Mineral Evolution

ROBERT M. HAZEN, Guest Editor

Mineralogy in the Fourth Dimension
Evolution of Elements and Isotopes
Mineral Evolution of Meteorites
Mineral Environments on the Earliest Earth
The Great Oxidation Event
The Rise of Skeletal Biominerals
Themes and Variations in Complex Systems
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Guest Editor: Robert M. Hazen

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Robert M. Hazen and John M. Ferry

The Evolution of Elements and Isotopes
Hendrik Schatz

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Timothy J. McCoy

Mineral Environments on the Earliest Earth
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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, discounts for 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 sciences, including crystallography, geochemistry, petrology, environmental science, and economic geology. The society furthered its aims through scientific meetings and the publication of scientific journals, books, and monographs. The society publishes Mineralogical Magazine (print and online) and Clay Minerals (print and online). Members receive a discount on the annual membership fee of charge. All members receive Elements.

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The Mining 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. Many are 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 at 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 in clay science by 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 ship benefits include reduced registration fees to the annual meeting, discounts on the CMS Workshop Lectures, and Elements.

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The Geochemical Society (GS) is an international organization with members from 54 countries, founded in 1955 for students and scientists involved in the practice, study, and teaching of geochemistry. Our programs include co-sponsoring the annual Goldschmidt Conference®, editorial oversight of Geochemica et Cosmochimica Acta (GCC), supporting geochemical symposia through our Meeting Assistance Program, and supporting student development through our Student Travel Grant Program. Additionally, GS annually recognizes excellence in geochemistry through its medals, lectures, and awards. Membership recipient to Elements magazine, special member rates for GCC and G-aval, publication discounts, and conference discounts.

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The European Association of Geochemistry was founded in 1985 to promote student research and teaching in geochemistry 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 (IAG) 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 specialized scientific symposia and the activities organized by its working groups and by supporting its journal, Applied Geochemistry. The administration and activities of IAG are conducted by its Council, comprising an Executive and ten ordinary members. Details of annual conferences and IAG business subscription is performed through the IAG Business office.

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The Société française de Mineralogie, Minéralogie et Cristallographie, the French Mineralogy and Crystallography Society, was founded on March 21, 1878. The society is to promote mineralogy and crystallography. Membership benefits include the bulletin de la Société (in French), the European Journal of Mineralogy, 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, andSubscriptions to Elements.

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The Deutsche Mineralogische Gesellschaft (German Mineralogical Society) was founded in 1908 to “promote mineralology and all its subdivisions 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. Iaroslavsky, 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 awards. Membership benefits include the European Journal of Mineralogy, the DFGM Forum, GMF, and Elements.

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

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The Swiss Society of Mineralogy and Petrology (German: Mineralogische Gesellschaft der Schweiz; English: Swiss Society of Mineralogy and Petrology) was founded in 1924 by professionals from academia and industry and by amateurs to promote knowledge in the fields of mineralogy, petrology and geochemistry and to disseminate it to the scientific and public communities. The Society cooragizes the annual Swiss Geochemical Meeting, and publishes the Swiss Journal of Geochemistry jointly with the national geological and paleontological society.

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The subject matter of this issue of Elements, like many excellent ideas, will seem obvious to other scientists when put before them. Its elegance makes it appear simple. Mineral evolution provides a sense of progress, or at least of a progression from the simple to the complex, since the explosive beginnings of our universe. The idea of a process of ‘evolution’ that extends back in time for many billions of years before the emergence of any life form on Earth is particularly apt at a time when we have just celebrated the bicentenary of the birth of Charles Darwin, the man who essentially gave us biological evolution. However, there is at least one very important difference between the evolutionary development of life forms and that described here for minerals: it is that minerals, however rare, cannot become extinct, whereas for living organisms extinction is the rule rather than the exception. Probably more than 99% of all the organisms that have ever lived are now extinct.

So what can we say about the Earth and its ‘systems’ in the context of evolution and extinction at the beginning of the year 2010? Chiefly that Earth is a planet dominated by one mammalian species whose actions have already led to the extinction of numerous life forms and threatened the extinction of many others. At the time of writing this editorial, the Copenhagen Conference on climate change has just ended with little real progress towards dealing with the dangers of greenhouse gas emissions as the cause of potentially catastrophic changes in global climate, sea level, ocean currents and ocean chemistry. I will not dignify the arguments of the tiny handful of ‘climate-change deniers’ with an attack on their follies – their case has already led to the extinction of numerous life forms and threatened the extinction of many others. At the time of writing this editorial, the Copenhagen Conference on climate change has just ended with little real progress towards dealing with the dangers of greenhouse gas emissions as the cause of potentially catastrophic changes in global climate, sea level, ocean currents and ocean chemistry. I will not dignify the arguments of the tiny handful of ‘climate-change deniers’ with an attack on their follies – their case has already led to the extinction of numerous life forms and threatened the extinction of many others.

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What, if anything, might we do as scientists in the face of this unprecedented challenge? Clearly there is the possibility of contributing to technological ‘fixes’, which include the capture and storage of greenhouse gases emitted from power plants and vehicles, the development of alternative (green) forms of energy, helping to solve problems associated with existing low- or zero-emission energy forms (notably the waste-disposal problems of the nuclear industry), and even novel ways of modifying Earth’s atmosphere or the input of heat from the Sun. The latter might involve some means of directly extracting CO₂ from the atmosphere and disposing of it in the deep ocean, in deep sedimentary formations, or through reaction with Mg and Ca in silicate rocks such as basalts. Other novel proposals include ‘geoengineering’ stratocumulus clouds by injecting into them a fine spray of sea salt from the ocean surface which would act as nuclei to increase the number of water droplets and cause them to reflect more of the Sun’s heat. However, at present, some deus ex machina total solution to our climate problems seems very unlikely. We will surely need to call upon many of these ways of reducing the impact of our human activities on the global climate. We will also have to accept the need to make changes in our lifestyles and the need to help our more threatened neighbours in poorer countries, both technically and financially. Amongst the most important things we can do is to waste no opportunity to educate our fellow citizens about the dangers we all face and the terrible price we may all pay for inaction. It is astonishing, so the pollsters tell us, that very many of the general public either do not ‘believe’ in global warming and its consequences or think that it does not pose a serious threat to our survival.

The mineral world is remarkably beautiful, but even those of us who spend our working lives studying it would not wish to see it ‘evolve’ to outlast the living world.

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Tim comments that “Elements has been very successful in producing a magazine that is fun to read and addresses topics that are of wide interest within our community. It is having a real impact. I look forward to continuing this tradition and, in particular, to addressing topics of societal importance where Elements can play a role in educating the public and decision makers.”

Goldhaber and Yardley Triple Point Coordinators

Since volume 1, issue 1, Elements has published Triple Point, which contains opinion pieces about different aspects of our science (teaching, publishing, historical notes, etc.), our societies, funding, policy, and political issues. Peter Heaney acted as Triple Point coordinator for the first three years and Rod Ewing took over for the next two. When Rod informed us that he would like to be replaced at the end of 2009, we decided to split the position. We are pleased that Bruce Yardley and Marty Goldhaber have accepted our invitation. Both are Earth scientists well connected in the geosciences community, interested in issues affecting our community and our science, and recognized as talented writers. Each will provide three columns a year, with one of these being an invited contribution.

Marty Goldhaber is a Senior Scientist at the USGS, where he received the Department of the Interior Meritorious Service and Presidential Rank awards. He has been a member of the Geochemical Society since 1972 and has been involved in that society in a number of roles, including his current position as past president. He is a fellow of the Geological Society of America and the Society of Economic Geologists. He has served on the editorial boards of Economic Geology, American Journal of Science, and Geochimica et Cosmochimica Acta and on advisory boards for the Geological Society of America, the Ocean Drilling Program, NASA, and NSF. He is the author or coauthor of approximately 100 refereed publications and over 100 published abstracts.

Bruce Yardley is a professor of metamorphic geochemistry at the University of Leeds. He obtained his PhD and DSc from Bristol University. His research interests concern the interactions of rocks with fluids in varied crustal settings and, in particular, the development and application of new techniques for the analysis of fluid inclusions. In addition to studying metamorphic fluids, he has worked on fluids in ore deposits and in oilfields. Bruce has written a textbook and a picture atlas of metamorphic rocks. He has been active in several societies and is a past president of the European Association of Geochemistry. You can read his first Triple Point article on the following page.

Dutrow Chair of Executive Committee

Elements’ Executive Committee, which consists of representatives from each of the participating societies, recently elected Barb Dutrow to serve a two-year term as its new chair. She succeeds Rod Ewing, whom we thank for his extraordinary service. For the past two years, Barb has served as the MSA representative. Her commitment to the mineralogy-petrology-geochimistry community also includes serving as the 2007 MSA president and on various committees of the Geochemical Society, GSA, AGU, and IMA. She was also an Alexander von Humboldt Fellow in Germany, where she interacted with many European colleagues. Her research focuses on elucidating the thermal evolution of metamorphic terrains through combining computational modeling with field and mineral chemical studies. She is the Adolphe Gueymard Professor at Louisiana State University. Her e-mail address is dutrow@lsu.edu.

ELEMENTS AT IMA 2010

IMA 2010, which will be held in Budapest from August 21 to 27 (www.ima2010.org), will present a series of Elements plenary lectures, one each day of the conference, to underline Elements’ 5th anniversary of publication. Principal Editor David Vaughan and Past Principal Editor Ian Parsons have assembled a great cast of authors and guest editors from previous issues of Elements to act as speakers.

Sunday – Eva Valsami-Jones
(Phosphates, v4n2)

Monday – Rodney C. Ewing
(Nuclear Fuel Cycle, v2n6)

Tuesday – Nigel M. Kelly
(Zircon, v3n1)

Wednesday – Mihály Pöstlai
(Mineral Magnetism, v5n4)

Thursday – Nita Sahai
(Medical Mineralogy, v3n6)

Friday – Glenn A. Waychunas
(Nanogeoscience, v4n6)

David Vaughan, Hap McSween, Susan Stipp, Tim Drever, and Pierrette Tremblay
DO WE NEED MORE APPLICATIONS OF GEOCHEMISTRY?

Last year, Rod Ewing wrote a Triple Point column on the theme “Is Geochemistry Important,” in which he made a compelling case for the importance of mineralogy and geochemistry in the modern world. For my first foray as a Triple Point editor, I would like to take his topic in a different direction and question how effective we are at recognising the practical use of geochemistry (and of course mineralogy).

All scientists hope that their work will prove of lasting value to humanity in some way or other, although there is some doubt as to whether this wish is always fulfilled. The Earth sciences deal with some of the most challenging aspects of the world we live in, and there is an enormous amount of popular curiosity about the topics we investigate, from the origins of the planet to the human impact on it. However, as well as being interesting to the public, Earth scientists are useful: resource geology, for example, has underpinned every civilisation that has left a record, and doubtless many that have not. So where does geochemistry/mineralogy belong in the pantheon of useful sciences? We have little doubt that what we do is important and valuable, but is that reflected in industry’s demand for graduates?

I fear that all too often geochemistry research is not seen as of great economic or social value, and our good students are much more likely to continue in research than be offered jobs in industry. The world of applied geochemistry is quite small relative to academic geochemistry, and the interface has become less porous with time. Is this a situation that we should try to change, or does it just reflect the way of the world? I began to appreciate the scale of the differences between geochemistry and some other areas of the Earth sciences when I served on the Council of the Geological Society of London. I was taken aback to discover that the GSL has about 3000 members, of whom academics make up a tiny proportion and industry scientists the vast majority. By contrast, the Geochemical Society has around 3000 members worldwide, most from academia and government. So not only are there a lot more geologists and geophysicists than geochemists, but a far higher proportion of geology and geophysics graduates become industrial practitioners than go into research. Does this mean that what we do has less value to the outside world than we suppose? Does a little geochemistry go a long way? Or is the world just slow to respond to modern advances in geochemistry?

Perhaps the answer to all three of these questions is “yes”. Some years ago I attended a small mineral deposits meeting with several excellent presentations on the origins of gold deposits. I asked a senior geologist from Rio Tinto how important this research would be for his company. The response was that, although gold deposits are the subject of a high proportion of ore deposits research, they make only a small contribution to the company profits. Most of the profits came from mining iron ore, which is the subject of rather little geochemical research. Before we all get too excited about the potential of iron ore research, remember that if a deposit can be evaluated by geophysics and the ore-rich zones identified remotely, then understanding why it is there, however intellectually satisfying, is unlikely to have a commercial impact until the resource is almost exhausted. As far as inorganic geochemistry is concerned, the view from the hydrocarbon industry is not so very different. There are some fields in this industry with problems which require an understanding of geochemistry, but it is not such a big issue that even major oil companies have to employ a lot of inorganic geochemists. So a small amount of geochemistry can result in sufficient understanding to allow many industries to go their own way for quite a while. Geologists and geophysicists are needed on the ground all the time, not just during exploration but also to inform production strategies.

On the other hand, most geochemists (those involved in geochemical mapping are an obvious exception) provide general concepts to develop exploration or production approaches, but at a level where ideas can be transferred without the need for the work to be repeated everywhere. The main area where geochemistry is being used in a practical, day-to-day manner is in the environment. Detailed geochemical input is needed to deal with waste and groundwater issues, and each site has to be investigated separately. That means that geochemists have to be involved on a site-by-site basis. In many countries, it is difficult for researchers to get funded for academic research that is designed to repeat at a new location what has been done elsewhere, but applied science is exactly about applying basic research to specific new areas where it will be useful. Geochemistry will not mature as a major scientific discipline until a bunch of geochemists is doing exactly that.

Should we conclude that too much geochemistry is too academic to be of practical use in the foreseeable future? Well, a lot of it certainly is, but I believe that there are industries that could benefit from geochemistry if they were more engaged with it. For example, a recent Elements issue concerned carbon dioxide sequestration. Here is a field which, despite the obvious chemical implications of injecting carbon dioxide into wet rocks, has proceeded happily at the level of engineering trials with relatively little geochemical input. Reservoir engineers develop plans for injection with geochemical input at the chemical engineering level, but without a fundamental understanding of longer-term reactivity in the reservoir, despite the enormous impact that such reactions might have on storage capability and the risk of leakage. Such work is going on, but is seldom closely tied to what companies are doing today. Likewise, many examples of the application of geochemical and isotopic techniques to unravel environmental problems have been published, but this has not trickled down to routine practice and regulatory requirements.

If geochemistry is going to be used for the good of society, we must communicate what we do beyond our immediate academic circles, but we also need to understand the nature of the problems that industry deals with. Often their main concerns are with the quantities of materials present – the law of mass balance; on the other hand, many geochemists find it hard to see beyond the evaluation of approach to equilibrium – the law of mass action. Perhaps if we can engage better with real problems that industry faces, we may be able to show that geochemistry can make a difference. But our community must also recognise and respect the importance of applications of geochemistry. At present, our societies do not offer the level of professional support that practitioners need, and few societies whose names suggest that they embrace geochemistry or mineralogy as a whole give medals to people who work with practical applications. These are things we can do something about.

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Robert M. Hazen is Senior Staff Scientist at the Carnegie Institution’s Geophysical Laboratory and the Clarence Robinson Professor of Earth Science at George Mason University. He received his BS and SM degrees in geology at MIT and his PhD in Earth science at Harvard University. A past president of the Mineralogical Society of America, Hazen’s recent research focuses on the role of minerals in the origin of life and the coevolution of the geo- and biospheres. He currently serves as Principal Investigator of the Deep Carbon Observatory (http://dco.ciw.edu).

Timothy J. McCoy received his MS from the University of New Mexico and PhD from the University of Hawai‘i. He has worked at the Smithsonian Institution since 1996 and is the curator-in-charge of the meteorite collection. He studies meteorites and works on unmanned spacecraft missions to understand a variety of geologic problems, in particular the melting of asteroids in the early history of the solar system.

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Mineral evolution, which frames mineralogy in a historical context, is based on the premise that the geosphere and biosphere have coevolved through a sequence of deterministic and stochastic events.

Three eras of mineral evolution—planetary accretion, crust and mantle reworking, and biologically mediated mineralogy—each saw dramatic changes in the diversity and distribution of Earth’s near-surface minerals. An important implication of this model is that different terrestrial planets and moons achieve different stages of mineral evolution, depending on the geological, petrological, and biological evolution of the body.

**THE FIRST MINERALS**

In the beginning, none of the approximately 4400 known minerals existed. Cosmologists estimate that it took perhaps a half million years after the Big Bang before the first atoms of hydrogen and helium (and probably some lithium) condensed from the hot, dense, primordial fireball. It may have taken millions more years for the first stars to form, ignite, and seed space with the initial pulse of heavier, fusion-generated elements (Schatz 2010 this issue).

Only then, as giant stars exploded into the first supernovae, did minute bits of condensed, crystalline matter form in the cooling, expanding, gaseous stellar envelopes. Possibly a dozen micro- and nanoscale mineral species appeared. Diamond and graphite were likely the most abundant crystalline phases in those carbon-rich environments, with a sprinkling of carbides, nitrides, oxides, and magnesium silicates. For perhaps tens of millions of years, these few microscopic primeval “ur-minerals” were the only crystals in the universe.

**ERA 1: PLANETARY ACCRETION**

The diversification of minerals had to wait for the emergence of planets because planets are the engines of mineral formation (Hazen et al. 2008). Initial pulses of mineralogical novelty came in stellar nebulae, as nascent stars ignited and bathed the nearby concentrations of dust and gas with a refining fire. We define three eras and ten stages of mineral evolution in our own solar system (Table 1; Fig. 1). During Stage 1, perhaps 60 different mineral species appeared as primary condensates almost 4.6 billion years ago, when the Sun entered its intense T-Tauri phase. Among the mineralogical innovations were the first iron–nickel metal phases, sulfides, phosphides, and a host of familiar refractory silicates and oxides like those found in the least-altered chondrite meteorites.

These planet-forming materials quickly clumped into planetesimals, some of which became large enough to partially melt, differentiate, and experience a range of thermal and aqueous alteration processes (Stage 2; Fig. 2). The mineralogy of the solar system expanded to about 250 different phases, which are still found today in the diverse suite of meteorites that fall to Earth (McCoy 2010 this issue).

Since the formation of our solar system’s four inner planets and Earth’s moon, three primary mechanisms have driven mineral diversification: (1) the progressive separation and concentration of the elements from their original relatively uniform distribution in the presolar nebula; (2) an increase in the range of combinations of intensive variables, such as pressure, temperature, and the activities of H₂O, CO₂; and (3) the biological mediation of mineralogy (Hazen et al. 2008; Table 1).

**TABLE 1 THREE ERAS AND TEN STAGES OF EARTH’S MINERAL EVOLUTION**

<table>
<thead>
<tr>
<th>Era/Stage</th>
<th>Age (Ga)</th>
<th>Cumulative no. of species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prenebular “Ur-Minerals”</td>
<td>&gt;4.6</td>
<td>12</td>
</tr>
<tr>
<td>Era of Planetary Accretion (&gt;4.55 Ga)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Primary chondrite minerals</td>
<td>&gt;4.56 Ga</td>
<td>60</td>
</tr>
<tr>
<td>2. Achondrite and planetesimal alteration</td>
<td>&gt;4.56 to 4.55 Ga</td>
<td>250</td>
</tr>
<tr>
<td>Era of Crust and Mantle Reworking (4.55 to 2.5 Ga)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Igneous rock evolution</td>
<td>4.55 to 4.0 Ga</td>
<td>350 to 500*</td>
</tr>
<tr>
<td>4. Granite and pegmatite formation</td>
<td>4.0 to 3.5 Ga</td>
<td>1000</td>
</tr>
<tr>
<td>5. Plate tectonics</td>
<td>&gt;3.0 Ga</td>
<td>1500</td>
</tr>
<tr>
<td>Era of Biologically Mediated Mineralogy (&gt;2.5 Ga to Present)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Anoxic biological world</td>
<td>3.9 to 2.5 Ga</td>
<td>1500</td>
</tr>
<tr>
<td>7. Great Oxidation Event</td>
<td>2.5 to 1.9 Ga</td>
<td>&gt;4000</td>
</tr>
<tr>
<td>8. Intermediate ocean</td>
<td>1.9 to 1.0 Ga</td>
<td>&gt;4000</td>
</tr>
<tr>
<td>9. Snowball Earth events</td>
<td>1.0 to 0.542 Ga</td>
<td>&gt;4000</td>
</tr>
<tr>
<td>10. Phanerozoic era of biomineralization</td>
<td>0.542 Ga to present</td>
<td>4400+</td>
</tr>
</tbody>
</table>

* Depending on the volatile content of the planet or moon
Each of the ten stages of mineral evolution saw a change in the diversity and/or surface distribution of mineral species. This timeline is accompanied by photos of near-surface Earth materials illustrative of each stage. Stage 1: chondrite meteorite, courtesy of Smithsonian Institution; stage 2: pallasite meteorite, courtesy of Smithsonian; stage 3: zircon grains, courtesy of John Valley; stage 4: tourmaline, courtesy of Robert Downs; stage 5: jadeite, courtesy of Robert Downs; stage 6: stromatolite, courtesy of Dominic Papineau; stage 7: curite, courtesy of Robert Lauf; stage 8: water, Mauro Marzo | Dreamstime.com; stage 9: glacier ice, Petr Keil | Dreamstime.com; stage 10: trilobite, Hazen Collection, Smithsonian Institution, photo by Chip Clark.
In Stages 3 to 5 of mineral evolution, a variety of Stage 1 of mineral planets and moons experienced only the first era. An additional two eras and eight stages, whereas most other stages. On Earth we envision a history with an additional two eras and eight stages, whereas most other mineral evolution. On Earth we envision a history with an additional two eras and eight stages, whereas most other planets and moons experienced only the first era.

ERA 2: CRUST AND MANTLE REWORKING

The initial mineral evolution of Earth’s crust depended on a sequence of geochemical and petrologic processes, including volcanism and degassing, fractional crystallization, assimilation, regional and contact metamorphism, plate tectonics, and associated large-scale fluid–rock interactions. These processes, which produced the first continents and ultimately resulted in an estimated 1500 different mineral species, can be divided into three evolutionary stages.

All rocky planets and moons experience Stage 3 mineral-forming igneous processes, as outlined in Norman Bowen’s classic text, The Evolution of the Igneous Rocks (Bowen 1928). Even on a volatile-poor body like Mercury or the Moon, such processes yield as many as 350 different mineral species. If, however, H₂O and other volatiles are abundant, then the mineralogical diversity is enhanced by the development of hydrous minerals—hydrates, carbonates, and evaporite minerals—a total of approximately 500 mineral species. A once-wet Mars appears to have progressed this far in its mineral evolution.

Stage 4 of mineral evolution requires that a planet possess sufficient inner heat to remelt its initial basaltic crust, resulting in the formation of granitoids. Pulses of mineralogical novelty arise from repeated partial melting and concentration of rare elements to form complex pegmatites and their approximately 500 distinctive minerals. Li, Be, B, Nb, Ta, U, and a dozen other rare elements (Fig. 3). These elements have been present since the time of the ur-minerals, but in concentrations too low for the formation of discrete phases rich in the rarer elements.

ERA 3: BIOLOGICALLY MEDIATED MINERALOGY

Abundant and diverse life-forms distinguish Earth from all other planets and moons in the solar system. Life has transformed the near-surface environment—conspicuously the oceans and atmosphere, but rocks as well. Indeed, we argue that fully two-thirds of all known mineral species are the consequence of Earth’s transformation by living organisms.

The earliest life on an anoxic Earth had relatively little effect on mineralogical diversity (Stage 6; Pope 2010 this issue). To be sure, new biologically mediated rock formations appeared, including extensive banded iron formations and localized carbonate reefs. But the land was still barren, surface weathering was slow, and life contributed very little to expand the number or distribution of the approximately 1500 preexisting mineral species.

