechanisms of abiotic or microbial redox transformations of radionuclide contaminants occurring at interfaces with silicates and common metal oxide earth materials. Authoritative experience in materials and/or solution characterization using bulk and surface-sensitive spectroscopic tools, and demonstrated strong data interpretation skills are strongly desired. Tools of interest include but are not limited to FTIR methods, colorimetry, laser-based optical spectroscopies, electrochemical measurements, or conventional surface analytical spectroscopies.

For the position of **Research Scientist in Reactive Transport** (Reference #116125), the successful candidate will have a background in reactive transport experimentation with expertise in experimental design, data production, and data interpretation for understanding linked hydrologic and geochemical processes controlling solute migration in subsurface environments. Initial research opportunities include collaborative investigation of coupled reaction and diffusive mass transfer processes and kinetics for radionuclides relevant to contaminated sediments at the Hanford Site. Authoritative experience in the conceptualization, implementation, and scientific interrogation of multi-scale chemical and physical transport processes through the use of column, batch, reactive flow apparatus, and/or field experimentation is required. Familiarity with the parameterization and application of reactive transport models is strongly desired. Ancillary experience in the use of imaging, spectroscopic, and/or microscopic tools for characterization of porous media properties or geochemical reaction products would be beneficial.

PNNL is also searching for **post-doctoral candidates** (Reference # 116117) to assist with experimental design, data production and interpretation for understanding radionuclide reactive transport processes in subsurface environments. Working as part of a multi-disciplinary team, the candidate will be expected to design and perform laboratory experiments focused on determining kinetics of metal, radionuclide, or nanoparticle transport through heterogeneous mineral media, and contribute to a fundamental understanding of the physical and chemical mechanisms controlling transport. Authoritative experience with a range of bulk analytical characterization methods for solids and/or aqueous solutions is required. Experience with development or application of reactive transport simulations is highly desired.

Incumbents for the Research Scientist positions will be expected to immediately contribute to existing research projects and adhere to robust publication requirements. The successful candidates will have the skills and motivation to lead successful research projects and author peer reviewed proposals to the U.S. Department of Energy's Office of Science. Excellent written and oral communication skills are essential for all positions.

Apply on-line at jobs.pnl.gov and enter the corresponding reference number.

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Geological Sciences

GRADUATE STUDY

Department of Geological Sciences

University of Michigan

For information contact: Anne Hudon, Graduate Program Coordinator
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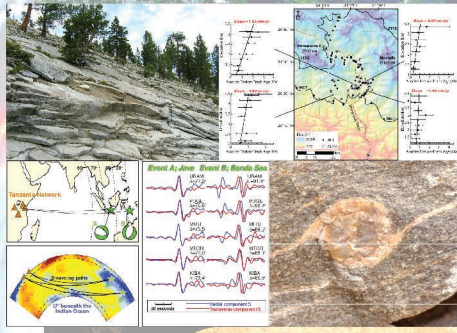
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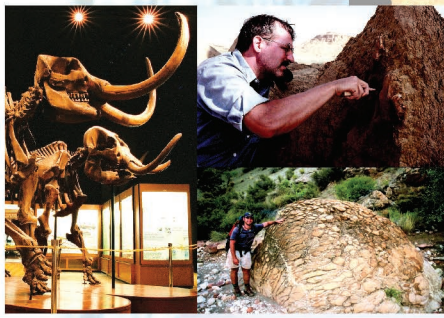
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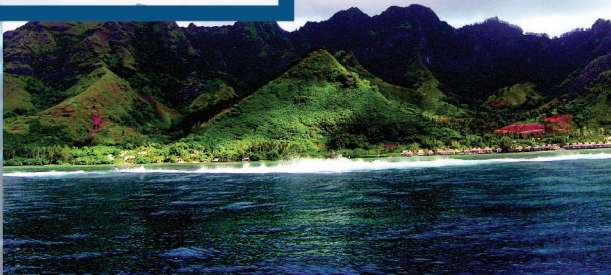
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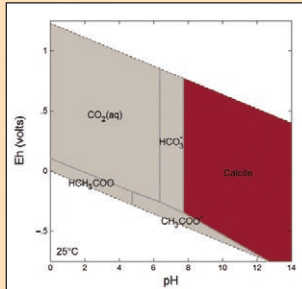
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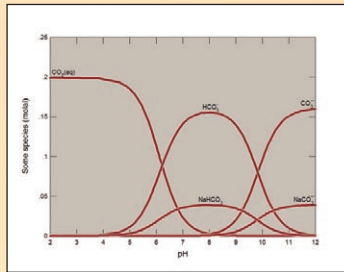
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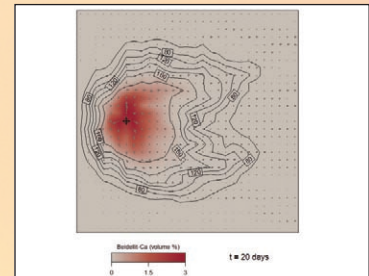


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