That situation changed in a geological instant with the remarkable biological innovation of oxygenic photosynthesis and the rise of an oxygen-rich atmosphere (Stage 7). The “Great Oxidation Event” (GOE) (starting ~2.4 Ga), when atmospheric oxygen may have risen to >1% of modern levels, irreversibly transformed Earth’s surface mineralogy. More than 2500 minerals are hydrated, oxidized weathering products of other minerals, and these
new minerals are unlikely to have developed in an anoxic environment. Biochemical processes associated with the GOE may thus be responsible, directly or indirectly, for most of Earth's 4400 known mineral species (Sverjensky and Lee 2010 this issue).

The next billion years or so (Stage 8), referred to as the “Intermediate Ocean” (or, more whimsically, the “Boring Billion”), appear to have been a time of relative mineralogical stasis. This period may be considered as a time when the interface in the ocean between an oxic surface layer and anoxic depths gradually got deeper (Anbar and Knoll 2002). However, the “boring” label more likely reflects our ignorance of rock formations that have been relatively little studied compared to much older and much younger ones.

The ninth stage of mineral evolution marks a half-billion-year interval during which at least two global glaciations occurred, commonly referred to as “snowball Earth” episodes (1.0 to 0.542 Ga). Whether ice completely covered the planet is a matter of debate (Hoffman et al. 1998), but ice certainly became the dominant surface mineral for periods in excess of 10 million years. Volcanoes continued to pierce the frozen veneer and contribute to surface mineral diversity, and interglacial periods experienced new pulses of mineral formation, notably the deposition of thick, fast-growing “cap carbonates” with giant crystal fans of aragonite (Pierrehumbert 2004; FIG. 5) and a rapid increase in the generation of clay minerals (Kennedy et al. 2006).

The Phanerozoic mineralogical innovation of bioskeletons of carbonate, phosphate, and silica (FIG. 6) resulted in new mechanisms of mineralization that continue to influence Earth’s near-surface mineralogy (Stage 10; Dove 2010 this issue). At the dawn of the Cambrian Period, Earth’s subaerial surface was, as it had been for most of the previous 4 billion years, mostly barren rock. The rise of land plants about 400 million years ago not only dramatically altered Earth’s surface appearance, but it also led to rapid production of soils, including an order of magnitude increase in the rate of clay mineral production.

**IMPLICATIONS OF MINERAL EVOLUTION**

The 4.5-billion-year chronicle of mineralogical change underscores the crucial role of time in mineralogy. Every Earth scientist knows that geology is history. It is remarkable, then, that the study of minerals has remained divorced from the dimension of time. Specimens in almost every mineral museum are organized by the Dana system, with composition first, followed by structure type. Each label records a name, chemical formula, locality, and perhaps a crystal class or space group. But with few exceptions, nothing is mentioned about the age of the mineral specimens. Time is not a traditional variable.

There are several good reasons to reframe mineralogy in its historical context. From a planetary perspective, the concept of mineral evolution allows each terrestrial body in the solar system to be placed in a broader mineralogical context. Mineral evolution provides an intellectual framework for identifying mineralogical targets in the search for extraterrestrial life. From the perspective of complex evolving systems, which have often become a lightning rod for debates over biological evolution, mineral evolution provides an excellent example of a nonliving system that diversifies over time through well-known physicochemical mechanisms (Hazen and Eldredge 2010 this issue).

Most importantly, by framing mineralogy as a historical narrative, intimately entwined with the drama of planet formation, plate tectonics, and the origin and evolution of life, mineralogy rightfully claims a central position in the Earth sciences.

**ACKNOWLEDGMENTS**

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The Evolution of Elements and Isotopes

Hendrik Schatz*

The basic building blocks of all minerals are the approximately 290 stable or long-lived isotopes of 84 elements. Yet, when the universe began and nuclear reactions ceased after about 15 minutes, the only elements present were hydrogen, helium, and traces of lithium. After the groundbreaking work by Cameron and Burbidge and coworkers in the 1950s, it is now understood that all the other elements are made in stars in an ongoing cycle of nucleosynthesis. Stars form, create new elements via nuclear reactions, and finally disperse the new elements into space via winds and explosions, forming the seeds for new stars.

Keywords: nucleosynthesis, stellar evolution, r-process, s-process, isotopes

STARS: NATURE’S ISOTOPE FACTORIES

The isotopes found today in our solar system (Lodders et al. 2009) were formed in numerous cycles of nucleosynthesis over the ~10 billion years from the Big Bang to the formation of the solar system. But how did the composition of the universe evolve from the simple mix right after the Big Bang to the complex distribution of isotopes shaping our world today? Our understanding of this process of chemical evolution is still fragmentary.

The origin of the heavy elements beyond iron in the periodic table (about 2/3 of all elements) figures prominently among the many open questions. The existence of these elements in nature is somewhat surprising. Nuclear fusion reactions, the energy source of stars, cease to produce energy once the most tightly bound isotopes in the iron region are formed. At that point the star has squeezed out as much nuclear energy as it can, and the formation of heavier elements, which would consume energy, does not take place. Yet, nature has found a way to produce the heavier elements in stellar environments, albeit in rather low concentrations. These elements are thought to be formed mostly by two classes of neutron-capture processes: the so-called slow neutron-capture process (s-process) and the rapid neutron-capture process (r-process). Each process produces a distinct pattern of elements and together they add up to the observed composition. In both processes, seed nuclei capture neutrons until unstable isotopes form. These isotopes then undergo beta decay, converting a neutron inside the nucleus into a proton, an electron, and an electron antineutrino. The result is a new element with the atomic number increased by one. The new element then captures more neutrons, repeating the process until, step by step, the heavy elements are formed.

Even though the newly formed elements are less tightly bound than their seed nuclei, the additional binding of the free neutrons more than compensates and makes the process exothermic. However, these neutrons are unstable and decay with a half-life of about 10 minutes. The challenge for theorists is to identify stellar sites with sufficiently intense sources of neutrons. The site of the s-process has been identified in a certain class of red giant stars (AGB stars) and in the cores of massive stars, where helium-burning nuclear reactions can produce neutrons that are then captured on iron nuclei from previous stellar generations (Käppeler 1999). On the other hand, the site and exact reaction sequence of the r-process are still not known with certainty (Cowan and Thielemann 2004). Given that this process is responsible for about 40% of the heavy elements and is the sole source of uranium and thorium in the universe, these are some of the most important open questions in nucleosynthesis. The challenge is to find a considerably more intense source of neutrons for the r-process—mind-boggling free-neutron densities of up to 10 kg/cm³ are likely needed. Not unexpectedly, most proposed models therefore involve neutron stars in one form or another, for example, the neutron-rich outflows from a neutron star forming as a result of a supernova explosion (Fig. 1), or the matter ejected during the merging of two neutron stars to form a black hole.

UNANSWERED QUESTIONS

All proposed nucleosynthesis scenarios for the r-process have major problems. Observations and experiments are needed to provide guidance and to verify or falsify the numerous theoretical possibilities. Major insights come from recent advances in astronomy, which are beginning to revolutionize our understanding of chemical evolution. Large-scale surveys of millions of stars in our Galaxy have led to the discovery of more and more stars that are extremely iron-poor (Yanny et al. 2009). These low-mass stars formed in the early stages of galactic chemical evolution, when stellar winds and explosions had just begun to enrich the Galaxy in the first heavy elements and iron was still scarce. The spectroscopic analysis of the surface compositions of these stars reveals the chemical makeup of the Galaxy at the time and location of their formation (with the caveat that in some stellar binary systems there may have been later pollution via mass transfer from the...
into the complex distribution of elements found today transform the simple composition just after the Big Bang of chemical evolution, revealing the steps nature took to a rough “chemical” clock that allows one to date the companion star. The iron content of the star can serve as a rough “chemical” clock that allows one to date the sample. These stars represent an emerging “fossil record” of chemical evolution, revealing the steps nature took to transform the simple composition just after the Big Bang into the complex distribution of elements found today (Fig. 2).

Of particular interest are the few most iron-poor stars found today—stars that have iron contents of 1:100,000 of that of the Sun and possibly provide a glimpse of nucleosynthesis in the very first generation of stars (Frebel et al. 2009). Slightly less iron-poor stars provide information on another interesting epoch of galactic chemical evolution. During these early times, the r-process dominated the synthesis of the heavy elements, because the iron seed nuclei required by the r-process had not yet been produced in sufficient quantity.

Several stars with a composition completely dominated by the r-process have now been discovered, and they are thought to illustrate the abundance patterns of heavy elements created by individual r-process events in the early Galaxy (Sneden et al. 2008). Among the most intriguing insights into the unknown site of the r-process is the apparent consistency, from event to event, of the abundance pattern for elements from Ba to just below Pb in the periodic table. Moreover, this characteristic pattern is also consistent with the solar r-process contribution. This consistency may thus hint at a particularly narrow range of conditions leading to an r-process. On the other hand, the production of U, Th, and Pb seems to vary from star to star, at least occasionally, making attempts to use the actinides for radioactive dating of the r-process events difficult. Maybe most intriguing are variations for elements below Ba that indicate the existence of a separate process—either a variant of the r-process or something entirely new. A fascinating aspect of this field is that new nucleosynthesis processes are still being discovered. Currently a number of large-scale surveys to search for metal-poor stars are underway, and extensive programs for follow-up high-resolution spectroscopy using the largest telescopes are in place. These efforts promise a drastic increase in the number of iron-poor stars with detailed information on their composition. It is reasonable to expect that within the coming decade a much more complete “fossil” record of chemical evolution will emerge.

Along with such dramatic advances in observations, similar progress is needed in our understanding of the underlying nuclear processes that drive chemical evolution. The structure of nuclei has been referred to as the “DNA” of chemical evolution (Woosley et al. 2003), in the sense that it encodes and defines, together with environmental cosmological conditions, the composition of the universe. Nuclear reactions are the mechanisms by which nature translates this “DNA” into chemical abundance features. New generations of stars begin with an initial composition enriched by new abundance features, and in that sense they inherit a modified “DNA” that, through differences in the resulting nuclear reactions and atomic processes, affects their nature and the further evolution of the elements.

The structure of nuclei and their reactions under astrophysical conditions therefore need to be deciphered to understand chemical evolution. Nuclear physics enables one to predict the abundance signatures of specific astrophysical models, which can then be compared to observations. Many of the nuclear reactions in stars involving stable nuclei have been studied in the laboratory, though many surprises and challenges still remain. For example, most measurements of reactions between charged particles have been performed at higher energies than occur in stars, because the electrostatic repulsion between nuclei can then be overcome more easily, leading to sufficiently large event rates in the experiments. Extrapolating these measurements to lower energies requires theoretical assumptions that are not always correct. For example, recent measurements of the rate of proton capture on 14N have been done with new techniques, such as improved detection systems (Bunkle et al. 2005) or the use of the European underground laboratory LUNA (Formicola et al. 2004), to extend experimental conditions to lower energies and lower event rates. As a result, the newly established rate that sets the speed of hydrogen burning via the CNO cycle in stars is a factor of 2 slower than previously assumed. The CNO cycle is a circular sequence of nuclear reactions involving carbon, nitrogen, and oxygen nuclei effectively fusing hydrogen into helium. It plays a small role in the Sun, but is the dominant hydrogen-burning process in more massive stars. Another example is the 12C fusion rate in stars—there is currently a debate about whether the rate at stellar energies is reduced by many orders of magnitude due to a new fusion-hindrance effect discovered at Argonne National Laboratory in other reactions (Jiang et al. 2007), or whether it is increased by many orders of magnitude due to a hitherto unknown resonance (Spillane et al. 2008). Major technical developments are now underway to enhance the sensitivity of such experiments so that they can be performed closer to the stellar energy range. One such development is the planned DIANA facility at the new U.S. underground laboratory DUSEL.

**FIGURE 1** X-ray image of the supernova remnant G292.0+1.8 from the Chandra X-ray observatory (color), overlaid with optical data (white). Various elements synthesized in the supernova explosion can be identified through their characteristic X-ray energies and are color coded in blue (silicon and sulfur), green (magnesium), and yellow and orange (oxygen). Unfortunately, r-process elements are too rare to be detected. CREDIT: X-RAY DATA FROM NASA/CXC/PSU, STATE S. PARK ET AL., OPTICAL DATA FROM PALOMAR OBSERVATORY DIGITIZED SKY SURVEY.
RARE ISOTOPES IN THE COSMOS

The study of the many rare, unstable isotopes participating in nucleosynthesis processes has been even more challenging. Rare isotopes are nuclei with extreme neutron to proton ratios that do not exist on Earth unless produced in a nuclear reaction, because they decayed a long time ago. For example, cadmium has 8 naturally occurring isotopes with mass numbers 106, 108, 110–114, and 116. However, unstable, rare Cd isotopes with mass numbers as low as 95 and as high as 132 have been discovered, and many more are thought to exist. For a few rare isotopes with particularly long half-lives of millions of years, there is some geological evidence that they existed at the time of solar system formation but have decayed since (Meyer and Clayton 2000). These isotopes offer exciting possibilities for probing directly the last nucleosynthesis events that contributed to the solar elements. However, most rare isotopes have much shorter half-lives and often decay within fractions of seconds. These isotopes are extremely difficult to produce and study in laboratory experiments. However, at certain extreme conditions in stellar explosions, they are created copiously, and, despite their fleeting existence, they imprint their properties on the composition of the erupted material and therefore on the composition of the universe (Schatz 2008).

Rare isotopes play a particularly important role in the origin of the r-process elements. How do we know this if we haven’t even identified the site? It turns out that our current sparse knowledge of the physics of rare isotopes provides, when combined with observations, the first clues. From observations of metal-poor stars and from the composition of the solar system—from which we can subtract the contribution of the better understood s-process (though there are still uncertainties in this procedure)—we have a fairly good picture of the characteristic element and isotope abundance patterns created by the r-process.

The most pronounced features in this pattern are the peaks at mass numbers A = 130 and A = 195, which correspond to particularly large abundances of tellurium/xenon and gold/platinum in nature, respectively. In a neutron-capture process, such peaks are produced naturally when the reaction sequence passes through nuclei with closed neutron shells, the so-called “neutron magic” nuclei. Just like the atomic electrons in chemistry, nuclei exhibit a shell structure for neutrons (and protons). At certain “magic numbers” of neutrons, the nucleus has a completely filled (closed) shell, leading to the analogue of a noble gas electron configuration in atomic physics. For such nuclei, the rates for further neutron capture are drastically reduced and, once a neutron is captured, the rate for removing it via bombardment of photons is drastically increased. As a consequence,
the neutron-capture process slows down dramatically, leading to an increased production of such nuclei. However, the stable $^{130}$Te (78 neutrons) and $^{195}$Pt (117 neutrons) isotopes found with increased abundance do not have closed neutron shells. Those closed shells rather occur at the magic numbers of 82 and 126 neutrons. We therefore have to conclude that the r-process passes through unstable progenitor isotopes with closed neutron shell numbers, and that these isotopes later decay into $^{130}$Te and $^{195}$Pt. Though some neutron emission can occur during this decay process, the mass number most likely does not change by much. It follows then that the path of the r-process passes through isotopes with mass numbers (A) and neutron numbers (N) of A ~ 130, N = 82 and A ~ 195, N = 126. These are $^{130}$Cd, a rare isotope of cadmium with a half-life of 160 ms, and $^{195}$Tm, an extremely neutron-rich rare isotope of thulium that has never been observed in a laboratory. How can such short-lived rare isotopes be produced by neutron capture, if isotopes with fewer neutrons, which have to be made first, decay within fractions of seconds? The best explanation is an extremely large neutron density at the r-process site, which makes neutron capture rates even faster than some of the beta decay rates.

This rough constraint on the nature of the r-process had already been postulated in the seminal papers by Burbidge et al. (1957) and Cameron (1957) and led to the notion of the existence of an r-process in the first place. However, it hinges on the assumption that the magic numbers for exotic rare isotopes are the same as the well-established magic numbers for stable isotopes. We now know, thanks to pioneering experiments with rare isotopes, that this is not true in general. Classical magic numbers for lighter nuclei have been shown to disappear in unstable isotopes, and new magic numbers can appear (Otsuka et al. 2001). There is now some evidence that N = 82 is still a strong neutron closure at $^{130}$Cd (Jungclaus et al. 2007), but for $^{195}$Tm the jury is still out.

In principle, the r-process abundance pattern contains much more information about the r-process. It contains signatures of the history of the temperature and neutron density conditions during the r-process. Also, the pattern might have been further shaped by, for example, exposure to strong neutrino irradiation. In fact, the many possible models proposed so far for the r-process site, while all producing abundance peaks at A = 130 and A = 195, otherwise exhibit largely different abundance patterns. Unfortunately, the various possibilities for the unknown nuclear physics of most r-process isotopes can lead to similar or larger variations in predicted abundance patterns (Kratz et al. 1993). Because of this lack of knowledge about the nuclear physics of the r-process, to date the observed r-process abundance pattern cannot be exploited to falsify or verify the theoretical possibilities for the site.

The major challenge is to produce and study experimentally the exotic r-process nuclei. Some impressive progress has been made. Among the important nuclear properties are the beta decay lifetimes of the rare isotopes along the r-process, typically in the range of milliseconds to seconds. A slow lifetime will slow down the r-process, and the respective isotope will be produced in larger quantity because its production will tend to be faster than its decay. This net accumulation translates into a signature in the final abundance pattern once the unstable r-process isotopes have decayed into stable ones. Since the pioneering experiments that determined the first half-lives of the r-process nuclei $^{80}$Zn and $^{130}$Cd in 1986, half-lives of about two dozen r-process nuclei have now been measured (Kratz et al. 2005). A recent milestone was the measurement of the half-life of $^{78}$Ni at Michigan State University (Hosmer et al. 2005; Fig. 3), the only doubly magic nucleus along the main r-process path (though $^{132}$Sn is close).

Another critical quantity is the precise mass of an r-process isotope. Model calculations have shown that nuclear mass changes of the order of just 1:100,000 can lead to dramatic changes in the produced r-process abundances. Techniques are now available to measure nuclear masses with this precision, but they require larger production rates for the rare isotopes compared to what is required for the simpler lifetime measurements. Therefore, only very recently were the masses of $^{80}$Zn and $^{130}$Cd determined experimentally for the first time, in the case of $^{80}$Zn through the characteristic motion of the nucleus in the magnetic field of an ion trap at CERN/ISOLDE (Baruah et al. 2008) and the University of Jyvaeskyla ( Hakala et al. 2008). A similar technique has been used at Argonne National Laboratory (Van Schelt et al. 2008) to measure masses of nuclei near the r-process path. In the case of $^{130}$Cd, a measurement of the maximum energy of the beta spectrum has been used to determine the mass, albeit with somewhat less precision (Dillmann et al. 2003). Neutron-capture rates are even more difficult to determine, as both projectile and target are radioactive. Here progress has been made using reactions resulting from radioactive beams striking deuterium targets. The resulting neutron transfer reaction that leaves a proton in the target and adds the neutron to the incoming radioactive beam resembles the capture of a neutron, and from the rate of the reaction one can in principle constrain the stellar neutron-capture rate. Pioneering experiments at the HRIBF facility at Oak Ridge National Laboratory have recently been performed to explore this possibility for $^{130}$Sn. The rate of neutron capture on $^{130}$Sn has been shown in model calculations to affect the balance of free neutrons during late stages of the r-process (Jones 2009).
THE FUTURE

Despite this impressive progress, the relevant properties of the vast majority of the r-process nuclei are out of reach of both theorists and experimental facilities. At the same time, a comprehensive theory of the rather heavy r-process nuclei grounded in first principles and with a predictive power sufficient for r-process models is lacking, in part due to the absence of experimental information that could reveal the relevant aspects of the nuclear force. However, major advances in our understanding of rare isotopes are expected in coming years from experiment and theory. New accelerator facilities around the world promise to produce most of the important r-process nuclei. The most advanced of this new generation of accelerators is the Facility for Rare Isotope Beams (FRIB), a project of the U.S. Department of Energy now underway at Michigan State University (www.frib.msu.edu). New theory initiatives and advances in computing promise to develop new frameworks for a reliable description of heavy nuclei that, once calibrated with new experimental data, might be able to predict reliably the properties of the few r-process nuclei remaining out of reach. Initiatives such as the Joint Institute for Nuclear Astrophysics (www.jinaweb.org), a Physics Frontiers Center of the U.S. National Science Foundation, are bridging the gaps between nuclear physics and astrophysics to forge a new interdisciplinary approach to the problem of the origin of the elements. We now seem to be at the threshold of finally deciphering the “DNA” of the chemical evolution of the cosmos. In the end, we might gain more than just an understanding of the origin of the elements making up the world around us. The understanding of the chemical evolution of our Galaxy might also provide new insights into its formation history, allowing us to address a broader range of fundamental questions in cosmology.

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Meteorites and the Early Solar System II
Edited by DANTE S. LAURETTA · HARRY Y. MCSWEEN
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—Lunar and Planetary Information Bulletin
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Mineralogical Evolution of Meteorites

Timothy J. McCoy*

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The approximately 250 mineral species found in meteorites record the earliest stages of the birth of our solar system. Refractory minerals that formed during the violent deaths of other stars and during condensation of our own solar nebula mixed with a wide range of silicates, sulfides, and metals to form the most primitive chondritic meteorites. Subsequent aqueous alteration, thermal metamorphism, and shock metamorphism further diversified the minerals found in meteorites. Asteroidal melting at first increased and then dramatically decreased mineralogical diversity, before a new phase of igneous differentiation that presaged the processes that would occur in terrestrial planets.

Keywords: mineral evolution, meteorites, asteroids, metamorphism, differentiation, shock

FRAGMENTS FROM THE BEGINNING

As Earth evolved over the last 4.5 billion years, its mineralogy changed. As we peer back through Earth's history, it seems logical to think that our lens would grow increasingly fogged and our light ever more dim. How do we see beyond the oldest preserved rocks and minerals, after billions of years of volcanism, plate tectonics, and weathering? How do we see past the Moon-forming collision, which would have melted the early Earth? Where is the starting point for the mineralogical evolution of Earth and the other terrestrial planets?

Scientists are fortunate that gravitational perturbations from Jupiter prevented the formation of a planet in what is now the asteroid belt. Asteroids, cosmic relics of our solar system's formation, not only preserve this earliest history, they also generously shed pieces that carry their treasure trove of information to Earth. This continuing flux of meteorites provides a clear picture of early mineralogical evolution.

This earliest record is more diverse and more complicated than we might have ever imagined from the mineralogy of Earth alone. Earth's mineralogical evolution began long before there were planets. The nebula from which our solar system originated was seeded with minerals formed in the cauldrons of dozens of dying earlier-generation stars. As the solar nebula cooled, minerals formed, reacted with the gas, and disappeared, but pieces were sequestered and preserved along the way. Even these earliest-formed minerals were reworked by chemical reactions, heating, and alteration in the solar nebula. Once asteroids accreted, water ice melted and alteration minerals appeared. Impacts transformed minerals under intense heat and pressure. Radiogenic heating produced mild metamorphism at first, but eventually transformed some asteroids into molten worlds that formed crusts, mantles, and cores reminiscent of our own planet. It is this history—from the melting of planets—that we explore in this article.

THE STELLAR CAULDRON

Earth's mineralogical evolution began not in the heat of an early molten planet but in the blast furnace of stars that predated our solar system. More than 4.6 billion years ago, presolar grains formed when temperatures in the expanding envelopes of red giants or in supernova ejecta fell sufficiently to allow condensation. These grains entered the interstellar medium, where many were destroyed by supernova shocks and sputtering by stellar wind. Eventually, grains from a diversity of stars were incorporated into the dense molecular cloud from which our solar system formed, and they accreted to form asteroids.

Although the existence of presolar grains was inferred from hydrogen, noble gas, and oxygen isotope anomalies in meteorites (Black and Pepin 1969), these grains were positively identified only in the late 1980s. Using chemical dissolution and physical separation steps (akin to burning down the haystack to find the needle), the earliest workers identified diamond, silicon carbide, and graphite in meteorites (Zinner 2004; Bernatowicz et al. 2006). These grains typically are up to only a few micrometers in size, and their abundance ranges from parts per billion to hundreds of parts per million. Subsequent to these discoveries, a range of presolar grains were identified. The ion microprobe and transmission electron microscope were used to study both individual grains within acid residues after chemical dissolution of the meteorite and in situ grains, particularly in interplanetary dust particles (IDPs). These presolar minerals include the nitrides osbornite (TiN) and nierite (α-Si₃N₄); the carbide cohenite ([Fe,Ni,Co,]C); the alloy "kamacite" (Fe,Ni); the oxides rutile (TiO₂), corundum (Al₂O₃), spinel (MgAl₂O₄), and hibonite (CaAl₂SiO₆) (Fig. 1); and the silicates forsterite (Mg₂SiO₄) and perovskite-structured MgSiO₃ (Zinner 2004).

To date, these dozen or so minerals are the only record of the minerals that accreted to form our solar system, but this is far from a complete inventory. Presolar-grain research is perhaps the most active area in the field of meteoritics, and new minerals are being discovered continuously. Among the materials known but not yet character-
ized as minerals are Ti-, Fe-, Zr-, and Mo-carbides (Zinner 2004), a new Al₂O₃ structure (Stroud et al. 2007), FeO (Floss et al. 2008), and TiO₂ (Nittler et al. 2008). Further, much of the presolar material observed in IDPs and primitive chondrites is amorphous, nonstoichiometric, or partially crystalline. While not qualifying as minerals, these materials certainly suggest that a much more robust selection of solid matter accreted to form the early solar system. The methods for detecting presolar grains—either harsh chemical dissolution or in situ study of extremely small areas—limit our ability to characterize fully these solid materials. Finally, the processes in the early solar system almost certainly destroyed many presolar materials. Thus, while our current inventory of presolar minerals is small, our mineralogical view of this epoch may change dramatically over the next decade.

FROM THE NEBULA

The earliest materials formed within our own solar system are the so-called calcium–aluminum inclusions (CAIs). These millimeter- to centimeter-sized, rounded to irregular, typically light-colored particles first drew significant attention after the fall of the Allende carbonaceous chondrite meteorite in February, 1969, although they had been described a year earlier by Christophe Michel-Lévy (1968). The Allende meteorite provided researchers with hundreds of kilograms of material containing centimeter-sized CAIs. Early attention focused on the similarity between CAI mineralogy and the first phases predicted to condense out of a gas of solar composition (Grossman 1972). We now recognize that nearly all CAIs experienced prolonged histories of reaction with nebular gas, multiple heating and/or melting episodes, and alteration in the nebula and/or the asteroid parent bodies. Nonetheless, their fascinating high-temperature mineralogy reflects their formation from high-temperature condensates in the solar nebula.

While some two dozen mineral phases are known from CAIs, a few dominate, including spinel (MgAl₂O₄–FeAl₂O₄), melilite [gehlenite (Ca₄Al₂SiO₇) to akermanite (Ca₃MgSi₂O₇)], perovskite (CaTiO₃), hibonite, calcic pyroxene, anorthite, and forsterite. Less common minerals include grossite (Ca₃Al₂O₆), corundum, and thömeite [Ca₂(Mg,Al)₂Ti(Al, Si)₂O₆] (MacPherson 2004; Beckett et al. 2006). Even at this earliest stage of mineralogical evolution, all the major crystal systems were represented. Although the different types of CAIs vary among different classes of chondritic meteorites, spinel–pyroxene-rich and melilite-rich CAIs are found in virtually all chondrites (MacPherson 2004). Further, these minerals are highly depleted in volatile trace elements, such as alkali metals, and iron. As is the case for presolar grains, the mineralogy of CAIs is incompletely understood. The field of nanomineralogy (e.g. Ma et al. 2009) is revealing a broad array of minerals found only at the scale of a few to ten micrometers. Each of these minerals testifies to unique combinations of chemical composition and intensive variables (e.g. temperature, pressure, and oxygen fugacity).

Although the CAIs were highly processed within the solar nebula, the range of CAI bulk compositions and, by extension, the minerals that formed from them may largely reflect the temperature of condensation of the CAI precursor. Thus, the precursors to refractory Type A CAIs rich in melilite, spinel, and hibonite formed at higher temperatures than the precursors of Type B CAIs rich in melilitic, calcic pyroxene, anorthite, and spinel (MacPherson 2004). The minerals in CAIs record the first appearance in the solar system of distinct environments with different intensive variables (e.g. temperature). This creation of differing environments over the next 4.5 billion years produced the mineralogical diversity observed today.

While calcium–aluminum inclusions exhibit some of the most important mineralogical diversity observed among primitive nebular materials, they represent a volumetrically minor component of these materials. The full range is shown by chondritic meteorites, which are essentially cosmic sedimentary rocks (Scott and Krot 2004). Millimeter-sized spheres called chondrules (Fig. 2) were formed during flash melting in the solar nebula and volumetrically dominate chondritic meteorites (Lauretta et al. 2006). The fine-grained matrix between the chondrules and CAIs is largely silicate material but contains a diversity of metals, sulfides, oxides, and phosphates. The chondrites themselves are diverse, particularly with respect to oxygen fugacity, and range from the highly reduced enstatite chondrites to the oxidized carbonaceous chondrites and R chondrites. Metamorphism, aqueous alteration, and shock all modified
Among these minerals, Mg-rich olivine, Mg-rich pyroxene, and plagioclase dominate the silicate mineralogy. Most of the mineralogical diversity is observed among the minor minerals. In the highly oxidized meteorites, minerals such as pentlandite and magnetite are prevalent. In contrast, the highly reduced enstatite chondrites include very unusual carbides (cohenite), silicides [perrryite, (Ni,Fe)6(Si,P)3], phosphides [schreibersite, (Fe,Ni)P], and, especially, sulfides [oldhamite, CaS; caswellsilferite, NaCrS2; niningerite, (Mg,Fe,Mn)S] (Keil 1989). Many of these minerals were first described from, and some are only known from, enstatite meteorites. Their presence testifies to the ability of the early solar nebula to create a broad range of chemical and physical environments, some of which were never duplicated during the later history of the Earth.

**ASTEROIDS: BAKED AND STIRRED**

Although the mineralogical evolution of meteorites began in the fiery cauldrons of other stars, it progressed to a frozen snowball stage. Perhaps the most important mineral that accreted during the formation of chondritic asteroids is one that has never been documented in any meteorite—ice (H2O)! Much as the Earth has a snow line that separates ecosystems, the early solar system had a snow line that separated the ice-free rocky planets and asteroids from the ice-rich gas giant planets, ice-rich asteroids, and comets. As asteroids grew and began to experience modest heating by the decay of short-lived radionuclides (e.g. 26Al, whose half-life is 720,000 years), the melting of ice and the subsequent alteration of the asteroids at low temperatures (<100°C) produced many new minerals (Brearley and Jones 1998; Brearley 2006). The evidence for this alteration is most prominent in the fine-grained matrix of carbonaceous chondrites (particularly the CI and CM groups), but can be found in unexpected forms in other meteorite groups. As ice melted and water reacted with the olivine-rich matrix, many minerals emerged for the first time. These included the phyllosilicates montmorillonite [(Na,Ca,Al)0.5Si3O10(OH)2·nH2O], chrysotile [Mg3Si2O5(OH)4], and crostredite [(Fe2+,Fe3+)2(Si,Fe3+)O5(OH)4]; the oxides magnetite and ferrhydrite (FeO·9H2O); the sulfides pyrrhotite and pentlandite; the carbonates dolomite and calcite; and the sulfates gypsum and epsomite (MgSO4·7H2O). As in earlier eras, some of the products of this alteration were not well crystallized and thus do not qualify as minerals. An alteration product termed PCP (poorly crystallized phase) is common in some carbonaceous chondrites.

While carbonaceous chondrites most dramatically illustrate aqueous alteration, other types of meteorites contain spectacular evidence for the melting of ice. Aqueous alteration of ordinary chondrites formed smectite, maghemite, Ni-rich pyrrhotite, and calcite in the matrix of the type 3.0 chondrite Semarkona. While evidence of such alteration was thought to be confined to the least metamorphosed ordinary chondrites, Zolensky et al. (1999) demonstrated that the Monahans ordinary chondrite contained fluid inclusion-bearing halite crystals in the matrix (Fig. 3).

Emerging from their frozen state, many asteroids continued to warm. While heating of ice-bearing carbonaceous chondrites produced extensive aqueous alteration, heating of largely anhydrous ordinary and enstatite chondrites produced new minerals as a result of thermal metamorphism at temperatures up to the FeNi–FeS cotectic temperature of ~950°C (Brearley and Jones 1998; Huss et al. 2006). As sodium-rich chondrule glass recrystallized, albite plagioclase appeared in metamorphosed ordinary chondrites. Oxidation of phosphorus may have been largely responsible for the formation of the phosphates apatite and merrillite. Nepheline, rutile, and cristobalite have all been observed in metamorphosed ordinary chondrites. In the highly reduced enstatite chondrites, cristobalite was joined by tridymite and quartz. Other minerals apparently formed during metamorphism of enstatite chondrites include the nitride sinoite (Si,N2O), the amphibole richterite [Na(Al,Mg)5Si8O22(OH)2], and roedderite [KNa(Mg,Al)(Si2O6)2(H2O)]. While relatively few new minerals formed during metamorphism of the water-poor chondrites, collectively they suggest that recrystallization of glass and other poorly crystalline phases in type 3.0 chondrites, coupled with oxidation and reactions during metamorphism, provided new environments for the formation of minerals.

Even while this aqueous alteration and thermal metamorphism were occurring in asteroids, an era of intense bombardment began, and impacts would continue for the entire 4.5 billion years of solar system history. Impact fragmentation would reshape asteroids to what we observe today, form the Earth’s moon, and scar the inner rocky planets. Not surprisingly, these impacts formed new minerals as chondritic asteroids were subjected to intense heat and pressure (Brearley and Jones 1998; Sharp and DeCarli 2006). The dominant mafic silicate olivine [(Mg,Fe)2SiO4] was transformed into the high-pressure spinel polymorph ringwoodite (Fig. 4) and the high-pressure orthorhombic polymorph wadsleyite. Ringwoodite is a particularly important mineral and is thought to be a major component of Earth’s mantle. Pyroxene in these heavily shocked rocks was transformed into the high-pressure garnet structure majorite, the ilmenite structure akimotoite, and the perovskite structure. SiO2 was transformed into the coesite and stishovite forms. Rubin and Scott (1996) suggested that submicron-sized diamonds discovered in the impact melt breccias of the Abee enstatite chondrite were formed by shock.

**Figure 3** Halite crystals in the Monahans ordinary chondrite contain trains of fluid inclusions filled with trapped ancient water. Field of view is ~0.15 mm. Photo courtesy of Mike Zolensky.
The Youndegin IAB meteorite formed from a metallic melt rich in phosphorus, carbon, and sulfur, which cooled and crystallized to form a host of new minerals. The orthogonal texture was formed during slow cooling of the metal, when low-Ni kamacite exsolved from high-Ni taenite. The elongated kamacite lamellae contain cohenite. The dark-colored inclusions are rich in troilite (FeS) and graphite. The specimen is ~40 cm long.

CONCLUSIONS (OR BEGINNINGS?)

In meteorites, we see the earliest stages of the mineralogical evolution of our planet. Many meteoritic minerals are unknown on Earth. The solar system records ranges of temperature, chemistry, and oxygen fugacity never duplicated on Earth. In some cases, the very processes that formed these minerals can never be repeated, processes such as the condensation of the nebular gas that produced the myriad of minerals we know today.

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THE IMA–CNMNC DOMINANT-CONSTITUENT RULE REVISITED AND EXTENDED

The criteria for the definition of a new mineral species currently used by the Commission on New Minerals, Nomenclature and Classification (CNMNC) of the International Mineralogical Association (IMA) involve what should now be called the rule of the dominant constituent. The term ‘constituent’ may designate atoms (cations or anions), molecular groups, or vacancies. According to the rule, a mineral is a distinct species if the set of dominant constituents at the sites in the crystal structure is distinct from that of any other mineral with the same structural arrangement. Nickel (1992) called this rule for the sake of brevity the 50% rule, a name which unfortunately is a source of confusion as this name can only be applied in binary systems.

The current dominant-constituent rule is applied in most approved new-mineral proposals. On the one hand, this rule has sometimes been applied rigorously, thus leading to some proliferation of new mineral species as, for example, in the complex labuntsovite and eudialyte groups. On the other hand, besides the well-known problems in the nomenclature system in the complex amphibole group, new nomenclature systems for minerals of the arrojadite and epidote groups have recently been approved by the CNMNC, but these systems do not follow the current definition of the dominant-constituent rule. For this reason, Hatert and Burke (2008) submitted a proposal to clarify, revise and extend the dominant-constituent rule, taking into account the recent problems encumbering or prohibiting a strict application of the rule.

The Dominant-Constituent Rule

In solid-solution series which involve mutual substitution of only two kinds of atoms, two different mineral names are required for each compositional range from the end members to the 50 mol% mark. When more than two kinds of homovalent atoms occur on a single crystallographic site, the predominant atom has to be considered for defining the mineral species. Consequently, the 50% mark is not applicable any more, and instead the limits become 33.3% (3 atoms), 25% (4 atoms) or 20% (5 atoms) in the dominant-constituent rule.

Valency-Imposed Double-Site Occupancy

Single-site heterovalent substitutions lead to end members with (disordered) sites occupied by two constituents, imposed by the differences in valency of the two constituents: this is valency-imposed double-site occupancy. An example is given by the substitution Fe²⁺ → 0.5 Li¹⁺ + 0.5 Al³⁺ on the Y sites of the tourmaline mineral schorl, NaFe²⁺Al₃(Si₈O₂₂)(BO₃)(OH)₂, which leads to the end member elbaite, Na(Li¹⁺Al³⁺)Al₃(Si₈O₂₂)(BO₃)(OH)₂.

Coupled heterovalent substitutions on two sites also lead to end members with valency-imposed double-site occupancy when there is a disparity in the multiplicity of these two sites. For example, the substitution Na⁺ + Ca²⁺ → Na⁺ + Na⁺ in the amphibole mineral tremolite, Ca₂Mg₆(Si₈O₂₂)(OH)₂, leads to a valency-imposed double occupancy of the B site in the end member richterite, Na(CaNa)Mg₆(Si₈O₂₂)(OH)₂, because there are two atoms on the B site, but only one on the A site.

The Dominant-Valency Rule

Coupled heterovalent substitutions, on a single site or on two sites, become more complex when an additional homovalent substitution takes place. This nomenclatural problem can be solved by considering the elements of the homovalent substitution as a whole, so that the group of cations with the same valency are still dominant. Consequently, species with such coupled heterovalent/homovalent substitutions must be defined by the most abundant amongst the cations with the same valency state. This rule is called the dominant-valency rule, and is necessary to preserve charge balance in any end member formula. This rule is thus an extension of the current dominant-constituent rule, by considering a group of atoms with the same valency state as a single constituent.

An important implication of this valency rule becomes evident when analyses of such minerals are plotted in a ternary diagram. As shown in Figure 1, the usual boundaries crossing at the centre of the diagram (33.3% of each component) are significantly displaced, and atom C needs dominance over the group (D + E) on the N site to allow the definition of a new species. More complex examples of minerals for which this dominant-valency rule has to be applied have recently been provided by Cámara et al. (2006) and Chopin et al. (2006) in the arrojadite group and by Armbruster et al. (2006) in the epidote group.

Grouping of Crystallographic Sites

It is frequently observed that a group of similar cations or anions can occupy more than one crystallographically distinct site. Such sites, with similar crystal-chemical roles, may be considered as a whole for nomenclature proposals. For example, the olivine structure has two octahedral sites, M₁ and M₂, which in the forsterite–fayalite series are occupied by Mg and Fe²⁺, in a not completely disordered way. However, recognition of only two species is deemed to be appropriate as the two intermediate compositions and their implied arrangements are not approached in nature.

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Frédéric Hatert and Ernst A. J. Burke

Vice-Chairman and Chairman Emeritus of the Commission on New Minerals, Nomenclature and Classification (CNMNC)
The oldest vestiges of crust and marine environments occur only in a few remote areas on Earth today. These rocks are Hadean–Eoarchean in age (~4.5 to 3.6 billion years old) and represent the only available archive of the mineral environments in which life originated. A mineral inventory of the oldest rocks would thus help to constrain the likeliest minerals involved in the origin of life. Such a survey is important from the perspective of mineral evolution, as the emergence of life and subsequent global changes caused by organisms were responsible for more than half the 4400 known minerals on the modern Earth.

**THE DAWN OF GEOLOGY**

The first 700 million years of Earth history, called the Hadean Eon (from ~4.5 to ~3.85 billion years ago, or Ga for giga-annum), is poorly documented because of the lack of a significant rock record. Nevertheless, a mineral inventory of crustal rocks from this eon and from the subsequent Eoarchean Era (3.85 to 3.60 Ga) may yield information for constraining the nature of the aqueous environments in which life emerged. The availability of specific minerals in the earliest surface environments, where prebiotic chemical reactions took place, was likely a key factor for the emergence of life and was strongly influenced by Hadean–Eoarchean rock types. Determining the mineral inventory of Hadean and Eoarchean metamorphic rocks is challenging, however, due to extensive metamorphic recrystallization and metamatism resulting from high-temperature crustal fluids. These processes likely changed and homogenized the chemical and mineral compositions of Hadean–Eoarchean protoliths (the precursor lithologies of the metamorphic rocks). These alterations likely reduced the diversity of rock-forming minerals in ancient metamorphic rocks. Protoliths of metamorphic rocks can generally be inferred from a variety of mineralogical, geological, and geochemical criteria. Here I document the mineral diversity of the first billion years of Earth history in the context of mineral evolution at the time of life’s emergence.

Following planetary accretion and differentiation, mineral diversity rapidly increased from the approximately 60 different mineral phases found in unaltered meteorites—the starting point of planetary mineral evolution (Hazen et al. 2008). The initial mineral diversity of Earth’s crust depended on a sequence of geochemical and petrological processes that included volcanism and degassing on the surface, fractional crystallization and assimilation reactions in the mantle, crystal settling in magma chambers, and regional and contact metamorphism in the crust. Processes in the original mafic crust at plate boundaries initiated large-scale fluid–rock interactions and ultimately produced granitoids, metamorphic belts, and zones of surface weathering.

Oceans have influenced Earth’s surface since about 4.4 Ga. Interactions between the crust and the anoxic ocean–atmosphere system during the Hadean–Eoarchean should have led to a progressive increase in ocean-water ion content and to the deposition of silt, carbonate, chert, iron-rich sediment, and evaporite. Although the oldest rocks are highly metamorphosed, their mineral diversity contains clues about the nature of the earliest habitable environments. The rise of life in oceans during the Hadean or Archean (the latter from 3.85 to 2.5 Ga) slowly began to change Earth’s mineralogical landscape. By the time biological processes began to affect Earth’s surface mineralogy, large-scale surface mineral deposits were being precipitated under the combined influences of early Hadean crustal recycling and an anoxic atmosphere and ocean. Combined with the formation of later pegmatites and hydrothermal ore deposits, these processes resulted in an estimated 1500 different mineral species by the end of the Archean (Hazen et al. 2008; Hazen and Ferry 2010 this issue).

**INITIATION OF IGNEOUS ROCK EVOLUTION**

**Early Crust and Mantle Differentiation**

The first granitoid rocks resulted from partial melting in the mantle, after the initial formation of basaltic crust. Hadean and Eoarchean orthogneisses (i.e. formed from igneous rocks) are generally inferred to have granitoid protoliths of the tonalite–trondhjemite–granodiorite (TTG) series. These plutonic rocks are thought to have formed from the melting of older, hydrated, mafic crust (Nutman et al. 2007; Nutman and Friend 2009) and are composed mostly of quartz, plagioclase, biotite, and K-feldspar (Table 1). A wide variety of minor mineral species are also found in Eoarchean TTG-type rocks. The tectonic context during the formation of TTG suites is still debated, owing to uncertainties regarding the existence of plate tectonics and the styles of subduction at that time.

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**TABLE 1.** A variety of minor mineral species are also found in Eoarchean TTG-type rocks.
Hadean Time Capsules

Earth’s oldest minerals are tiny detrital zircon grains from the Mesoarchean (3.2 to 2.8 Ga) Jack Hills conglomerate in the Yilgarn Craton, Western Australia (FIG. 1). These grains have yielded a range of Hadean–Archean ages up to 4.4 Ga (Wilde et al. 2001; Mojzsis et al. 2001). Their trace element compositions have been interpreted to indicate that granitic continental crust was produced within 200 million years of Earth’s accretion. Oxygen isotopes of Hadean zircon are often heavier than in the mantle; this fact suggests that early Hadean oceans were involved in the recycling of continental crust during subduction (Cavosie et al. 2005). While views diverge on the degree of hydration of early Hadean crust and the styles of tectonic processes, there is consensus on the existence of granitoid crust and probably of supracrustal assemblages within 200 million years of Earth’s formation. These developments are significant, because the recycling of continental crust is a process central to the global carbon cycle and to mineral diversification.

Numerous mineral inclusions have been reported from Hadean zircon grains, including quartz, muscovite, biotite, K-feldspar, plagioclase (albite), chlorite, hornblende, and many less common mineral species (FIG. 2, TABLE 1; Trail et al. 2004; Nemchin et al. 2008; Hopkins et al. 2008). This remarkable suite of mineral inclusions is the only terrestrial archive currently known for the oldest mineralogical diversity on Earth. Collectively, these mineral inclusions in pre–4.0 Ga zircon grains are characteristic of silica-saturated, peraluminous crust, such as TTG-type granitoids and their subducted-hydrated equivalents, and possibly supracrustal assemblages. However, because of their limited distribution, these postulated early Hadean granitoid masses were likely recycled into the mantle prior to the end of the Hadean and thus are not preserved, and outcrops of them are not currently known.

THE HADEAN–EOARCHEAN ROCK RECORD

The Oldest Rocks on Earth

The Acasta orthogneisses in the Slave Craton are generally accepted as the oldest rocks on Earth (FIG. 1, which shows all localities mentioned in this section). These highly deformed rocks have been dated to be as old as 4.06 Ga and inferred to have various protoliths, including TTGs, amphibolite, gabbro, granite, and diorite (Bowring and Williams 1999). Their mineral assemblages are typical of TTGs and are dominated by plagioclase, quartz, hornblende, feldspar, and biotite, along with various minor phases (TABLE 1; Iizuka et al. 2007). Interestingly, a zircon xenocryst dated at 4.20 Ga from a sample of Acasta Gneiss, and presumed to be inherited from an older rock and incorporated in the tonalitic melt, was found to have an inclusion of apatite. The weathering of the oldest Hadean TTGs may thus have been a source of phosphorus for the early ocean and have contributed to its nutrient budget (see below).

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>MINERALS COMMONLY REPORTED FROM HADEAN ZIRCON GRAINS AND HADEAN–EOARCHEAN ORTHOGNEISSES</th>
</tr>
</thead>
</table>
| **Minerals in Hadean–Eoarchean TTG gneisses** | **Major minerals** quartz, plagioclase (albite, anorthite), K-feldspar (microcline, orthoclase, perthite), biotite, muscovite, amphibole, epidote | **Minor minerals**
| & | zircon, titanite, apatite, garnet, chlorite, phengite, clinopyroxene, orthopyroxene, tourmaline, sulfides |
| **Mineral inclusions in pre–4.0 Ga zircon grains** | quartz, muscovite, plagioclase (albite), K-feldspar, biotite, chlorite, hornblende | titanite, apatite, monazite, xenotime, Ni-rich pyrite, thorite, rutile, iron oxyhydroxides, diamond, graphite |


† These minerals are not always found in the listed rock types.

‡ These minerals may be secondary alteration phases as they often occur within cracks in zircon.
The oldest rocks in Antarctica are part of the Napier Gneiss Complex, located in Enderby Land. Highly metamorphosed gneissic granites and tonalites at Mount Sones contain zircon grains with ages up to 3.93 Ga (Black et al. 1986), which gave these rocks the status of the oldest rocks on Earth until the discovery of the pre–4.0 Ga Acasta Gneiss. It is unclear, however, if the parent melt inherited these >3.9 Ga zircon grains, and a reevaluation of the original datasets suggests that the main zircon population in the orthogneiss precursors, presumably recording the magmatic protolith age, is instead 3.85 Ga (Harley and Kelly 2007). Eoarchean orthogneisses and paragneisses at Mount Sones, many with uncertain protoliths, include pyroxene granulites, garnet quartzites, garnet–sillimanite metapelites, and rare sapphirine-bearing gneisses.

The recent discovery of Hadean–Eoarchean supracrustal rocks in the Nuvvuagittuq Supracrustal Belt in northern Québec (David et al. 2002) has reignited excitement about the possibility of finding other Hadean crustal remains. Unusual amphibolites from this belt have been dated directly at 4.28 Ga with a $^{146}$Sm/$^{142}$Nd model age (O’Neil et al. 2008). Zircon grains from felsic gneisses interpreted to crosscut a banded iron formation (BIF) unit have ages of ~3.75 Ga, which represents the minimum age of the belt (Cates and Mojzsis 2007). Thus far, no zircon grains of Hadean age have been found in the Nuvvuagittuq Supracrustal Belt, and therefore a Hadean age for the belt has yet to be confirmed. Metasedimentary rocks in the Nuvvuagittuq Supracrustal Belt include BIFs with varied mineralogy (magnetite + amphibole + quartz ± hematite ± carbonate; Fig. 3). Other possible metasedimentary rocks in the belt include schists (quartz + biotite + garnet ± hornblende), polymictic conglomerates, and metacarbonate rocks (quartz + carbonate + magnetite ± hematite) (Table 2; O’Neil et al. 2007).

**Eoarchean Supracrustal Assemblages**

Besides occurrences in the Nuvvuagittuq Supracrustal Belt, there are very few exposures of Eoarchean metasedimentary rocks worldwide. Examples include the Itsaq Gneiss Complex in southwestern Greenland, the Saglek Complex of the Nain Craton in northern Labrador (Canada), and possibly the Narryer Gneiss Complex of Western Australia and the Anshan area of the North China Craton. Other localities that may preserve Eoarchean supracrustal rocks, but that are currently known to contain only orthogneisses or their weathered components, include the Kaapvaal Craton in southern Africa, with TTGs as old as ~3.7 Ga (Kröner et al. 1996); the Minnesota River valley and northern Michigan, with components up to ~3.8 Ga in age (Goldich and Hedge 1974); and the Assean Lake area of northern Manitoba, which contains Archean metasedimentary rocks hosting detrital zircon grains with ages up to 3.8 Ga (Böhm et al. 2003).

The Itsaq Gneiss Complex of southwestern Greenland is dominated by tonalitic and granitic orthogneisses, with subordinate quartz diorite and ferruginous gabbro, which intruded older supracrustal rocks between 3.87 and 3.62 Ga. Metasedimentary rocks worldwide have very few exposures of Eoarchean orthogneisses and paragneisses in the Nuvvuagittuq Supracrustal Belt.

**TABLE 2** MINERALS AND MINERAL GROUPS COMMONLY REPORTED FROM EOARCHAEAN SUPRACRUSTAL VOLCANOSEDIMENTARY ROCKS

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Possible protoliths</th>
<th>Major minerals</th>
<th>Minor minerals*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metavolcanic rocks</strong></td>
<td>greenstone, komatiite, amphibolite, ultramafic rock</td>
<td>olivine, clinopyroxene, garnet, orthopyroxene, biotite, chlorite, amphibole (hornblende)</td>
<td>serpentine, antigorite, magnetite, talc, magnesite, epidote, phlogopite, kyanite, chromite, rutile, ilmenite, sulfides, dolomite, calcite, K-feldspar, plagioclase, cordierite, apatite</td>
</tr>
</tbody>
</table>

| Banded iron formation | BIF, ferruginous chert | quartz, magnetite, amphibole | clinopyroxene, orthopyroxene, olivine, garnet, chlorite, tremolite, calcite, magnesite, hematite, geothite, apatite, sulfides, zircon, graphite |

| Schist (metapelite) | ferruginous shale, mudstone, siltstone, argillite | quartz, biotite, amphibole, garnet, chlorite | muscovite, sillimanite, kyanite, staurolite, andalusite, cordierite, plagioclase, epidote, microcline, clinzoisite, tourmaline, magnetite, ilmenite, rutile, graphite, sulfides, zircon |

| Quartzite | chert, sandstone? | quartz, amphibole | magnetite, clinopyroxene, orthopyroxene, biotite, chlorite, epidote, plagioclase, zircon, fuchsite, hematite, sulfides, carbonate |

| Calc-silicate and metacarbonate rocks | limestone?, chert, metamorphic contact?, hydrothermal edifice? | quartz, siderite, dolomite, calcite, ankerite, magnesite, magnetite | clinopyroxene, orthopyroxene, olivine, amphibole, garnet, phlogopite, biotite, feldspar, muscovite, chlorite, epidote, fuchsite, apatite, hematite, sulfides, graphite |

* These minerals are not always found in the listed rock types.
billion years ago (Nutman et al. 2007). The oldest supracrustal rocks in the Itsaq Gneiss Complex are those of the Isua Supracrustal Belt and the Akilia Association, which collectively include amphibolite, felsic volcanic rocks, and gabbro–anorthosite, as well as metasedimentary units of BIF, metapelite, ferruginous quartzite, and possible metaconglomerate (Nutman and Friend 2009). The Isua Supracrustal Belt is the most extensive single geological unit in which Eoarchean supracrustal rocks are found. It contains possible metasedimentary rocks, including schists with uncertain protolith, typically composed of the assemblage quartz + biotite + garnet + plagioclase. Banded iron formations deposited in marine environments are common and dominated by quartz, magnetite, and amphibole (Table 2). Calc-silicate rocks in the Isua sequence are composed of quartz + carbonate + diopside + tremolite + garnet assemblages and are commonly in close association with chert, BIF, and ultramafic and ferruginous schists (anthophyllite + talc + magnesite + chlorite, and quartz + garnet + biotite). Based on their close association with ultramafic schists and metasomatic veins, these complex calc-silicate rocks have been interpreted to be metasomatic in origin (Rose et al. 1996), although others have proposed a possible volcanosedimentary origin.

The Saglek Complex of Labrador is composed of the Eoarchean Nulliak supracrustal assemblage and TTG gneisses. Igneous zircon cores from orthogneisses in the area have Eoarchean ages up to 3.8 Ga (Schiotte et al. 1989). Rocks of the Saglek Complex have been correlated with the Itsaq Gneiss Complex in southwestern Greenland on the basis of similarities in their age, metamorphic history, and modern geotectonic setting on the west side of the Labrador Sea. The Nulliak supracrustal assemblage is dominated by amphibolite and other metavolcanic rocks derived from komatiite and tholeiite (Nutman et al. 1989). Supracrustal rocks of sedimentary origin, including BIF dominated by quartz + magnetite + amphibole + pyroxene assemblages and possible metapelitic schists composed of the assemblage quartz + sillimanite + garnet + biotite, are also present. In some areas, BIF is associated with calc-silicate rocks composed of quartz, carbonate, diopside, amphibole, and other minor phases.

The Narryer Gneiss Complex of Western Australia is dominantly composed of Paleoarchean to Neoarchean TTG orthogneisses, but also contains some Eoarchean crust. The Mesoarchean Jack Hills rocks (which host Hadean zircon grains) are located near the southern margin of the Narryer terrain and represent one of the few supracrustal belts in the complex. The oldest rocks in the Narryer terrain are known as the Man福德 Complex and include metanorthosite and other orthogneisses with ages up to 3.73 Ga (Kinny et al. 1988). Supracrustal enclaves located in the vicinity of Mount Narryer that may have Eoarchean ages include mafic and ultramafic rocks, BIF, metaconglomerate, quartzite, and calc-silicate rocks.

Last, Eoarchean crust is also present in the Anshan area of eastern China. Granitoid gneisses from this area contain zircon grains with ages up to 3.8 Ga (Liu et al. 1992). These TTG-type orthogneisses typically consist of variable mixtures of quartz, plagioclase, K-feldspar, and hornblende (Liu et al. 2008). Minor bands of quartz and biotite within these TTGs may represent Eoarchean metasedimentary enclaves. Younger Paleoarchean supracrustal rocks also occur in the Anshan area and include units of amphibolite, BIF, quartz–biotite schist, and quartzite.
HADEAN–EOARCHEAN SURFACE ENVIRONMENTS

The Oldest Preserved Marine Environments

A simplistic view of surface environments in the Hadean and Archean posits a mostly mafic crust with sporadic volcanism, a weakly reducing atmosphere with \( \text{N}_2 \) and \( \text{CO}_2 \) as the dominant gases, and anoxic oceans with some prebiotic macromolecules and other organic compounds. Low- and high-temperature reactions between organic molecules and minerals in oceanic environments ultimately gave birth to life on Earth (Cody 2005). The original mineral diversity of Hadean–Archean marine environments in which life originated is now represented by metamorphic and metasomatic minerals in the limited archive of the oldest geological record.

Eoarchean sedimentary rocks deposited in marine environments either incorporated detrital components from nearby weathered rocks or formed under the influence of hydrothermal activity on the seafloor. Protoliths of metapelitic schists include mudstone and siltstone, whereas protoliths of early life may include both phyllosilicates and sandstones. Eoarchean BIF and ferruginous chert have chemical sedimentary precursors that precipitated on the seafloor from siliceous and ferruginous gels, probably under hydrothermal conditions. Precursor minerals for biotite and garnet in these rocks may have included ferruginous aluminosilicates, phyllosilicates, and other hydrated silicates that form during the weathering of feldspars and micas. Chlorite, biotite, amphibole, and garnet crystallize from mineral reactions between quartz and intermediate phases of ferruginous silicates and/or from reactions involving carbonate and quartz (Klein 2005). Pyroxene can form from reactions between Fe-rich carbonate and quartz, but also from the dehydration of amphibole during prograde metamorphism. Notably, graphite is common in most of these Eoarchean rock types, but its origin, and that of its carbon, is ambiguous. Possible sources of reduced carbon in graphite from Eoarchean metasedimentary rocks include abiogenic synthesis from the catalyzed reduction of carbon monoxide with hydrogen (e.g. Fischer–Tropsch-type reactions), decarbonation of carbonates during metamorphism, mantle fluids containing methane and carbon dioxide, extraterrestrial delivery by meteorites, prebiotic organic compounds, and remains of microorganisms from the depositional environment.

Possible Mineralogical Evidence of Early Life

Six elements—carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorus—dominate every living organism. These elements are found in a variety of igneous rock-forming minerals, but can also be incorporated in various sedimentary minerals formed during the decomposition of biological organic matter or from metabolic by-products. Evidence for early life in Eoarchean metasedimentary rocks is a highly contentious subject, and no mineral associations in these rocks provide unambiguous evidence for early life (Schopf 2006). Apart from the petrological and mineralogical context, stable isotopes and trace element compositions of specific minerals may provide independent lines of evidence consistent with a biological influence on their geochemistry.

Graphite is known to occur in Eoarchean BIFs, schists, and calc-silicate rocks, but to assess the possible sources of this carbon, stable isotope and elemental compositions need to be determined. Biological metabolisms involved in carbon fixation impart carbon isotope fractionation, but these signatures are blurred by high-temperature metamorphism, which also strongly fractionates carbon isotopes. For instance, some Eoarchean schists and metaturbidites of marine origin from the Isua Supracrustal Belt contain bands of graphite globules with \( ^{13}\text{C} \)-depleted carbon, which has been interpreted as evidence of Eoarchean life (Rosing 1999). Another example of possible mineralogical remains of early life is the occurrence of apatite–graphite associations in an Eoarchean quartz–pyroxene rock from the island of Akilia, which also contains \( ^{13}\text{C} \)-depleted carbon (Mojzsis et al. 1996). Apatite–graphite associations also occur in a quartz–magnetite–amphibole BIF from the Nuvvuagittuq Supracrustal Belt (Fig. 4). Apatite–graphite associations can form as a result of postdepositional diageneric maturation and oxidation of organic matter, a process that releases phosphate into pore solutions. Other possible geochemical evidence for Eoarchean life may exist in phyllosilicates, sulfides, and Fe oxides. During the decomposition of marine sedimentary organic matter, ammonium and hydrogen sulfide can be released into sediment pore solutions and subsequently be incorporated structurally in phyllosilicates and sulfides, respectively. Quartz–garnet–mica schists from the Isua Supracrustal Belt contain biotite with high concentrations of structural ammonium that is occasionally \( ^{15}\text{N} \)-depleted; signatures that are possibly consistent with a biological source for nitrogen (Papineau et al. 2005). However, while the sulfur isotope composition of sulfides in Eoarchean metasedimentary rocks may preserve evidence of biological fractionation, no unambiguous signature has been found so far (Papineau and Mojzsis 2006). Nevertheless, there are hints from the Akilia quartz–pyroxene rock that such signatures may exist (Mojzsis et al. 2003). Finally, Eoarchean BIFs from localities in Greenland and elsewhere contain \( ^{56}\text{Fe} \)-enriched minerals that may be consistent with biological Fe-metabolisms (Dauphas et al. 2004). These results and interpretations are contentious, however, and future work should aim to discover similar evidence in metasedimentary rocks from other Eoarchean supracrustal belts.

SUMMARY AND OUTLOOK

The mineral diversity of Hadean–Eoarchean surface environments has been blurred by repeated metamorphic and metasomatic events and decreased by geochemical homogenization. However, insights into the earliest mineral environments can still be gained from the mineralogy of Hadean zircon inclusions and from Eoarchean metagneous and metasedimentary rocks. On the basis of the various Hadean–Eoarchean rock types found today, it can be concluded that ancient mineral diversity was less than today’s, with perhaps no more than about 1500 different
mineral species (Hazen et al. 2008). While trace levels of oxygen could have been present in local Archean oases, it was not until the Paleoproterozoic (2.5 to 1.6 Ga) that both a significant accumulation of atmospheric oxygen and a significant leap in mineral evolution occurred. Such global oxygenation events and associated biogeochemical processes were responsible for the irreversible and significant increase in Earth's mineral inventory.

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The Great Oxidation Event and Mineral Diversification

Dimitri A. Sverjensky* and Namhey Lee*

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BEFORE THE GREAT OXIDATION EVENT (GOE), at ~2.4 Ga, the mineralogical record of the near-surface continental environment indicates a low partial pressure of oxygen during weathering, which restricted many elements to a low oxidation state and limited the number of possible minerals formed from these elements. Calculations show that local pulses in the production of O2 by photosynthesis could mobilize some metals (e.g. Mo and Re, but not U), but this O2 would be completely consumed. After the GOE, many elements could occur in one or more oxidized forms in minerals in the near-surface environment. This development resulted in an explosive growth in the diversification of minerals.

KEYWORDS: Archean, oxidation, weathering, Great Oxidation Event

THE RISE OF OXYGEN

The stretch of time between about 3.0 and 2.0 billion years before the present (Ga) is one of the most remarkable periods in Earth history. The sedimentary geologic record for this time contains rocks such as the great banded iron formations of Western Australia and the huge conglomerate-hosted gold and uranium deposits of the Witwatersrand, South Africa. These formations have long been recognized as indicating that near-surface atmospheric, continental, and marine conditions were very different from those of the present day. In recent years, detailed isotope studies have focused on the period of time referred to as the Great Oxidation Event (Holland 2006). It began at 2.45 Ga, the last time that the sulfur isotope record shows evidence of large mass-independent fractionation, and it probably continued until about 2.0 Ga, based on major excursions in the carbon isotope record of marine carbonates. During this time, an irreversible increase in the oxygen content of the near-surface atmosphere and the continental and marine environments occurred (Holland 2009; Sessions et al. 2009).

The mineralogical expression of the Great Oxidation Event (GOE) is the theme of this article. Studies of the mineralogical record of the near-surface continental environment before the GOE indicate severe environmental limitations on the diversity of minerals. The very low partial pressure of oxygen in the atmosphere typically restricted elements with possible multiple oxidation states to a single, low oxidation state, which in turn limited the number of possible minerals of such elements. In contrast, after the GOE and achievement of significant partial pressures of O2 in the atmosphere, a vast array of new minerals became possible. Essentially any element with more than one possible oxidation state could then be present in one or more oxidized forms in minerals in the near-surface environment. This development resulted in an explosive growth in the diversification of minerals (Hazen et al. 2008).

THE MINERALOGICAL RECORD BEFORE THE GREAT OXIDATION EVENT

Evidence from Detrital Minerals

Minerals such as siderite (FeCO3), uraninite (UO2), and pyrite (FeS2) alter rapidly on laboratory and geologic time-scales in the present-day, near-surface environment containing abundant O2. The Fe, U, and S in these minerals are all oxidizable under these conditions. However, several detailed studies have documented that these minerals occur as detrital phases in ancient, fluviatile, sedimentary rocks formed from sediments transported long distances in well-aerated waters before the GOE. After the GOE this did not happen. These observations, reviewed below, can be interpreted to place severe restrictions on the oxidation state of the weathering environment, and in turn on the evolution of the diversity of minerals before the GOE.

As an example, petrographic and sedimentological studies of three sets of sandstones from the Pilbara region in Western Australia, deposited between 3.250 and 2.715 Ga, have documented the occurrence of abundant detrital siderite in the heavy mineral fraction of one sandstone formation, minor detrital uraninite in two formations, and abundant pyrite in the heavy mineral fractions of all three formations (Rasmussen and Buick 1999). These minerals were transported and deposited by turbulent, well-aerated, braided river systems. Notably, none of these sandstones have been subject to hydrothermal mineralization. Detrital siderite in Archean sedimentary rocks has also been reported from the 3.2 Ga Moodies Group in the Barberton greenstone belt, South Africa (Hessler et al. 2004).

A second example involves the long-studied Witwatersrand conglomerates, which, although fluviatile in origin, have been affected by metamorphism and hydrothermal activity. Despite the long-standing controversy over the relative importance of detrital sedimentary versus hydrothermal processes in the origin of the uraninite, pyrite, and gold in these deposits, substantial evidence supports a modified placer origin (Frimmel 2005). Textural, isotopic, and compositional characteristics of the uraninite, pyrite, and gold in the deposits point to deposition as detrital grains
in the host sediments. The strongest evidence includes (1) the rounded shape of the particles (Fig. 1), (2) ages greater than those of the host rock as indicated by isotopic dating, and, (3) for the rounded uraninite grains, a great variation in the Th/U ratio, consistent with derivation from a variety of sedimentary provinces, and a much higher Th content than would be expected from hydrothermal alteration (Hazen et al. 2009). Furthermore, the Witwatersrand sediments have been subject to intense weathering, whereas detrital uraninite grains in the modern Indus River are part of a system that has not been subject to intense chemical weathering (Maynard et al. 1991). Additional examples of Archean placer uraninite and pyrite deposits similar to those of the Witwatersrand but with only minor amounts of gold are widespread (Frimmel 2005). In contrast, the Proterozoic (2.1 Ga) gold deposits of the Tarkwaian System of Ghana, although hosted by quartz-pebble conglomerates similar to those in the Witwatersrand, contain detrital hematite and magnetite associated with the gold instead of pyrite (or siderite), with no uraninite reported (Frimmel 2005).

The above examples provide strong evidence that, during the Archean, siderite, uraninite, and pyrite underwent prolonged transport as detrital minerals in aqueous near-surface continental environments, which we have every reason to believe were in contact with the Archean atmosphere. The characteristics of these transport and depositional processes suggest that kinetic inhibition of oxidation is not the reason for the survival of these minerals. Siderite reacts quickly on a laboratory timescale (Berner 1981). Uraninite oxidation may proceed rapidly, particularly if a surface layer of altered uraninite is formed (De Pablo et al. 1999), and pyrite weathers rapidly in the presence of oxygen (Anbar et al. 2007). Instead, it seems more likely that the survival of siderite, uraninite, and pyrite in the near-surface Archean environment was due to a lack of a thermodynamic driving force for their destruction. In other words, the combined atmospheric and aqueous-solution chemical conditions during weathering were such that these minerals were stable.

**Implications for the Archean Atmosphere**

The conditions required for a lack of a thermodynamic driving force for the oxidation of pyrite and siderite are shown in Figure 2. The relative stabilities of these minerals depend on the partial pressures (fugacities) of O₂, S₂, and CO₂ gases. Preserving siderite from oxidation or sulfidation requires values of log fO₂ (i.e. the logarithm of the oxygen fugacity) less than about –73 to –60 at 25°C and 1 bar, depending on the partial pressure of CO₂ (Fig. 2). Aqueous solutions that will not oxidize either siderite or pyrite require similar, low values of log fO₂.

The above conditions are also consistent with the preservation of uraninite from oxidation in either rainwater-like or river water-like aqueous solutions (Fig. 3). Depending on the pH of the solutions, uraninite (containing U⁴⁺) could oxidize to aqueous UO₂²⁺, soddyite, or uranophane (all containing U⁶⁺) over a range of log fO₂ values, but a maximum of about –44 is indicated (Fig. 3). This value would be higher if the uraninite were impure, but lower if aqueous complexes of UO₂²⁺ were considered or if the concentration of aqueous Ca²⁺ or SiO₂ were higher than in Figure 3B.

The solid lines separate fields of mineral stability labeled with the name of the stable mineral. The dashed line labeled “pyrene” represents the upper stability limit of this polynuclear hydrocarbon. The dashed line labeled “water” represents the lower stability limit of liquid water relative to 1 atm of H₂ gas.

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**Figure 1** Coarse sedimentary rocks from the Witwatersrand contain rounded, detrital clasts of pyrite. The truncated, well-rounded, oolitic pyrite (arrow) is consistent with a near-surface oxygen fugacity of <10⁻⁶⁰ bars. Scale bar = 0.5 cm. From Frimmel (2005), reprinted with permission from Elsevier.

**Figure 2** Stabilities of minerals in the Fe–S–C–O system at 25°C and 1 bar as functions of the logarithms of the fugacities of the gaseous species O₂ and S₂ where the logarithm of the fugacity (in bars) of CO₂ is fixed at (A) –3.0, (B) –1.5, and (C) 0.0, respectively, to cover a range of values consistent with suggestions in the literature for the period 2.0 to 3.0 Ga (Hessler et al. 2004).
Values of log $f_{O_2}$ less than about –73 to –60 (at 25°C and 1 bar) in the near-surface Archean environment have long been suggested in the geochemical literature (Garrels et al. 1973; Krupp et al. 1994; Frimmel 2005). Although seemingly low, these values are consistent with upper limits deduced from atmospheric models (Kasting 1993; Catling and Claire 2005), paleosols (Rye and Holland 1998), and models inferred from sulfur isotope data (Pavlov and Kasting 2002). However, atmospheric models have also suggested a lower limit of $f_{O_2}$ equal to about 10^{-15} bars (Kasting 2002). This lower limit may be applicable to the lower atmosphere right down to the boundary with an aqueous phase such as seawater, below which it could be 10^{-63} bars (Kasting and Walker 1981). This lower limit may be applied to the lower atmosphere right down to the boundary with an aqueous phase such as seawater, below which it could be 10^{-63} bars (Kasting and Walker 1981). We assume that the aqueous weathering environment on the continents during the Archean can be represented similarly.

The quantitative chemical implications of weathering conditions on land in the Archean have not been sufficiently explored. Specifically, what role do reactions with minerals in multicomponent systems play? Reducing conditions are presumably influenced by the supply of reductants, such as $H_2$ and $CO$ from volcanic sources (Catling and Claire 2005), although these must have reacted with exposed rocks via aqueous solutions during weathering processes. In addition, after the rise of oxidogenic photosynthesis, there would probably have been a period of time during which weathering and atmospheric reductants competed with the $O_2$ released by photosynthesis. The implications of these processes are explored below through model calculations that simultaneously consider weathering, volcanic gases, and $O_2$ released by photosynthesis.

WEATHERING IN THE ARCHEAN ATMOSPHERE

Weathering Reactions

How rainwater from an Archean atmosphere reacted with volcanic gases and continental crust is of interest from at least three standpoints: the types of minerals that may have resulted, the evolution of water chemistry, and the oxidation state of the near-surface environment. Insight into the chemical complexities of such processes can be obtained from models of the irreversible chemical mass transfer associated with the reactions (Helgeson 1979). An example is shown in Figure 4. In these calculations, the minerals enstatite, ferrosilite, diopside, anorthite, albite, and magnetite provide an approximation to a basaltic crustal composition. Excess amounts of these minerals are permitted to react irreversibly with model rainwater with a starting composition similar to that of the present day (Berner and Berner 1996), except that it has initial values of log $f_{O_2} = -70$ and log $f_{CO_2} = -1.5$ (cf. Fig. 2). Simultaneously, the rainwater is reacted with a mixture of $H_2$, $H_2S$, $SO_2$, $CO_2$, and $CO$, representing the composition of volcanic gases, based on discussions in the literature (Zolotov and Shock 2000; Catling and Claire 2005). The reactions produce a Na–Mg–Ca–HCO$_3$ water and minerals such as pyrite, kaolinite, chalcedony, siderite, calcite, and lizardite (Fig. 4, exsolutions). Lizardite is not expected to form during weathering but is included here as a proxy for a more complex Fe–Mg–Al-type clay mineral for which we do not have an adequate thermodynamic characterization. The iron dissolved during weathering reaches a maximum molar value of about 10^{-4.3}, or 3 ppm, when siderite begins to precipitate. Thus, as anticipated by Garrels et al. (1973), depending on the extent of reaction, significant quantities of $Fe^{2+}$ could be produced during weathering and possibly transported in Archean rivers to the oceans.

The full reaction path can be followed as a function of log $f_{O_2}$ and pH in Figure 4C. Of interest here is that the changes in log $f_{O_2}$ are small. The oxidation state of the system stays roughly constant (about ±2 units of log $f_{O_2}$). The pH, however, evolves towards more alkaline conditions depending on the extent of reaction. In practice, for real flow-through systems, the extents of reaction are probably limited, perhaps less than about log $ξ = -2$. For limited extents of reaction, the aqueous-solution chemistry is near to both the $H_2S–SO_2$ and the $NH_4^+–N_2$ lines of equal activity (Fig. 4C). Therefore aqueous solutions during Archean weathering could have significant amounts of either the reduced or oxidized $S$ and $N$ species when the log $f_{O_2}$ values are around –70.

Overall, the weathering reactions shown in Figure 4 indicate that the Archean near-surface weathering environment during reactions involving rainwater, volcanic gases, and basaltic rocks does not result in significant changes in oxidation state. Nor are minerals other than kaolinite,
pyrite, and silica, and minor amounts of siderite (depending on the extent of weathering) to be expected. This situation could presumably have prevailed for a prolonged period, until perturbed by the rise of oxygenic photosynthesis.

**Effects of Oxygenic Photosynthesis**

Much discussion in the literature has focused on the apparent gap in time between the beginning of oxygenic photosynthesis and the development of an oxygenated atmosphere, a gap that may be several hundred million years or much longer (Holland 2006; Knoll and Beukes 2009). A possible explanation for this gap is that the O$_2$ steadily produced by photosynthesis was consumed entirely by a sufficiently reducing near-surface environment (e.g. Carling and Claire 2005 and others). This scenario has not been tested quantitatively in a way that includes weathering processes. Anbar et al. (2007) recently suggested that widespread oxidative weathering by O$_2$ started at about 2.5 Ga, based on anomalous spikes in the Mo and Re concentrations in marine shales of that age. These scenarios can be investigated by expanding the scope of the reaction path calculations on weathering described above to include input of O$_2$ gas as a reactant. In the model, O$_2$ can be added steadily, along with the other reactants, to simulate gradual oxygenic photosynthesis, or rapidly, to simulate a pulse representing localized oxygenic photosynthesis.

The steady addition of $10^{-3}$ moles of O$_2$ per kilogram of rainwater corresponds to a reaction path that reaches a maximum log $f_{O_2}$ of only $-66$ (Fig. 5a). Mineralogically, this value corresponds to the production of less pyrite and siderite than mentioned in Figure 4. Consequently, a steady production of O$_2$ by photosynthesis could indeed be completely consumed by weathering in the near-surface environment. In contrast, a pulse of the same amount of O$_2$ added much more rapidly relative to the rates of reaction of the rainwater with the volcanic gases and basaltic rock results in a rapid excursion in log $f_{O_2}$ that reaches values as high as about $-60$ (Fig. 5a). The reaction path shown crosses the boundary for oxidation of MoS$_2$ and reaches the boundary for oxidation of Re$_2$S$_4$. It stops short of the boundary for oxidizing uraninite. Such a pulse could indeed mobilize Mo and Re, but not U, during weathering. Mo and Re could then be transported to the oceans as the soluble oxyanions Mo$_4$$^2$- and ReO$_4$$^-$ and reduced again and precipitated in marine shales. Mineralogically, even less pyrite and siderite and a small amount of hematite (about $10^{-3}$ moles) are produced. However, the maximum log $f_{O_2}$ reached is still so low that O$_2$ does not accumulate in the atmosphere.

The above calculations strongly suggest that production of O$_2$ by oxygenic photosynthesis could proceed steadily in the near-surface environment without any accumulation of O$_2$ in the atmosphere. In the shallow marine environment, a pulse of O$_2$ could have resulted in a “rain” of ferric hydroxide precipitates, contributing to the formation of banded iron formations. On the continents, a pulse in the production of O$_2$ could mobilize Mo and Re during weathering without mobilizing U, but not contribute any measurable O$_2$ to the atmosphere. Neither scenario would necessarily lead to the introduction into the geologic record of any significant amount of oxidized minerals of metals other than Fe. That diversification had to wait until oxygenic photosynthesis completely dominated reductants released to the near-surface environment from biological and nonbiological sources. It is assumed here that such a domination had been achieved by 2.0 Ga.

**THE EXPLOSION OF MINERALOGICAL DIVERSITY AFTER 2.0 Ga**

As soon as molecular O$_2$ started to accumulate in the atmosphere and reached 1% of the present atmospheric level, weathering reactions proceeded very much like they do today. Fe and U in particular oxidized readily. In the near-surface environment in contact with such levels of O$_2$, siderite and pyrite oxidized to iron oxides. Trendall and coworkers estimated that “90 percent of the tonnage of all known iron formations was probably deposited between ca. 1.9 and 2.6 Ga” (Holland 2005). These great banded iron formations could represent the removal of dissolved Fe$^{2+}$ from the shallow marine environment in response to oxidation of the atmosphere. From the standpoint of the diversification of minerals, however, iron oxides were not new, just hugely abundant compared to other times in Earth history. The main change for iron minerals after the GOE was the cessation of deposition of detrital siderite and pyrite and the end of riverine transport of Fe$^{2+}$ to the oceans.

In contrast, uranium presents a dramatically different picture. Deposition of detrital uraninite ceased after the GOE, but the oxidation of uraninite exposed at the surface of the Earth in an O$_2$-bearing atmosphere resulted over time in the appearance of approximately 200 uranyl minerals that were unlikely to have existed prior to the GOE (Hazen et al. 2009). These colorful minerals include hydrous uranyl oxides and silicates, such as soddyite, weeksite, curite, sklodowskite, and uranophane. Uraninite alteration also commonly leads to the complex mixed-phase material “gummite,” a fine-grained mixture of soddyite, curite, kasolite, uranophane, boltwoodite, and clarkeite. Oxidized uranium can also precipitate as the uranium carbonate rutherfordide and a large suite of uranyl phosphate minerals, such as autunite and saléèite (Fig. 6).

Even the amount of uraninite exposed at Earth’s surface for weathering was probably greatly increased by the development of an oxygenated atmosphere. Prior to the GOE, uraninite (rich in Th) was formed in magmatic environments and was then exposed at the surface after uplift and erosion. After the GOE, major hydrothermal U deposits, such as the unconformity-type deposits of northern Australia (1.6 Ga) and western Canada (1.8 Ga) formed, and when these were exposed by uplift and erosion the full variety of secondary and tertiary uranium minerals could develop. The unconformity-type deposits were formed from shallow, hydrothermal circulation systems in Earth’s crust involving fluids with unusually high log $f_{O_2}$ values. These physicochemical conditions were probably achieved through the interaction of the hydrothermal fluids with sulfate-bearing evaporites, which were not present in any significant abundance in the geologic record until after the GOE (Kominou and Sverjensky 1995).

Thus, just for one chemical element, U, a huge increase in the number and variety of minerals occurred after the GOE. Similar considerations must also apply to other elements with multiple oxidation states, such as Cu, which occurs in 321 oxide and silicate minerals (Hazen et al. 2008), and the elements B, V, Mn, Se, Te, As, Sb, Bi, Ag, and Hg. Finally, a host of biologically mediated minerals proliferated in association with the development of microbial life (Dove 2010 this issue).
The mineralogical expression of the Great Oxidation Event is dramatic. Before the GOE, detrital siderite, pyrite, and uraninite were transported and deposited in sedimentary systems that must have been in contact with the Archean atmosphere. Thus there was probably no thermodynamic driving force for the destruction of these minerals. In other words, the combined chemical conditions in the atmosphere and in aqueous solutions were such that these minerals were stable, suggesting values of log fO₂ of ~60 to ~67 at 25°C and 1 bar. These conditions are also consistent with the preservation of uraninite from oxidation in either rainwater-like or river water-like aqueous solutions in the Archean.

Irreversible reaction path models indicate that reaction of such an Archean atmosphere with rainwater, volcanic gases, and basaltic rocks does not result in significant changes in the oxidation state during weathering. Kaolinite, pyrite, silica, and minor amounts of siderite can be expected until perturbed by the rise of oxygenic photosynthesis. Consequently, the Archean environment placed severe environmental limitations on the diversity of minerals. The very low partial pressure of oxygen during weathering restricted elements with possible multiple oxidation states to a single low oxidation state, which in turn limited the number of possible minerals of such elements.

CONCLUDING REMARKS

Irreversible reaction path models indicate that reaction of such an Archean atmosphere with rainwater, volcanic gases, and basaltic rocks does not result in significant changes in the oxidation state during weathering. Kaolinite, pyrite, silica, and minor amounts of siderite can be expected until perturbed by the rise of oxygenic photosynthesis. Consequently, the Archean environment placed severe environmental limitations on the diversity of minerals. The very low partial pressure of oxygen during weathering restricted elements with possible multiple oxidation states to a single low oxidation state, which in turn limited the number of possible minerals of such elements.

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Calculations further suggest that even with a low but steady production of O$_2$ by photosynthesis in the Archean near-surface environment, no O$_2$ would accumulate in the atmosphere. A local pulse in the production of O$_2$ could mobilize Mo and Re without mobilizing U, but would not contribute to any measurable O$_2$ in the atmosphere. Both scenarios would lead to Fe-minerals as the only oxidized minerals in the geologic record. The calculations presented here suggest that the Archean atmosphere could persist until a drastic change in the production of O$_2$ relative to the available amount of biologic and abiologic reductants.

In contrast, after the GOE and the achievement of a measurable partial pressure of molecular O$_2$ in the atmosphere, a vast array of new minerals became possible. Essentially any element with more than one possible oxidation state could then be present in one or more oxidized forms in minerals in the near-surface environment. This development resulted in an explosive growth in the diversification of minerals.

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**Oxidation Event on uranium mineral diversification. PHOTO COURTESY OF JOHN VEEVAERT, TRINITY MINERAL CO.**
The ability of organisms to synthesize skeletons and functional biomineral structures is one of the most remarkable events in the timeline of mineral evolution. The relatively abrupt rise of such forms in the fossil record marks the beginning of a new type of chemistry whereby biology develops a playbook of mineralization processes whose strategies scientists are only beginning to decipher. The first outlines of an impressive picture are emerging, in which the biochemical machinery and sequence of instructions that pass forward to subsequent generations are being defined. Yet, skeletons are anything but static in the transfer. The fossil record shows the dynamic responses of skeletal structures to shifts in environmental conditions over geologic time.

**LIFE AND MINERALS**

In the framework of mineral evolution (Hazen et al. 2008; Hazen and Ferry 2010 this issue), Stage 10 marks a crowning achievement in biology—the emergence of new pathways for mineral nucleation and growth that are actively controlled by biological systems. By the beginning of the Phanerozoic Eon (542 million years ago), multicellular organisms from many different phyla had developed the biochemical machinery to direct the timing, location, and morphology of mineral components into functional mineralized tissues.

There are three principal classes of skeletal biominerals—calcium carbonates, calcium phosphates, and silica. Skeletons are, by far, dominated by carbonate minerals, but the phosphates and amorphous silica phases also have extensive occurrences and hold special significance for Earth history and elemental cycling. Organisms have developed the ability to mineralize an amazing variety of other mineral types to modify the properties of their tissues for additional functions. The more than 64 different mineral phases that have been documented from diverse phyla include metal sulfides, oxides, hydroxides, and silicates.

Regardless of mineral chemistry, all biominerals share a critical commonality in that they are found in intimate associations with proteins, polysaccharides, and other macromolecules. This defining characteristic gives rise to a favorite quote and gentle reminder: “A biomineral without proteins is just a rock.” It is precisely this high degree of inorganic/organic association and assembly that gives biomineral structures remarkable strength-to-weight properties and their versatility to perform diverse biological functions. The envy of any materials designer, these functions include structural support, filtration, grinding and cutting, light harvesting, gravity sensing, and magnetic guidance.

High-resolution studies of biomineralized structures show that the structural basis for these diverse functions arises from the ability of organisms to synthesize skeletal minerals with a wide variety of morphological and structural configurations. For example, single crystals of calcite are used by certain species of brittlestars to form beautiful assemblies of oriented, spherical crystals in their arm structures (FIG. 1). More than a skeletal support, the crystals are also components in a photoreceptor system that serves as a simple type of compound eye. Organisms also form complex composites by interlayering oriented crystals with organic matrix (FIG. 2). This synergistic organization of mineral and organic allows mollusks and bivalves to form shells with remarkable toughness and fracture strength. For example, strategic incorporation of 1–5 wt% organic matter in an organic/aragonite composite helps to give the nacre of these materials a fracture toughness that is approximately 1000 times greater than that of pure aragonite (Zaremba et al. 1996; Nudelman et al. 2007 and references therein).

Another type of composite is bone, a family of materials built up from mineralized collagen. With highly complex intergrowths of apatite and organic, up to seven hierarchical levels of organization (Fig. 3) have been identified (Veiss 2003; Pasteris et al. 2008). Other biominerals, such as the amorphous silica of diatom frustules, are molded within specialized organelles that sequester Si and direct nucleation and growth. The resulting forms (FIG. 4), sometimes called Nature’s most beautiful glass houses, are precise and lightweight structures.

**BIOLOGICALLY CONTROLLED MINERALIZATION**

The most basic requirement for skeletal formation is a space or compartment to provide a local environment that can be supersaturated with respect to one or more mineral phases. Nature has developed a variety of clever compartment configurations, but the two most common types are intracellular and extracellular (e.g. Mann 2001).
Compartment must delineate size and shape, control ion flow and composition, and provide the necessary macromolecular chemistry. Last, but certainly not least, is the need for organic surfaces that control the onset of nucleation and regulate growth processes. Mineral precipitation itself consists of a highly controlled sequence of events whose timing is determined by signals or changes in the local biochemical environment.

The organic templates or macromolecular assemblies that are present in these settings have specific arrangements of chemical groups that are believed to be critical in regulating the timing and location of mineral formation. Most mineralized tissues, regardless of phylum, share two types of macromolecules: (1) relatively hydrophobic framework compounds of chitin and collagen, and (2) acidic glycoproteins and/or proteoglycans, commonly referred to as "acidic macromolecules" (Lowenstam and Weiner 1989). Here I focus on acidic macromolecules. Their detailed compositions are varied, but they nonetheless share a carboxyl-rich chemistry that arises from the high proportion of aspartic or glutamic amino acids. Some of these macromolecules also exhibit phosphorylated serine and threonine groups that confer additional acidity. These compounds are broadly implicated in mineral formation within living tissues. But as evidence of the youth of this field, there is little understanding of the mechanistic basis of their activity. To date, their importance is largely based upon their ubiquitous occurrence in sites of mineralization, or "guilt by association."
Biochemical similarities also extend to the molecules that inhibit CaCO₃ mineralization (Knoll 2003a). There is evidence organisms sculpt mineralized skeletons via “anticalcifying” macromolecules that locally inhibit crystal growth. For example, spontaneous calcification of cell and tissue surface may have been a problem in highly oversaturated Proterozoic oceans (Grotzinger 1989; Knoll et al. 1993). Marin et al. (1996) reasoned that molecular inhibitors evolved early as anticalcification defenses and were later recruited for the physiological control of skeleton growth. Moreover, molecular inhibitors are necessary to retard spontaneous calcification of internal tissues in vertebrates, including our own (Pasteris et al. 2008). The similarities of anticalcifying molecules in mollusks and a number of other organisms support the hypothesis that inhibitory activity also developed early in evolutionary history. This is another reminder that skeletons of dissimilar structures nonetheless share very similar underlying physiological pathways.

THE PRECAMBRIAN SETS THE STAGE

To understand the origins of skeleton formation is to first recognize that the deep history of all life is microbial. After the emergence of single-celled organisms, a long coevolution of Earth and environment continued to shape the composition of our atmosphere, crust, and oceans. Indeed, the Precambrian claims most of Earth history. Events during this period set the stage for biological systems to influence the very nature of multicellular organisms yet to come. Several billions of years transpired to produce the basic biochemical templates of life that first emerged with the Bacteria and Archea, then marked the later appearance of photosynthesis with the Eukarya and algal species.

The Tree of Life provides genealogical relationships of all living organisms. Modern diagrams are based upon comparisons of molecular sequences in the genes that code for ribosomal RNA. This quantitative approach to classifying life has removed the ambiguity and errors associated with traditional schemes that were based upon morphological similarities and differences. With this new information in hand and because the history of skeletal development is intimately written in phylogenetic relatedness, our own scientific development is now ready to explore a largely untapped roadmap to biomineral evolution. This promises to be an exciting time as biomolecular characterizations become integrated with in vivo studies of skeleton formation at every scale.

THE EMERGENCE OF SKELETONS

With fundamental biochemical motifs established in the Precambrian, a few lightly mineralized skeletons developed near the end of the Ediacaran Period (630–542 Ma). Most skeletons and functional materials first developed, however, during the time that we mark as Cambrian. Oft described as the Cambrian “explosion,” their appearance was not instantaneous; rather, skeletal abundance and diversity increased over an interval of 25 million years. Most of the known skeletal forms developed during this time: more than 178 distinct architectures are recognized in calcifying marine animals (Thomas and Reif 1993), including spicules, tubular and conical exoskeletons, and early composites comprised of mineral-impregnated cuticles that molted as the animal grew (Knoll 2003a). Various hypotheses hold that this event came about because of environmental changes that allowed mineral precipitation into and onto membranes and tissues. But early predation may have favored this development of mineralized skeletons as the evolution of a protective armor (Knoll 2003c).

The Cambrian also saw the first phosphate-based skeletons with the appearance of lingulid brachiopods, which may have precipitated substantial amounts of phosphate (Knoll 2003a). The record shows phosphatic biomineralization of
Carbonate skeletogenesis increased markedly as part of the broader Cambrian diversification of animals. However, after the extinction of major skeleton formers near the end of the Early Cambrian, carbonate biominerals contributed relatively little to accumulating limestones for more than 40 million years (Knoll 2003a,b). Renewed animal diversification in the Ordovician Period led to a major increase in the genera and quantity of calcified skeletons, which provided a permanent, globally important source of carbonate sediment (Pruss et al. 2010). The Ordovician thus marks the time when the marine carbonate (and silica) cycles both came under substantial biomineralogical control (Maliva et al. 1989). The later formation of calcite skeletons by foraminifera and coccolithophorids that began in the Devonian and Late Triassic, respectively, also exerted a strong influence on environmental and geographic patterns of carbonate deposition in the oceans.

In studies of the fossil record, paleobiologists have made convincing arguments that the ability to form skeletons and other types of biomineral structures could be a liability or an asset over geologic time. In particular, species-specific patterns of extinction and survival during the largest-known mass extinction, at the end of the Permian (252 Ma), suggest that the physiology of skeleton formation played an important role in determining biological responses to environmental change and, hence, which organisms survived (Knoll 2003c). For example, organisms that produced massive carbonate skeletons, but had limited physiological control over the fluids from which minerals precipitated, disappeared almost entirely at the Permian–Triassic boundary (Knoll et al. 2007). In contrast, Permian groups that fashioned skeletons from materials other than calcium carbonate lost only 10% of their genera. It is intriguing that extinction and survival patterns match predictions made on the basis of physiological research for present-day ocean acidification (Knoll et al. 2007 and references therein).

**PHYSIOLOGY VERSUS ENVIRONMENT IN SKEL TAL INNOVATION**

It is widely recognized that natural selection has shaped the forms and functions of skeletons over geologic time. Less obvious, however, is that the physiological pathways by which organisms precipitate skeletal minerals also constrain biomineral evolution and environmental history (Knoll 2003b). Skeletal biomineralization requires energy and so imposes a metabolic cost on skeleton-forming organisms. Because this cost reflects the physical chemistry of an organism’s surroundings, the cost/benefit ratio must also change as a function of Earth’s environmental history. Thus, biological benefits of biomineralization must outweigh its energy cost, and this relation is not static over time (Knoll 2003a).

One example of where environmental change significantly shifted evolutionary patterns is found in marine silicifying organisms. With the Cenozoic expansion of diatoms (approximately 100 million years ago), the abundance of silica at the surface of modern oceans became severely limited (Maliva et al. 1989). The fossil record shows that sponges, radiolaria, and the diatoms themselves all responded by using less silica in their skeletons or by retreating to deeper waters where silica concentrations were higher (Harper and Knoll 1975; Lazarus et al. 2009). None of the calcifying organisms have had a comparable influence on the chemistry of the world’s oceans, but physical changes in marine chemistry through time have episodi-
FIGURE 5

The pillbug (Armadillidium vulgare) stores amorphous calcium carbonate (ACC) until it is needed for the molt stage, a necessary but vulnerable period of growth for organisms with an exoskeleton (Tao et al. 2009). The ability to rapidly transform ACC into calcite confers an ecological advantage for survival. (A) Photographs of five molt states and (B) the corresponding SEM images showing the typical spherical morphology of ACC and sequential transformation to calcitic exoskeleton. COURTESY OF R. TANG

LOOKING AHEAD

The next 10 years promise to be an exciting time of discovery in how modern and ancestral organisms form skeletons. One overarching goal will be to learn how biomineral construction works at multiple scales, from nano- to macroscopic, to achieve a coordinated and integrated sequence of processes. As traditional scientific boundaries melt away and current students engage in unprecedented levels of collaboration, we can look forward to a new generation of truly cross-disciplinary research programs. We will surely find that organisms have long used a cache of mineralization processes that were never before considered possible. At least four areas hold significant opportunities for important breakthroughs:

1. Nonclassical pathways to mineralization

The realization that many calcified skeletons form by processes that involve a transient phase of amorphous calcium carbonate (ACC) has opened the door to new paradigms for mineralization. High-resolution tissue studies show that organisms employ this mineralization strategy across the phylogenetic tree (Weiner et al. 2003), which implies that this process has been around for a very long time. Calcification begins by sequestering and stabilizing highly reactive ACC until one or more triggers promote its rapid transformation into the final crystalline phase(s). Mineral formation via ACC stands in sharp contrast to classical crystal growth by step growth (Wang et al. 2009) and raises the question of how far insights from traditional crystallization processes will apply.

2. Concepts and strategies across time and length scales

Future studies will increasingly probe the sequential nature of biomineral construction from nano to organism scale. It will take some time to build an understanding of the chemical and physical complexities of accumulation, transformation, and assembly. But each of these processes will provide powerful insights into an integrated and mechanism-based understanding of how mineralized tissues and skeletal parts are assembled. A recent study of the humble pillbug (Fig. 5) provides a glimpse into the promise of probing stages of in vivo biomineral formation.

3. Biomolecules in morphogenesis

The functions of macromolecules in biomineralization are certain to receive increasing attention. Such studies will be facilitated by the growing toolbox of advanced techniques for structural and molecular characterizations, high-resolution experimental methods, and ever-larger simulations. This many-faceted effort will include experimental and theoretical (e.g. molecular dynamics) investigations of the interfacial properties of organic architectures in these macromolecular systems. For example, how do macromolecules influence the earliest stages of nucleus formation? Biochemists have long recognized that the local solvation environment around macromolecules regulates the ability of calcium, and to some extent, magnesium to activate a variety of cellular functions. Now there is evidence that the local solvation environment around biomolecules can also modulate mineralization. Amino acids, peptides, and proteins accelerate the growth rate, and control the composition of calcite by a relationship that correlates with the hydrophilicity, or water-structuring ability, of carboxyl-rich biomolecules (Fu et al. 2005; Elhadj et al. 2006; Stephenson et al. 2008).

4. Biomolecular templates

With the advent of modern biochemical probes, pioneering studies will discern how biomolecular templates regulate the timing, location, and polymorph of mineral that forms. Surely templates also hold secrets to pattern formation. But there is much to be learned. Current views of template function are based on classical nucleation theory, some of which is untested by experiment. New in situ studies of simple model biotemplates are raising questions that challenge long-held assumptions. For example, carboxyl and amine groups interact synergistically to produce significant reductions in the kinetic barrier to silica nucleation—effects that are potentially as important as reductions in the thermodynamic barriers predicted by classical nucleation theory.
(Wallace et al. 2009). These findings thus indicate that the chemistry of organic matrices may be optimized to ensure the fastest nucleation, and not the lowest energy pathway. This perspective challenges traditional assumptions of how organic templates can regulate mineralization, and we can expect significant discoveries in this area of research.

In the coming years, we will surely explore the concept of emergence as a phenomenon that underlies biomineralization processes. The term refers to the observation in the physical and biological sciences that novel behaviors and patterns can exceed those predicted from individual components. This would seem to be a likely strategy for biomimetic formation as well. After all, the evolution process selects for configurations that confer functions and behaviors—a major driving force behind life. But at the present time, we know relatively little about the origins of higher-order complexity that are inherent to biomimetic construction. As scientists increasingly link reductionist methods with complex in vivo systems, we may uncover a new hierarchical approach that defines how arrangements and conformations of biochemical groups are the very essence of how a cellular environment directs biomimetic formation into complex materials. Given that controlled biomineralization is found throughout the Tree of Life, even in some bacteria, it will surely be important to revisit the properties of membranes and organelles through the lens of interactions between component molecules. Such insights may also inform future challenges as we ask how calcifying animals and algae will respond to ocean acidification—the next chapter in that restless interplay of environment and evolutionary innovation.

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Complex systems display diversification in type, patterning, and behavior over time through varied selective mechanisms. Such systems are observed in numerous natural and cultural contexts, including nucleosynthesis, minerals, prebiotic organic synthesis, languages, material culture, and cellular life. These systems possess such qualitatively similar characteristics as diversification into new environments (radiation), episodic periods of innovation (punctuation), and loss of types (extinction). Comparisons among these varied systems thus point to general principles of complexification.

**Themes and Variations in Complex Systems**

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**EQUIPMENT UNDER FIRE**

Biological evolution has become a lightning rod for controversy. No other topic in science has led to such contentious debate and rancor. In no other arena is the epistemological contrast between science and religion so starkly etched. Hardliners on both sides continue to polarize the issue, while many deeply conflicted nonscientists wonder if they must make the wrenching choice between science and God.

Here we propose a new rhetorical tack in this old debate. Systems that transform from relatively simple states to those of increasing complexity are not an isolated idiosyncrasy of biology, but rather a ubiquitous and recurrent characteristic of the physical and biological world (Chaisson 2001; Morowitz 2002; Zaikowski and Friedrich 2008). Examples include the formation of isotopes through stellar nucleosynthesis (Olive 2008; Schatz 2008, 2010 this issue); the evolution of mineralogy in terrestrial planets and moons (Hazen et al. 2008, 2009); the synthesis of prebiotic organic compounds at or near Earth’s surface (Morowitz 2002; Hazen 2005); the evolution of languages (Dixon 1997; Atkinson et al. 2008); and innovation, technology transfer, and competitive selection in material culture (Eldredge 2002, 2009; Temkin and Eldredge 2007). Complexification in this broader context is the process by which a wide variety of natural and engineered systems display increased diversity in type, patterning, and behavior over time. In this context, why should the evolution of life be different from all other complex systems?

Given the universal occurrence of complex systems, coupled with the special importance assigned to understanding biological evolution, it is useful to compare and contrast these varied natural and human systems. In particular, we explore the roles of such themes as selection, diversification, punctuation, and extinction, as well as such variable evolutionary aspects as mutability, heritability, and lateral transfer. These concepts, which are readily applied to biological evolution (e.g. Futuyma 2009), may have relevance to a much broader range of complex systems as well.

**WHAT IS “EVOLUTION”?**

The study of themes and variations in complex systems is complicated by two familiar but subtle terms that are shared across disciplines. “Species,” for example, has been formally applied to isotopes, minerals, and organic molecules, as well as to biological populations. However, the superficial similarity of these usages (meaning a distinct type or kind) may obscure the fundamental differences between the biological and nonbiological meanings. “Species” of isotopes, minerals, and molecules are characterized by immutable, quantifiable physical and chemical properties, in sharp contrast to the variable, evolving populations that comprise biological species.

Even more problematic is the word “evolution,” which has been applied to numerous so-called “complex evolving systems” (Bowen 1928; Chaisson 2001; Morowitz 2002; Hazen et al. 2008; Zaikowski and Friedrich 2008), albeit with some objections (Rosing 2008; Eldredge 2009). “Evolution” applies to all these systems only in the most general sense of “change over time,” or perhaps “change with diversification over time” (i.e. complexification). Such a broad usage of the word “evolution” fails to capture the distinct and nuanced nature of biological evolution by natural selection, which itself can be defined in several ways (Eldredge 2008). Paleontologists might prefer the idea that all species that have ever lived on Earth are descended from a single common ancestor—a concept elucidated by the fossil record. Geneticists, in contrast, focus on information transfer: evolution is any permanent change in genetic information. Neither of these linked biological definitions of evolution bears any relationship to those applied to the complexification of nonliving systems. In this context, neither individual mineral species nor Earth’s mineralogy in toto evolves.

**EXAMPLES OF COMPLEX SYSTEMS**

Diversification in type, patterning, and behavior is a universal property of complex systems that experience cycles of selective pressure, for example, through changing environmental conditions. In the following section we review distinctive characteristics of six familiar complex systems.

**Nucleosynthesis** Earth today hosts approximately 2000 different natural and anthropogenic isotopes, each representing a different combination of protons and neutrons. All of these isotopes emerged from reactions of the original four types of nuclei (H, D, He-4, and Li-6) that formed in...
nuclear condensation events within the first million years of the Big Bang (Olive 2008; Schatz 2008, 2010 this issue). Isotopic diversification began quickly with the formation of stars and the initiation of fusion reactions, which produced dozens of new isotopes of elements up to Fe in the periodic table (element 26). The first supernovae generated hundreds of new isotopes in dramatic punctuation events that seeded the cosmos with the raw materials of the first planets. Radioactive decay led to even greater isotopic diversity, while human engineering in the past 70 years has resulted in small-scale production of the heaviest-known elements and isotopes.

**Mineral “Evolution”** The mineralogy of the terrestrial planets has diversified over time as a consequence of a range of physical, chemical, and biological processes, as outlined in previous articles in this issue. In prestellar, dense, molecular clouds, widely dispersed microscopic dust particles contain approximately a dozen refractory minerals that represent the starting point of planetary mineralogy. Subsequent stages of mineral complexification, which led to the >4400 species known today, arose from three primary mechanisms. The first mechanism entailed progressive separation and concentration of elements by partial melting, crystal settling, phase separation, and other physicochemical processes. These various processes produced element concentrations in relatively small volumes compared to their original homogeneous distribution in the presolar nebula. New minerals also appeared as a result of an increase in the range of intensive variables, such as pressure, temperature, and the activities (effective concentrations) of H2O, CO2 and O2 (i.e. new mineralogical environments). Finally, thousands of new minerals formed on Earth as a result of biological activity, which notably generated far-from-equilibrium conditions such as increased concentrations of atmospheric oxygen.

**Prebiotic Organic Synthesis** A prerequisite for the origin of life was the synthesis and selection of organic, molecular building blocks, including amino acids, sugars, lipids, and bases—a process commonly referred to as “molecular evolution” or “chemical evolution.” Numerous experiments employing a variety of energy sources and environmental conditions have demonstrated the facile synthesis of these and many other prebiotic organic compounds (Hazen 2005). Organic synthesis is governed by equilibrium thermodynamics (Helgeson and Amend 1994), yet the stereochemical and isomeric plasticity of organic compounds, coupled with the similarities in free energy of numerous varied states, leads to a kind of mutability in organic chemical species not seen in isotopes or minerals. For example, in many organic molecular species –SH may substitute for –OH, or –CH3 for –H, with little change in the free energy of the system. Consequently, millions of different, plausible, small organic molecules may have populated Earth’s “prebiotic soup” (in contrast to the thousands of known isotopes and minerals).

**Languages** The evolution of languages provides an important example of a complex system with a form of heritable (and mutable) information. As language is passed from one generation to the next, it undergoes many gradual as well as relatively sudden changes, for example, in vocabulary, syntax, and idiom (Dixon 1997; Atkinson et al. 2008; Gray et al. 2009). Languages also display lateral transfer of vocabulary, and, especially when isolated in a small population, individual words and even entire languages may eventually become extinct.

**Material Culture** The rapid advance of material culture, especially in the realm of complex technologies, provides many of the most familiar and dramatic everyday examples of evolution, albeit by design (Eldredge 2002, 2009; Temkin and Eldredge 2007). Computers, cars, cornets, and countless other familiar objects change rapidly in competitive commercial environments, where personal choices by numerous individuals collectively apply selective pressure. Consider the case of cornets, a group of soprano brasswind musical instruments (Hazen and Hazen 1987; Eldredge 2002) that first appeared in 19th-century France as orchestral instruments and were most prominently employed at the Paris Opera (Fig. 1). By the mid-19th century, cornets had diversified, with numerous specialized models: over-shoulder designs for marching, higher- and lower-pitched versions for brass bands, tightly coiled “pocket” cornets for travel, and even jewel-encrusted cornets for popular soloists. Additional new styles of cornets were introduced as the instrument became a mainstay in American jazz, while older interior versions, or designs that simply fell out of fashion, gradually became extinct (Eldredge 2002).

**Cellular Life** Cellular life provides the quintessential example of an evolving complex system (e.g. Futuyma 2009). Biological evolution by natural selection shares some characteristics with complexification in other systems, but life’s evolution is fundamentally distinct in terms of its two intertwined defining characteristics: (1) common descent from a common ancestral cell or consortium of cells (Woese 1998) and (2) information transfer with genetic mutability as manifest in the variability of individual traits within populations.

**THEMES IN COMPLEX EVOLVING SYSTEMS** The six varied examples of complex systems cited above share several traits that collectively help to characterize such systems.

**Agents** An intriguing similarity among all complex systems is that each “type or kind (i.e. “species” in its most generic usage) can be described in terms of an arrangement of smaller building blocks, or “agents,” which can be combined in large numbers of configurations (Morowitz 2002; Hazen 2005). For example, all isotopes form from combinations of protons and neutrons; all minerals from arrangements of the 83 geochemically stable elements; and all cornets from standard components like mouthpieces, tubing, valves, and bells. Similarly, 26 different letters form words in English, whereas four different nucleotides encode genetic information in biological systems. The key to complexity is thus not a great diversity of agents, but rather a large number of potential configurations of those agents (Hazen 2009).

**Selection** In complex systems, new types or kinds arise through a selective process. Agents in these systems have the potential to adopt combinatorially large numbers of different configurations, such as combinations of protons and neutrons in isotopes, arrangements of atoms in minerals, and topologies of mechanical components in cornets. However, only a small fraction of all possible
configurations is observed owing to selection rules (e.g. Morowitz 2002; Szostak 1993; Hazen et al. 2007; Hazen 2009). Thus, neutrons and protons assemble into only a few hundred stable isotopes, while 83 chemical elements combine to form only a few thousand minerals. Similarly, while brass tubing and valves can be arranged into a vast range of intricate topologies, the laws of acoustics and human anatomy impose selective limits on the range of functional cornet designs. In all evolving systems, stochastic processes may influence specific outcomes of some selective events, but selection is ultimately guided by physical and chemical principles and thus, by definition, is not random.

**Environments and Radiation** Radiation into new environments is another common, if not universal, aspect of complex systems. New “species” (again in its most generic meaning) often populate new environments as they are created: new isotopes are formed in stellar cores, new evaporite minerals precipitate in dry lakes, and new amino acids are synthesized in Miller–Urey-type environments. One key to successful product marketing is the creation of new niches through clever advertising—a phenomenon seen repeatedly in the evolution of material culture (Eldredge 2009).

**Punctuation and Stasis** The proposal by Eldredge and Gould (1972)—that biological evolution may at times occur in rapid spurts of innovation between long intervals of relative stasis, or “punctuated equilibria”—reflects a common theme in a variety of complex systems. Punctuation is most often cited in a biological context (e.g. Pagel et al. 2006). Nevertheless, the near-instantaneous synthesis of hundreds of new isotopes in supernovae (Olive 2008; Schatz 2008), the diversification of near-surface minerals during the Great Oxidation Event (Hazen et al. 2008, 2009; Swerjensky and Lee 2010 this issue), the invention and introduction of technological innovations such as variants of the piston valve in brass musical instruments (Eldredge 2002, 2009; Temkin and Eldredge 2007), the publication of Noah Webster’s *American Dictionary of the English Language* (Atkinson et al. 2008), and geographical patterns of language change (Dixon 1997; Gray et al. 2009) can all be viewed in the context of punctuational events. Consequently, the introduction of new types or kinds in complex systems is not a steady process through time.

**Extinction** Extinction, the disappearance of some types or kinds, is a recurrent feature of complex systems. Short-lived radionuclides, such as $^{37}$Al (half-life = 0.73 Ma), played an important role early in the development of the solar system but are no longer found naturally on Earth. Some near-surface mineral species, for example, some hydrous minerals on Venus following the runaway greenhouse effect, become unstable and disappear permanently from a terrestrial planet (Donahue and Pollack 1983; Johnson and Fegley 2003). Extinction is also familiar in complex systems associated with life: new technological innovations inevitably replace the old (Fig. 2), some words become obsolescent, and more than 99% of biological species have become extinct.

**VARIATIONS: NECESSITY VERSUS CHANCE** In spite of their many similarities, the diverse complex systems described above differ fundamentally in the extent to which changes result from necessity, chance, or design. The physicochemical processes of nucleosynthesis, mineral diversification, and prebiotic organic synthesis (at least in their initial stages) all appear to be largely deterministic: the same elements, isotopes, rock-forming minerals, and simple organic molecules are likely to be present on any Earth-like planet. These systems complexify according to principles of equilibrium thermodynamics, and thus diversify principally in response to the emergence of new physical and chemical environments in nebular, stellar, and planetary systems.

By contrast, chance genetic variations introduced through such mechanisms as mutations, sexual reproduction, and lateral gene transfer play a central role in biological evolution by Darwinian natural selection. Yet, while biology is unique among complex systems in the extent to which such variations facilitate change over time, some other complex systems, including language and material culture, also display information transfer with stochastic attributes (Dixon 1997; Eldredge 2002, 2009; Gray et al. 2009). It is important to recognize, however, that while genetic variations may be random, subsequent selective processes are not. Thus, biological systems display a significant degree of determinism, as reflected in the convergent evolution of such traits as eyes for seeing, wings for flying, legs for walking, and fins for swimming. Similarly, all languages require words that serve as nouns, verbs, or adjectives and that are phonetically consistent with oral anatomy, while evolution in material culture is bounded by such constraints as the desired function and human physiology.

The fundamentally deterministic characteristic of cycles of random mutation followed by selection serves as the basis for a number of modern technologies. For example, the experimental evolution of RNA aptamers (RNA oligomers that selectively bind to target molecules) is accomplished by first generating a solution with $>10^{14}$ random RNA sequences (Ellington and Szostak 1990; Bartel and Szostak 1993). This RNA-rich solution is poured into a container with glass beads that have been coated with target molecules. Most RNA oligomers do not interact, but a few sequences bind weakly to the target molecule and thus remain attached to the glass. These binding RNA strands are recovered and replicated with mutations to produce a new population of approximate copies, some of which display enhanced binding. After several cycles of recovery, mutation, and selective binding, optimal RNA aptamers are achieved. This elegant evolutionary process is now used to produce RNA sequences with a wide range of specialized functions, including locking onto target viruses.

Genetic algorithms (Holland 1992; Goldberg 1989; Koza et al. 1997) provide a computational approach that mimics Darwinian evolution to optimize solutions for problems that are too complex to solve with traditional design strategies. Exceptionally difficult problems in such fields as fluid dynamics, materials science, and electronic circuit design are now routinely solved with this evolutionary approach. Of special interest in the context of minerals is genetic
algorithms designed to predict crystal structures, for example, of minerals under extreme pressure and temperature conditions (Glass et al. 2006; Oganov and Glass 2006). One strategy is to sample a wide range of structure space by first identifying relatively stable structural subunits and then shearing, stacking, or otherwise shuffling these subunits to converge on optimally stable structures. In some respects this computational process may mimic the actual physical shuffling of atoms and molecules in three dimensions during crystal growth.

**A FINAL COMMENT ON DESIGN**

Engineering by design, which stands in sharp contrast to engineering by computational evolutionary algorithms, can act as a powerful mechanism for complexification (Eldredge 2008, 2009). Obvious examples arise in material culture, where innovation drives the evolution of new products. Many other systems are also subject to evolution by design: dozens of human-made isotopes are produced in high-energy accelerators, thousands of new mineral-like compounds find technological applications, and millions of organic molecules have been synthesized in laboratories. Genetic engineering has resulted in numerous new varieties of single-celled and multicelled organisms, and holds the prospect of creating new species by design.

Nevertheless, the idea that life is “irreducibly complex” and, consequently, that the origin of life required an intelligent designer has been soundly refuted on both scientific and philosophical grounds (Pennock 2002; Forrest and Gross 2004). Indeed, in terms of generating systems of high complexity, evolution by the cyclic Darwinian process of mutation and selection has proven to be far more effective than design. Darwinian evolution thus emerges as the most dramatic example of the cosmic imperative of complexification, which leads inexorably from atoms, to stars, to mineral-rich planets, and perhaps ultimately to life that is learning to know itself.

**ACKNOWLEDGMENTS**

We thank M. J. Hazen and R. J. Hemley for valuable discussions and suggestions. This work was supported by NASA's Astrobiology Institute and the Carnegie Institution of Washington.

**REFERENCES**


**FEBRUARY 2010**
RICCARDO VANNUCCI – WINNER OF THE PLINIUS MEDAL 2009

During the opening ceremony of Geoitalia 2009 – 7th Italian Forum of Earth Sciences (Rimini, September 9–11, 2009), SIMP president Simona Quartieri conferred the 2009 Plinius Medal (the highest honour granted by SIMP) to Prof. Riccardo Vannucci, in recognition of his great expertise in the fields of geochemistry and of the evolution of the solid Earth.

Riccardo Vannucci is a full professor of geochemistry at the University of Pavia and has one of the highest ranks within the national and international scientific community dealing with solid Earth. His scientific activity is focused on the reconstruction of the subcontinental mantle in different geodynamic environments, based on data gathered through the study of geochemical tracers and their utilization in understanding magma genesis and evolution. He has also studied ash, minerals, and glass inclusions in lavas and pyroclastics at Etna and Stromboli volcanoes, in order to obtain information on magmatic feeder systems and deep and surface mechanisms. In only the last 10 years, he has published more than 50 high-impact-factor journals.

Among Riccardo’s distinguishing features is his enthusiasm for undertaking new scientific challenges, including carrying out geological surveys all over the world (Zabargad, western Alps, Corsica, northern Apennines, Canary Islands, Morocco, northeastern Brazil, southern Patagonia), setting up new laboratories and analytical methods, and studying atomic-scale processes during the incorporation and partitioning of trace elements into the principal and accessory minerals of a rock. Moreover, Riccardo has acted as a valued tutor towards a large number of younger colleagues and students, most of whom are now involved in important national and international research projects.

Among Riccardo Vannucci’s various commitments were his participation in the Council of the European Association of Geochemistry (1999–2004) and the Italian CNR (National Research Council); in the latter, he was a member of the scientific council of the Centro di Studio per la Cristallochimica e la Cristallografia in 1990–2000 and a member of the Committee of the Istituto di Geoscienze e Georisorse in 2000–2004. Currently, he is Area 04 representative for PRIN national research projects.

HIGHLIGHTS FROM THE SIMP WEB PAGES

Since the redesign of the Society website (www.socminpet.it), more sections have been added in order to provide useful and interesting information about mineralogical and geological events. Particular attention is here paid to two of them: Doctorate Schools in Italy (www.socminpet.it/Dottorati.php) and Mineral Collector Groups (www.socminpet.it/Collezionismo.php). The Doctorate Schools in Italy section gives an up-to-date outline of careers and research fields in a number of universities and provides information about related research fields. The Mineral Collector Groups section gives an overall panorama of the main mineral, fossil, and gem shows in Italy and is complemented by a section on relevant publications (www.socminpet.it/PubblicazioniCollezionismo.php) and by a set of links (www.socminpet.it/LinksCollezionismo.php) to various collector groups that have made important contributions to the finding of new and rare mineral specimens.
In 1978 as I prepared to graduate from college, my friends Alicia, Dana, Julie, Pam, Peter, Steve, Tom—and Claudia, to whom I have been married for the past 26 years—threw a farewell party for me that resonates to this day. On account of my then well-known fascination with geochemistry, they gave me a one-year subscription to Geochimica et Cosmochimica Acta as a going-away present, thereby making me a member of the Geochemical Society. Some 32 years later, I have become the first-ever elected president of the Geochemical Society. This is a worthy legacy of my predecessor, Marty Goldhaber, on whose watch the way we choose Society leaders has evolved. In years past, the position has been held by various luminaries in our field who were appointed by a self-renewing board of “society elders.” Then and now, the president commenced his or her duties following a two-year apprenticeship as vice president. I have benefited immensely from the tutelage of Marty Goldhaber, in whose hands the Geochemical Society held its first-ever election of officers and thrived in spite of the global economic downturn. We owe Marty much gratitude for his tireless efforts and many accomplishments while he held the reins over the past two years.

Much has changed during the last few years in how science is pursued and promoted, requiring a quantum leap forward in governance and outreach, or risking the tag of irrelevance and extinction. Chief among my priorities as president, therefore, will be the following objectives:

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

These ambitious goals cannot be fulfilled by a single person. Rather my duty should be to inspire wide participation in any one of these areas, mindful of the fact that our Society will survive only if it reaches out to the rest of the world in a progressive and committed fashion. I look forward to working with you in advancing the Geochemical Society into a bright future.

Samuel Mukasa, University of Michigan
GS President, 2010–2011

GOLDSCHMIDT 2010

Thank you to everyone who submitted abstracts by the February 21 deadline. If your budget is tight, remember that members receive a substantial discount on registration fees. Additionally there is an early registration discount for those who register before April 16, 2010.

GOLDSCHMIDT2010™ TRAVEL GRANT PROGRAM

The Geochemical Society, the European Association of Geochemistry, the Geochemical Society of Japan, and the Goldschmidt Conference Organizers will be providing support for the Goldschmidt2010 Travel Grant Program. This program provides financial support to students who are presenting the results of their own research in a talk or poster format at the 2010 V.M. Goldschmidt Conference in Knoxville, TN, USA. Additional funding for this program is also being sought from NSF, DOE and other organizations.

All students presenting at the conference may apply for funding. Please visit the Geochemical Society website at www.geochemsoc.org/programs for details on submission requirements and deadlines.

2010 DIRECTOR ELECTIONS

This year marked the second-ever online election of the Geochemical Society’s directorate. Seth Davis in the Geochemical Society’s business office managed the online ballots. Surveymonkey.com was utilized to notify members and verify results. The voting began on October 30, 2009, and concluded on November 15, 2009. The Board of Directors ratified the results on November 19, 2009. Three e-mail notices were sent to 3087 current members of the Geochemical Society and 954 ballots were received.

Elected vice-president
Richard Carlson

Elected directors
Catherine Chauvel, Richard Walker, Derek Vance

We want to thank everyone who voted and helped to keep the process of choosing the leaders of the Geochemical Society open. Special thanks go out to all the excellent and willing candidates in the 2010 slate of officers.

Stepping down from the board this year are:
Past President: Susan Brantley, Pennsylvania State University
Organic Geochemistry Division (OGD) Chairman: H. Rodger Harvey, University of Maryland
Director: Yaoling Niu, University of Durham
Director: Seth Krishnaswami, Physical Research Laboratory, Ahmedabad, India

Director: Marilyn Fogel, Carnegie Institute of Washington
Presenting our new officers

**Vice President Richard Carlson**
Richard Carlson is a staff scientist at the Carnegie Institution of Washington’s Department of Terrestrial Magnetism. His research focuses on the use of the elemental and isotopic composition of rocks and minerals to investigate the origin and evolution of the solar system, terrestrial planets, Moon, and Earth.

**Director Catherine Chauvel**
Catherine Chauvel is a professor at the University of Grenoble, France. Her research interests include high-temperature geochemistry using trace elements and isotope systems, studies of volcanic rocks and sediments as tracers of differentiation, and the evolution of the Earth.

**Director Derek Vance**
Derek Vance is a professor of isotope geochemistry in the Department of Earth Sciences, University of Bristol. His current research centers on marine geochemical budgets on the modern Earth and in the past, with implications for the interactions between chemical weathering, ocean chemistry, the carbon cycle, and life. He is currently an associate editor of *GCA*.

**Director Richard Walker**
Richard J. Walker is a professor in the Department of Geology, University of Maryland. His research interests include the geochemical evolution of the terrestrial planets, early solar system processes including planetary accretion and core formation, and the chemical evolution of the oceans and other major bodies of water.

**2010 Board of Directors**

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**THE GEOCHEMICAL NEWS PRESENTS:**

**Geochemical Research in China**


Authors and topics include:

1. Shan GAO (China University of Geosciences): The chemical composition of continental crust
2. Zhengtang GUO (Institute of Geology and Geophysics, Chinese Academy of Sciences): Loess geochemistry and Cenozoic environments
3. Xianhua LI (Institute of Geology and Geophysics, Chinese Academy of Sciences): Geochronology of high-temperature rocks and hydrothermal ore deposits
4. Fu-Yuan WU (Institute of Geology and Geophysics, Chinese Academy of Sciences): Geochemical applications of in situ isotopic analyses by laser ablation
5. Eddy Y. ZENG (Guangzhou Institute of Geochemistry, Chinese Academy of Sciences): Geochemical processes of organic pollutants in subtropical watersheds
6. Yong-Fei ZHENG (University of Science and Technology of China): Chemical geodynamics in continental subduction zones

《地球化学新闻》专辑, 3月中旬，2010年

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作者和主题包括:

1. 高山(中国地质大学教授): 大陆地壳的化学成分
2. 郭正堂(中国科学院地质与地球物理研究所研究员): 黄土地球化学与新生代环境
3. 李献华(中国科学院地质与地球物理研究所研究员): 高温岩石和热液矿床的同位素年代学
4. 吴福元(中国科学院地质与地球物理研究所研究员): 激光剥蚀原位同位素分析的地球化学应用
5. 曾永平(中国科学院广州地球化学研究所研究员): 亚热带气候带有机污染物的地球化学过程
6. 郑永飞(中国科学技术大学教授、中国科学院院士): 大陆间非活化学地球动力学

**HELP US REACH OUR 2010 MEMBERSHIP GOAL!**

Last year, the Geochemical Society surpassed 3000 members, and we need your help to maintain the rhythm! If you have not yet renewed your membership for 2010, this will be your last issue of *Elements*. Renewing is very easy with the secure online membership form on our website, www.geochemsoc.org. Annual dues are only US$30 for professionals and US$10 for students. If you have already renewed, thank you! Please help us further by recommending a Geochemical Society membership to your colleagues and students. You would be surprised how many are not members and are missing out on all the advantages of membership.

**GEOCHEMICAL SOCIETY BUSINESS OFFICE**

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FIRST POLISH TEXTBOOKS ON MINERALOGY

The Mineralogical Society of Poland (MSP) is celebrating its 40th anniversary. However, the tradition of the mineralogical sciences in this country is much older and dates back to the 18th century.

The pioneer book on “useful” minerals was published in Polish in 1781–1782 by a provincial priest, Jan Krzysztof Kluk (1739–1796). This monograph, Rzeczy kopalnych osobliwych szukanie, poznanie i zacytanie (Exploration, Identification, and Application of Useful Minerals), presented the state of the geosciences in the second half of the 18th century and was recommended by the Commission on National Education, founded in 1773, as a school textbook. The Commission significantly modernized the educational system in the Polish–Lithuanian Commonwealth and concentrated higher education in Cracow and Vilna, the capitals of the two united countries.

After the complete partition of Poland in 1795 by the three neighboring powers, Russia, Prussia, and Austria, when Poland and Lithuania disappeared from the map of Europe, the conditions of proper modern education were much more difficult due to the russification and germanization politics of the occupants. Consequently, scientific activity was concentrated mainly in the universities of Cracow and Vilna, which had been founded much earlier (in 1364 and 1579, respectively) and were already well known. Separate departments of natural history were formed in 1803 in the capital of Lithuania and eight years later (1811) in Cracow. The great activity of geoscientists in Vilna’s university was manifested by the publication in Polish of several textbooks on mineralogy. Their authors, former students of A.G. Werner (1750–1817), also lectured and promoted the system of mineralogy of their Freiberg master.

Roman Symonowicz (1763–1813) was the first lecturer in mineralogy in Vilna. In 1806, he published the first original Polish textbook on mineralogy, entitled O stanie dzisiejszym mineralogii (On the Present State of Mineralogy). It concisely presented Werner’s basic principles of oryctognosy (mineralogy) and geognosy (geology), as well as critical analysis of R.J. Haüy’s (1743–1822) system, which was based on the physical and chemical properties of minerals. Symonowicz was acquainted with the achievements of such mineral chemists as A.F. Cronstedt (1722–1765), M.H. Klaproth (1743–1817), and T.O. Bergmann (1735–1874), the author of the first chemical classification of minerals.

The first exhaustive university textbook (611 pages), Podług Wernera ułożone dla słuchczów akademickich (Rudiments of Mineralogy According to Werner for Academic Students), was published in 1816 by Feliks Drzewiński (1788–1850), who was another former student of the Freiberg master and lecturer in mineralogy at Vilna University. Adopting A.G. Werner’s approach, he paid particular attention to the external physical properties of minerals. Drzewiński applied the Werneriian systematics of minerals, based on Avicenna’s principles, but he took into account their chemical properties as criteria for subdivision into genera, species, and varieties. His unquestionable merit was in the proposed Polish nomenclature of minerals, in which the majority of names corresponded to polarized versions of generally accepted terms.

The third textbook on mineralogy, Wykłady oryktognozy i początków geognosy (Lectures on Oryctognosy and on Rudiments of Geognosy), published in Vilna in 1825 and reedited in 1827 by Ignacy Jakowicki (1794–1847), another of Werner’s pupils, is considered as a supplement to Drzewiński’s pioneer monograph.

These old Polish textbooks on mineralogy are important contributions to the European heritage in the mineralogical and geological sciences.

Wojciech Narebski, Museum of Earth PAN

MEETING ANNOUNCEMENTS

First Conference of the Geochemical Group
This meeting will be held on September 27–30, 2010, in Kielce (Holy Cross Mountains) and will be organized by the Geochemical Group of the Mineralogical Society of Poland and the Institute of Chemistry of the Jan Kochanowski University in Kielce. The theme will be “Contemporary problems in geochemistry.” The conference will include plenary sessions on September 28 and 29, as well as a tour entitled “Geodiversity and geologic heritage protection in Kielce.” The following field trips will be held on September 30:

“Influence of pyrite mineralization on the generation of acid mine drainage in the Wisniowka mining area,” and (2) “Biogeochemical and hydrogeochemical studies in Swietokrzyski National Park.”

The conference registration fee (including full board, bus transfers, and conference materials) will be around US$200. For information, contact Zbigniew Migaszewski (geochemistry2010@ujk.edu.pl).

17th Session of the Petrology Group
This meeting will be held on October 14–17, 2010, in the Kłodzko region, Sudetes, southwestern Poland. The theme will be “Lamprophyres and related mafic hypabyssal rocks – current petrological issues.” The Sudetes, at the northeastern margin of the Bohemian Massif, represent one of the larger lamprophyre subprovinces in the Variscan Belt of Europe. In this region, the emplacement of calc-alkaline lamprophyre dykes occurred in Carboniferous times. Recent studies have brought new data on the petrology, mineralogy, and geochemistry of these intriguing rocks, documenting their strong diversity (kersantites, minettes, vogesites, spessartites) and a complex magmatic evolution. During the conference, a field trip will take participants to selected lamprophyre localities in the Kłodzko region and will offer stimulating discussions on the emplacement and differentiation processes of lamprophyre magmas in late- to postorogenic settings. For information, contact Marek Awdankiewicz (marek.awdankiewicz@ing.uni.wroc.pl).

A link to the conference website is available on the MSP website page. Abstracts of oral presentations and posters (1–2 pages) for the above conferences will be published in Mineralogia, Special Papers, whereas full papers will appear in Mineralogia.
PRESIDENT’S REPORT

The International Association of Geoanalysts held its autumn Council meeting at the Natural History Museum in London on 10 December 2009. This six-hour meeting, involving Council members from five countries, addressed numerous significant topics which I would like to report on here.

GGR is the official journal of the IAG and is one of its core activities. Ed Williams, IAG Council member and managing editor of GGR, reported on the state of the journal. Thirty-five manuscripts were published in the four issues of 2009, and the page budget as agreed on in the publishing contract was respected. The number of papers submitted to the journal has again grown during this past year, which is attributed to the full online submission and review process available as a result of our collaboration with Wiley-Blackwell scientific publishers. Renewal rates are very much in line with earlier predictions, meaning that the recent economic turmoil has had, at most, a minimal impact on the journal.

Proficiency Testing

The GeoPT™ Programme run by the IAG has become a key tool for quality control for many geochemical laboratories. Over the past year the number of subscriptions to this twice-yearly proficiency testing instrument has grown by some 20 laboratories, making it worldwide one of the premier PT schemes for silicate rock analysis. The use of the automated, online data submission process has grown, which contributes to less data handling and an overall more rapid production of the reports for a given sample round. The coordination of sample selection for the GeoPT™ Programme with the anticipated needs of the IAG sample certification efforts has also been functioning well.

Certification Committee

The IAG’s Materials Certification Committee has been making much progress in recent months. Current work centres on two ultramafic materials which are targeting PGE; these will be the first ISO-compliant reference samples of this type. Work on the determination of the major and minor element concentrations in these materials has been completed and reported by the 30 expert laboratories which agreed to support this initiative. It is hoped that the certificates of analyses for both the harzburgite and the serpentinite will be completed by mid-2010. Finally, IAG Council took an important step in the advancement of the Association’s certification effort: a consensus decision was made to approve a memorandum of understanding with the Central Geological Laboratory of Mongolia for the collaborative production and ISO-based certification of new geological reference materials. This partnership is to last initially for two years, with the expectation that both parties will support its continuation thereafter.

ISO-REMCO

IAG Council has agreed to send a representative to the next ISO-REMCO meeting, which will be held on 3–7 May 2010 in Hangzhou, China. Council wishes to highlight the importance of the Association’s presence at the ISO-REMCO meeting, noting that the IAG is the sole representative of the geochemical community within this global body, which establishes future standards that impact the analytical sciences.

Geoanalysis 2012

Jacinta Enzweiler, IAG vice-president and chairperson of the Geoanalysis 2012 Organizing Committee, reported on progress in the organization of our next triennial meeting. Plenary speakers have already been contacted, and the response has been highly positive. Two themes, “In Situ Microanalysis,” and “Stable Isotope Analyses in Climate Research,” have been selected by the organizing committee as foci for the meeting. The meeting website (www.ige.unicamp.br/geoanalysis2012) will be greatly expanded during the coming six months, with much more detail about the conference venue and content.

Goldschmidt Conferences

IAG Council sees its ongoing presence at the annual Goldschmidt Conference to be highly productive with regards to furthering the Association’s goals. Council wishes to continue the Association’s presence at the upcoming meeting in Knoxville, USA, and has voted to sponsor again the Early Career Researcher Award. The hosting of a Quality Assurance Workshop in Knoxville was also approved.

Anyone interested in obtaining further information about IAG activities is invited to visit our website or to contact me directly.

Michael Wiedenbeck
michawi@gfz-potsdam.de
Mineralogical Society of Great Britain and Ireland

LONDON LORE

Richard Pattrick, of the University of Manchester, has taken over the presidential hot-seat from Michael Carpenter. Michael made an outstanding contribution to the Society over the two years of his presidency, devoting a lot of time to all aspects of the operation of the Society and in particular to how we run our conferences. Many thanks, Michael. Richard, who has served a number of terms on Council, including a period as chairman of the Applied Mineralogy Group, is looking forward to his term of office. See the next issue of Elements for his ‘vision’ of where the Society will be going in the next couple of years.

The running of Elements and its finances are discussed on a regular basis by its team of principal editors and by the Executive Committee. Each page of Elements comes at a considerable cost, and so the space in the society pages must be used carefully. Some readers would rather not see reports of events which have already taken place. Others believe that the tables of contents from our journals shouldn’t be included. These matters are not easy to resolve. It is Mineralogical Society policy to publish brief reports of its meetings and conferences in Elements, and in more detail on the Society website (www.minersoc.org). Publication in Elements serves two needs: (1) it provides an historical record of Society activities, and (2) it gives publicity to the online reports (which often include audio recordings and copies of presentations). Mineralogical Society pages will continue to include brief reports where possible. One of the reasons for societies to join the Elements family is the opportunity to advertise their ‘wares’ to a wider audience. Listing a table of contents for those who do not normally see Mineralogical Magazine, for example, is an important part of what Elements offers to the Mineralogical Society.

NATURE’S TREASURES II – ‘THE WONDER OF MINERALS AND GEMS’

The second in the series of Nature’s Treasures meetings took place in London in mid-December 2009. Over a hundred people gathered in the museum to hear eight high-quality talks from invited speakers. The meetings don’t have themes per se, but speakers are encouraged to make presentations with significant visual impact and to speak at a level which can be accessed by all members of the audience. The NTII audience included youngsters in their early teens, several others who have used their retirements to advance their interests in mineralogy/gemmology and all sorts in between, including a healthy representation from amongst the professional ranks.

The opening talk on diamonds, by Alan Collins, was an excellent introduction to the subject and included a description of the properties of diamond which make it precious and attractive. Martin Feely spoke about a course he runs in NUI-Galway (Ireland). The course covers the cross-over area between mineralogy and gemmology, and indeed geology. Martin’s happy hunting ground is the rugged west of Ireland. Chris Carlon spoke about the offshore mining activities of Anglo-American and presented stunning statistics about the amount of material now retrieved from the seafloor, even at a distance of 35 km from shore. Norman Moles spoke about his personal history – collecting minerals from basalt quarries in Northern Ireland and his job as editor of the journal of the Russell Society – as well as about the activities of that society.

During the lunch break, delegates had the opportunity to mingle, visit the various mineral displays and enjoy the excellent food. The afternoon session began with a talk by Ruth Siddall, who described how minerals are and have been used in pigments for thousands of years. She and her colleagues have examined how some of the colours were made, the careful degree of grinding required, etc. She was also kind enough to display images of some of the beautiful paintings she has examined. John Faithfull of the Hunterian Museum in Glasgow gave a most entertaining talk about the 250-year history of that museum’s mineral collection. He ended with the observation that, if you want your collection to mean anything to anybody in 200 years time, you must stick label numbers on your specimens and you need to make a catalogue now, giving as much information (name, location, cost, purchase details) as possible.

Jolyon Ralph, creator of the mindat.org website project, gave a fascinating account of the history of the mineral database, now the most used mineralogical website in the world. He revealed many astounding statistics, not least of which was that the database includes a quarter of a million images and that during the month of November 2009, it was visited almost half a million times. Jolyon also noted, with tongue firmly in cheek, that mindat is the 63,686th most popular website in the world (not bad out of a total of 156 million!).

The final talk of the afternoon was given by Guy Clutterbuck. Guy had intriguingly described himself as a ‘gemmologist and adventurer’ in his bio paragraph, so his talk was much anticipated. It didn’t disappoint. He spoke of his many adventures in northern Afghanistan (to collect lapis lazuli), in Burma (emeralds) and in Zambia (aquamarine and emeralds). Though his talk was about the business of gem purchasing, Guy also spoke movingly about the human side of dealing with people who extract/collect the precious stones under what are often very extreme conditions (of terrain, weather and politics).

The raison d’être of these meetings is to bring together people from three distinct groups (the Russell Society, Gem-A and the MinSoc). By doing so, each group is stepping out of its ‘comfort zone’ somewhat, thereby appealing to new people. The power of the combined Societies, though, means that we can spread the publicity about the meeting to a wide audience, and we attracted a healthy number of delegates (115) to the December event. Go to www.minersoc.org/pages/meetings/nature2/nature2-archive.html to read a full report and to view and hear the presentations.

Outreach to other groups is a common aspect of much of what we do in the Society. Our efforts include conferences, one-day special interest group meetings, publications, and co-operative ventures such as GeoScienceWorld and Elements.
CALL FOR NOMINATIONS FOR SOCIETY MEDALS

The nominations deadline for Society medals is 30 April 2010. Ask any of the 1000 or so members of the Society to name a mineral scientist they admire and each one will be able to do reel off a half dozen names. In short, there are hundreds of deserving candidates out there. Nomination is easy. You need a copy of the nominee’s CV, a letter of nomination, and a couple of letters of support. Please nominate somebody today – don’t leave it to somebody else!

Mineralogical Society Schlumberger Medal
To recognize scientific excellence in mineralogy and its applications, mineralogy being broadly defined and reflecting the diverse and worldwide interests and membership of the Society with its various specialist groups. Evidence of such excellence should be in the form of published work by a currently active scientist. Nominations on behalf of both younger scientists and well-established workers would be welcomed. Nominees do not have to be members of the Mineralogical Society.

Max Hey Medal
To recognize existing and ongoing research of excellence carried out by young workers, within the fields of either mineralogy, crystallography, petrology or geochemistry. Evidence of excellence should be in the form of work published in highly regarded, international scientific journals. Nominated candidates do not need to be members of the Mineralogical Society. On the closing date for nominations, candidates must normally be under 35 years of age, except where there has been a career break, detailed in the nomination, in which case the committee chair may agree to accept nominations from older candidates.

Collins Medal
The Collins Medal is awarded annually to a scientist who, during a long and active career, has made an outstanding contribution to pure or applied aspects of the mineral sciences and associated studies. Publications, teaching, outreach and other activities leading to the promotion of the mineral sciences, in the broadest sense, will be taken into account in making the award. Nominees do not have to be members of the Mineralogical Society nor nationals of Great Britain and Ireland.

MEETINGS, COURSES AND FIELD EXCURSIONS – ANNOUNCEMENTS

1
Annual Meeting
Groupe Français des Argiles
Autrans, France – May 6th–7th, 2010
http://gfocmg2010.obs.ujf-grenoble.fr/

2
PROCESS MINERALOGY OF METALLIFEROUS ORES: AN INTRODUCTION FOR GEOLOGISTS
A workshop hosted by Camborne School of Mines, University of Exeter, United Kingdom, and supported by the Applied Mineralogy Group.
22–25 June 2010. See http://tinyurl.com/yekprkn for details. Interested delegates may wish to combine the workshop with the field trip described below.

3
MINERALOGICAL SOCIETY FIELD EXCURSION TO CORNWALL, 28 JUNE–3 JULY 2010
The excursion will provide an introduction to the wide range of geology found in Cornwall, including the tectonics of the Devonian metasediments, the granites, the Lizard Ophiolite and the classic Sn, W, Cu and kaolin mineralisation. More information is available at www.minersoc.org/pages/meetings/cornwall-fieldtrip/cornwall-field.html. Registration is now open.

MINERALOGICAL MAGAZINE

We are very pleased to announce that Mineralogical Magazine is back on its publication schedule. Content from the December issue went online in December. Anyone involved in publishing a journal will know how easy it is to lose a month from the schedule, but how difficult it is to make it up. Many thanks go to Mark Welch, the team of Associate Editors and Pete Hill (Production Editor) for working so hard to catch up.

Journal Archive
You will have noticed that the Society journal archive has been temporarily disabled. By the time this article reaches you, we hope it will be back up and running. The problem was caused by a web-space problem and the need to relocate the entire site to a new host. This has now been done, following a careful review of the options and costs. It is gratifying to see how many people use the archive. During the down period we received up to a dozen messages per day from people seeking copies of material from the archive, which is freely available to all.

Some Papers from the December 2009 Issue

How low can you go? – Extending downwards the limits of plastic deformation in pyrite
C.D. Barrie, A.P. Boyle and M. Salter

Perovskite from the Dutoitspan kimberlite, Kimberley, South Africa: implications for magmatic processes
R.C. Ogilvie-Harris, M. Field, R.S.J. Sparks and M.J. Walter

Complex relationships among coexisting pyroxenes: the Palaeogene Eskdalemuir dyke, Scotland
B. Bagiński, P. Dzierczynski, W. Majszczak, R. Macdonald and B.G.J. Upton

Megacrysts and salic xenoliths in Scottish alkali basalts: derivatives of deep crustal intrusions and small-melt fractions from the upper mantle
B.G.J. Upton, A.A. Finch and E. Slaby

Kevin Murphy, Executive Director
FROM THE PRESIDENT
People Make MSA Great

Becoming an officer of MSA has opened my eyes to the character and contributions of the extraordinary people who serve our society. Let me begin with our business office in Chantilly, Virginia. For a member of MSA, the behind-the-scenes workings are easy to ignore. Like a well-oiled machine, the jobs get done competently, quickly, and with little fanfare. Some of the work we see directly (dues collection, news postings, book sales, etc.), but much of it we do not see (meetings and short course organization, inventory management, finances, legal requirements, etc.). We are fortunate indeed to have Alex Speer as our executive director. His management abilities, professionalism, experience, and memory make MSA run smoothly and well. In addition to keeping MSA on track, Alex shares his expertise and time with the Clay Minerals Society (which shares space with the business office), the Geological Society of Washington, *Elements*, and the new Mineralogy, Geochemistry, Petrology, and Volcanology Division of GSA. Alex is well supported in his management by Everett Johnson and Michael Harris, both staff members in the business office, whose skill and good work make the office hum.

*American Mineralogist*, which is the most visible and identifiable product of MSA, seems to magically appear eight times each year. However, the magic is the result of hard work and dedication by many individuals, including authors, reviewers, associate editors, editors, and especially the editorial and production staff in Chantilly. The team has too many players to name them all (see www.minsocam.org/MSA/AmMin/aes/aelist.html), but I must mention with admiration the editors, Jennifer A. Thomson, Dana T. Griffen, and Bryan C. Chakoumakos, and now Martin Kunz, who somehow are able to complete their enormous editorial tasks on top of their regular jobs. The editors are guardians of the scientific quality of *American Mineralogist*, and their importance to MSA cannot be overstated. Once the content is approved, the material goes to managing editor Rachel Russell and her assistants, Christine Eldred, Jane Watson, and Kris Herzog, whose competent work and high standards ensure that the authors’ words and figures become the masterful journal layout that makes *American Mineralogist* the pride of MSA.

The public face of MSA is also strongly influenced by the excellent work of Gordon Nord, our webmaster, and Jodi Rosso, Reviews series editor. Gordon keeps our society connected through an easily navigated website, online services, the MSA-Talk listserv, and in general all things electronic. Jodi works with short course conveners, providing quality book-length products on tight schedules. She is also digitizing older Reviews volumes to broaden their utility and impact. MSA would also like to claim a part of Pierrette Tremblay, managing editor of *Elements*, whose talents have a lot to do with the great success of this new publication.

In the balance, of course, it is MSA members who make the society. Our membership, now over 2700 strong, ranges from mineralogy students and mineral collectors to top scientists in the fields of mineralogy, crystallography, petrology, and geochemistry. Well over 100 members contribute many hours of their time to MSA each year by serving as officers and committee members and by organizing short courses, representing MSA, reviewing papers, writing papers, giving lectures, nominating others for awards, and much more. You can see some of their names on the MSA website (www.minsocam.org/MSA/Committees.html), but many others are hidden from view. MSA could not function without their service to the community. Member support also includes donations of money. About 25% of MSA members generously contribute amounts from a few dollars to hundreds of dollars each year. These donations help fund a number of MSA programs, in turn keeping dues low.

The Mineralogical Society of America is a wonderful organization indeed. Thank you, members, for all that you do to make MSA strong.

John Brady (jbrady@smith.edu)
2010 MSA President

NOTES FROM CHANTILLY

- All 2008 and 2009 MSA members have been contacted by mail, electronically, or both about renewing their membership for 2010. If you have not renewed your MSA membership, please do so. If you have not received a notice by the time you read this, please contact the MSA business office. You can also renew online at anytime.

- The slate of candidates for the 2010 MSA Council elections is:
  
  President: David L. Bish
  Vice President: George E. Harlow; Michael F. Hochella Jr.
  Treasurer: Darrell Henry
  Councillors (two to be selected): Jay J. Ague, Pamela C. Burnley, Guy L. Hovis, Kevin M. Rosso

Mickey Gunter continues in office as secretary. Continuing councillors are Penelope L. King, Marc M. Hirschmann, Wendy A. Bohrson, and Sumit Chakraborty. Election materials will be available to MSA members in April, in time for the voting deadline of August 1, 2010.

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

IN MEMORIAM

Haymo Heritsch – Honorary Fellow, 1965
Brian H. Mason – Life Fellow 1944
Arthur E. Smith Jr. – Member 1960
NOMINATIONS SOUGHT FOR 2011 AWARDS
Nominations must be received by June 1, 2010

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

The **Dana Medal** recognizes continued outstanding scientific contributions through original research in the mineralogical sciences by an individual in the midst of his or her career and who has not previously been recognized as a recipient of the MSA Award.

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

The **Distinguished Public Service Medal** is presented to an individual who has provided outstanding contributions to public policy and awareness about mineralogical topics through science. The next award will be given in 2011.

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

Mineralogical Society of America
Submission requirements and procedures are on MSA’s home page: www.minsocam.org

The **Mineralogical Society of America**

**2011 Grants for**

**Research in Crystallography**
from the Edward H. Kraus Crystallographic Research Fund with contributions from MSA membership and friends

**Student Research in Mineralogy and Petrology**
from an endowment created by MSA members

**MINERAL EVOLUTION STARTED HERE:**

“Mineral evolution,” a review article by Robert M. Hazen, Dominic Papineau, Wouter Bleeker, Robert T. Downs, John M. Ferry, Timothy J. McCoy, Dimitri A. Sverjensky, and Hexiong Yang

*American Mineralogist*, November-December 2008, volume 93, pp 1693–1720

**AND CONTINUED WITH**

“Evolution of uranium and thorium minerals,” by Robert M. Hazen, Rodney C. Ewing, and Dimitri A. Sverjensky


**PACROFI X 2010**

Las Vegas, Nevada, USA

June 7–10
on the University of Nevada, Las Vegas campus

Premeeting field trip to the Carlin gold deposits
Postmeeting field trip to the Colorado River Extensional Corridor
Premeeting short courses by Drs. Bob Bodnar and Steve Becker

Information and registration at http://geoscience.unlv.edu/PACROFI2010.html

We invite all fluid and melt inclusion researchers.

**MINERALOGICAL SOCIETY OF AMERICA AND GEOCHEMICAL SOCIETY**

**Short Course Announcement**

**DIFFUSION IN MINERALS AND MELTS**

**December 10–12, 2010**

Napa Valley Marriott Hotel & Spa
Napa, CA, USA
(before Fall AGU Meeting)

**Convenors**

**Youxue Zhang**
University of Michigan

**Daniele Cherniak**
Rensselaer Polytechnic Institute

This short course will focus on diffusion at high to moderate temperatures in minerals and silicate melts. Although theoretical aspects will be covered, the emphasis will be on fundamental details of diffusion for direct application to geological problems, including (1) experimental methods, (2) analytical techniques, (3) a summary and assessment of diffusion data in minerals and melts (including the data and equations).

More information and registration: www.minsocam.org

**Elements**

February 2010

**55**
THE PRESIDENT’S CORNER

For the past few years, the Executive Committee of CMS has met in January or early February for a long-range planning meeting. This was initiated as a means of looking at longer-term issues which often do not get the attention they deserve at the other yearly meeting of the Executive Committee, held in conjunction with the annual meeting of the Society, usually in June. Inevitably other pressing issues are discussed in order to keep the Society running smoothly, but there is a need to look to the future rather than at just the immediate day-to-day matters, and this year (2010), one of the issues on the agenda is “marketing” the Society. One of the appealing aspects of CMS is the wide variety of interests represented within the membership, but this makes it difficult to target particular areas of interest. A series of books/monographs on particular topics could be a way forward; another could be publication of a collection of the most significant papers published on an important topic. I would be pleased to hear suggestions from any members who have ideas about how best to “showcase” CMS.

I would like to remind CMS members and notify readers of Elements about the CMS listserver facility, available free of charge to anybody interested, not just CMS members. Operated through Purdue University, this e-mail facility is really a discussion forum and is intended to help individuals disseminate or request information and to prompt discussion among all those signed up to receive the messages. Anyone interested in taking advantage of this service should sign up at the website https://lists.purdue.edu/mailman/listinfo/clayminerals-l.

Derek Bain, President, The Clay Minerals Society
The Macaulay Institute, Aberdeen, UK
(d.bain@macaulay.ac.uk)

SEVILLE

The Clay Minerals Society (CMS), the Clay Science Society of Japan (CSSJ) and the Spanish Clay Society (SEA) will hold a trilateral meeting in Spain on 6–11 June 2010 devoted to clays and clay minerals. The aim of the 2010 Trilateral Meeting on Clays (2010TMC) is to offer a warm and friendly conference that will highlight innovative scientific and technical aspects of clays and related minerals. The 2010TMC will begin with a one-day “Workshop on Clays & Materials” to be held in Madrid, followed by a half-day field trip to the Mg-clay deposits of the region (i.e. sepiolite and smectite). The General Meeting will take place in Seville, with a field trip to the Rio Tinto Mines area (southwestern Spain). More details and forms for abstract submission and registration are available on the meeting website, www.sea-arcillas.es/2010TMC.

CMS MEMBERS AWARDED HONORARY MEMBERSHIP IN SPANISH CLAY SOCIETY

Four members of The Clay Minerals Society were recognized as honorary members of the Spanish Clay Society (SEA) during a scientific conference commemorating the 50th anniversary of the founding of the Spanish group. CMS members honored for their contributions to the field of clay science were Professors Ray E. Ferrell (Louisiana State University), Santiago Leguey (Autonomous University of Madrid), Jose L. Perez-Rodriguez (Scientific Research Council of Spain, Seville), and Thomas J. Pinnavaia (Michigan State University). Ferrell and Pinnavaia are past presidents of CMS. Other recipients of honorary membership were Professors Shlomo Nir and Arieh Singer of the Hebrew University. In 50 years, 26 clay scientists have been recognized as honorary members.

The technical meeting, presided over by Professor Eduardo Ruiz-Hitzky, president of SEA, featured more than 30 poster presentations by members of the Society and invited lectures by Professors Ferrell, Pinnavaia, and M. Ogawa (CSSJ and CMS). Honorary Members J. Serratosa and E. Galan provided personal insights on the history and development of SEA. The future holds great promise for the continued success of the Society.
MEMORIAL FOR HERBERT DAVID GLASS

Herbert (Herb) Glass passed away on August 20, 2009. In spite of some recent health setbacks, he had been doing pretty well and was in good spirits. He apparently died of cardiac arrest in his bed at age 93. He was buried on August 23, in Greensboro, North Carolina, USA.

Herb was born in Brooklyn on October 14, 1915. In his high school years he learned to love opera, and in later years he told of how he could stand in the back at the Metropolitan Opera for $0.50. His opinions about opera, and a number of other subjects, were always readily available. He earned a bachelor’s degree in geology from New York University, where his daughter, Carol, thinks he had a swimming scholarship. This seems likely because after graduating he swam in Billy Rose’s Aquacade in the 1940 World’s Fair held in New York. Johnny Weissmuller and Esther Williams were the initial stars, but Johnny was replaced by Buster Crabbe. Herb said he used to hang out with Buster between shows and taught him to play pinochle!

Johnny Weismuller and Esther Williams were the initial stars, but in Billy Rose’s Aquacade in the 1940 World’s Fair held in New York. Johnny was replaced by Buster Crabbe. Herb said he used to hang out with Buster between shows and taught him to play pinochle!

His higher education was interrupted by WW II, during which he rose with Buster between shows and taught him to play pinochle!

His higher education was interrupted by WW II, during which he rose with Buster between shows and taught him to play pinochle!

During his long career at the Survey, he helped many students with their thesis projects. He liked to present himself as gruff, but he was really a sweetheart. One student complained to him that his criticisms were too harsh. Always straightforward, Herb replied, “If I didn’t care, I wouldn’t say anything.” Many benefited from his talent for pointing out flaws of logic and unclear writing.

I inherited Herb’s slot at the Survey in 1987 when he ‘officially’ retired, but you wouldn’t know it if you were to check attendance. Herb hardly ever missed a day for the next ten or twelve years. Then he would occasionally take a day or two off. He finally moved to Chapel Hill, North Carolina, with his wife, Edna, in 2003. Herb and his demeanor were a defining element in the character of the Survey. There was, and I hope still is, a photo of Herb posing with the GE diffractometer when it was brand new. He was wearing a tie. I don’t think I ever saw him without a tie. I think he always wore a tie. I don’t think I ever saw him without a tie. I think he always wore a tie.

Herb is survived by his wife, Edna, and children, Carol and Jeffrey.

Dewey Moore, with the help of Carol Glass

FORTHCOMING PAPERS
IN CLAYS AND CLAY MINERALS

On the chemical composition of sepiolite and palygorskite
E. García-Romero and M. Sánchez

Stress-induced alteration of sudoite: structural and chemical modifications
Maria Dolores Ruiz Cruz, Maria Dolores Rodríguez Ruiz, and Carlos Sanz de Galdeano

Water uptake capacity of bentonites
S. Kaufhold, R. Dohrmann, and M. Klinkenberg

Hydrothermal synthesis of kaolinite and its formation mechanism
Kyung-Won Ryu, Young-Nam Jang, and Soo-Chun Chae

The combined inelastic neutron scattering (INS) and solid state DFT study of hydrogen atoms dynamics in kaolinite-dimethylsulfoxide intercalate
Lubomír Šmrčok, Daniel Tuneva, Aníbal Javier Ramirez-Cuesta, Alexander Ivanov, and Jana Václučová

Stacking disorder in a sedimentary kaolinite
Toshihiko Kagure, Jessica Elzea-Kogel, Cliff T. Johnston, and David L. Bish

Structure and properties of hydrogenated nitrile rubber (HNBR)/organo-montmorillonite (OMT) nanocomposites
Zheng Gu, Guojun Song, Weisheng Liu, Shijing Yang, and Jianming Gao

Determination of exchangeable calcium of calcareous and gysiferous bentonites
Reiner Dohrmann and Stephan Kaufhold

Ab initio molecular dynamics study of Fe-containing smectites
Xianfeng Liu, Evert Jan Meijer, Xiancai Liu, and Rucheng Wang

Approach to a descriptive model of a vermiculite charge reduction by hydrothermal treatment
Ana M. Campos, Sonia Moreno, and Rafael Molina

Performance of natural zeolite and sepiolite in free cyanide and copper-complexed cyanide ([Cu(CN)_3]L^2) removal
Esra Tarlan-Yel and Vildan Önen
PAUL MORRIS IS AAG’S NEW PRESIDENT

In spite of the slowdown in the mineral exploration industry over the past 18 months, the underlying importance of geochemistry, and associations such as AAG that foster it, was underlined by the attendance of more than 300 delegates at AAG’s biennial International Association of Geochemistry Symposium, held in Fredericton, New Brunswick (Canada) in June 2009. More than one-third of the attendees were students, another positive sign that geochemistry is still viewed as a worthwhile career option. AAG is aware that its future relies on increasing the number of members in general, and students in particular – of our 500 members, about 6% are students, and AAG is keen to grow these numbers. To that end, the Association offers financial assistance to students to attend IAGS meetings, provides reduced registration costs for students, and sponsors a student-paper prize. Fundamental to attracting students to AAG are the efforts of its senior members who hold academic positions and can promote the importance of geochemistry and associations, such as AAG, to their students.

AAG’s journal, Geochemistry: Exploration, Environment, Analysis (GEEA), continues to publish a wide variety of papers dealing with the use of geochemistry in mineral exploration and environmental assessment. Thematic issues such as Geochemical Mapping (volume 5, part 4, 2005) and Natural Analogues for Radioactive Waste Disposal Strategies (volume 6, part 1, 2006) exemplify the exploration and environmental interests of AAG members. GEEA is complemented by AAG’s quarterly magazine, EXPLORE, copies of which can be downloaded free of charge from AAG’s website (www.appliedgeochemists.org).

In 2011, the 25th International Applied Geochemistry Symposium will be held on 22–26 August in Rovaniemi, Finland. It is fitting that the Finns host an IAGS as geochemistry has well-established credentials on these two meetings have been published in previous issues of Elements (volume 5, number 5, page 328, and volume 5, number 6, pages 386, 401, and 402).

MEETINGS PAST AND PLANNED

In 2009, the IAGC was heavily involved in two major meetings: the 24th International Applied Geochemistry Symposium (IAGS 2009) and the eighth Applied Isotope Geochemistry Symposium (AIG-8). Reports on these two meetings have been published in previous issues of Elements (volume 5, number 5, page 328, and volume 5, number 6, pages 386, 401, and 402).

FEG 2011

The 2011 ‘Frontiers in Environmental Geoscience’ conference will be held in Aberystwyth, Wales, on 21–23 June 2011. This meeting will be the main meeting of the Mineralogical Society of Great Britain and Northern Ireland in 2011. It will cover a number of ‘hot topics’ of interest to those working in mineralogy, environmental mineralogy, waste management and contamination clean-up. We are expecting about 120 to 150 delegates (although more would be welcome). The following sessions have been proposed:

1. Mine drainage: Geochemistry and mineralogy
2. Tracking contaminant transport from geological media through the food chain to humans
3. Urban geochemistry and mineralogy: Impacts on water, air and health
4. Toxicity and environmental behaviour of man-made materials
5. Applied mineralogy in the critical zone: Metal reactions at mineral surfaces
6. Integration of computational and experimental environmental mineralogy
7. Environmental clay mineralogy and technology
8. Geochemistry of platinum-group minerals

We encourage IAGC members to get involved in the organization of these and other sessions and invite members to help by co-convening a session or by proposing/organizing special theme sessions. Interested persons should contact the convenor, Dr. Nick Pearce. For more information about the conference, please do not hesitate to contact him directly at njp@aber.ac.uk (telephone: +44 (0) 1970 622599).

RECENT TITLES IN GEOCHEMISTRY

One of the benefits of attending a large national/international geoscience meeting is visiting the display stands of the major textbook and research text publishers. IAGC members Bill Evans and Phil Verplank volunteered to spend a few hours during the recent Geological Society of America meeting, Portland, Oregon, on 18–21 October 2009, perusing the new-book offerings of the publishing companies present at the exhibition. A list of recent titles in geochemistry was published in IAGC Newsletter 51 and can be downloaded at www.iagc.ca/newsletters/IAGC_Newsletter_51.pdf. "ABANDONED MINING SITES: LESSONS LEARNED FROM HYDROGEOCHEMICAL STUDIES IN SARDINIA"

This article, by Rosa Cidu (Università di Cagliari), has been contributed as a short paper on a current environmental geochemistry topic and can be downloaded at www.iagc.ca/newsletters/IAGC_Newsletter_51.pdf. Previous articles in IAGC Newsletters have described options for nuclear waste disposal and environmental health in the Balkans. If you have a suitable article to contribute, please contact the newsletter editor, Mel Gascoyne (gascoyne@granite.mb.ca).
Tourmaline: An Ideal Indicator of Its Host Environment

Tourmaline-group minerals are ubiquitous accessory minerals in the Earth’s crust. They can adjust their composition to suit a wide variety of environments and therefore display a remarkable range in stability in terms of pressure, temperature, and chemical environment. Because of this compositional sensitivity, tourmaline is an excellent indicator of the environmental conditions in its host. This is enhanced by the fact that tourmaline shows negligible diffusion up to remarkably high temperatures and a strongly refractory character during subsequent host-rock alteration and weathering, as well as mechanical transport of grains. Whereas most prior tourmaline research focused on chemical and crystallographic characterization and the systematics of the tourmaline-group minerals, recent studies are oriented towards a quantitative reconstruction of host environmental conditions using a combination of tourmaline structural, compositional, and crystallographic characteristics. This special session highlighted these exciting advances and considered the obstacles to be overcome.

In his keynote talk, David London (University of Oklahoma) gave an overview of the experimental work on tourmaline and established the important constraints this research places on the formation of natural tourmaline. Of particular interest was his observation that the specification of elements in the melt has a strong control on subsequent tourmaline composition. Similarly, a proper understanding of coupled substitution mechanisms is crucial to the interpretation of compositional variations, as highlighted in presentations on the intimate links between crystal structure and composition by Ferdinando Bosi and Aaron Lussier. If tourmaline compositions are to be used properly, the constraints imposed by crystallography must be understood, and the presentations by Ferdinando Bosi and Christine Clark addressed this concern. Tourmaline has an impressive stability range, from diagenetic conditions to well into the eclogite and granulite facies. Different generations of tourmaline, as well as compositionally zoned grains, can record and preserve this complete history, and talks by Darrell Henry and Vincent van Hinsberg showed how information on pressure, temperature, and composition can be extracted from these grains. The poster session, with presentations by Kristen Longfellow, Maria Sokolov, and Eva Wadoski, highlighted how tourmaline texture and composition reveal information on the pressure, temperature, and chemical evolution of their host rocks.

The main conclusion of the session was that we are standing on the brink of a major breakthrough in the use of tourmaline as a quantitative indicator of the chemical and physical properties of its host environment and that these advances may well make tourmaline the prime indicator of the chemical and physical properties of its host environment. This is enhanced by the fact that tourmaline shows negligible diffusion up to remarkably high temperatures and has a strongly refractory character during subsequent host-rock alteration and weathering, as well as mechanical transport of grains. Whereas most prior tourmaline research focused on chemical and crystallographic characterization and the systematics of the tourmaline-group minerals, recent studies are oriented towards a quantitative reconstruction of host environmental conditions using a combination of tourmaline structural, compositional, and crystallographic characteristics. This special session highlighted these exciting advances and considered the obstacles to be overcome.

The session was held in honor of Frank Beales (1919–2004), who made many fundamental contributions to the understanding of Mississippi Valley Type deposits and their host rocks in the 1960s. The presentations addressed the genesis of carbonate-hosted deposits from Australia, Spain, Ireland, China, Zambia, Indonesia, and Honduras, as well as deposits from the Canadian Arctic, the Mackenzie Mountains, and the Maritimes. Along with the Mississippi Valley and Irish-type deposits, the formation of higher-temperature Zn–Pb–Ag skarns and Zn oxide deposits was also discussed, emphasizing some of the common processes involved in the formation of base metal deposits in carbonate rocks at a range of pressure and temperature conditions. The final talk of the oral session was given by a long-time friend and colleague of Frank Beales, Professor Greg Anderson of the University of Toronto, who aptly reminded all present that it all comes down to thermodynamics in the end.

Sarah Gleeson (University of Alberta)

Recent Advances in Trace Element and Isotopic Microanalysis of Accessory Minerals

MAC cosponsored this special session in conjunction with the Volcanology, Geochemistry, and Petrology Division of the AGU. The session was spread out over two days, and 14 oral and 5 poster presentations were given. A wide variety of topics were presented on the trace elements or isotopes of sulfide, silicate, oxide, and phosphate minerals from magmatic and hydrothermal environments. MAC sponsored Jacob Hanley from St. Mary’s University (Halifax), who (with coauthor M.K. Mackenzie) talked on the subject “Incorporation of Platinum-Group Elements and Cobalt into Subsidary Pyrite in Alkalic Cu-Au Porphyry Deposits: Significant Implications for Precious Metal Distribution in Felsic Magmatic-Hydrothermal Systems.” An invited talk given by J.R. Clark of McGill University (with A.E. Williams-Jones) was on the subject “Compositional Variability of Rutile in Hydrothermal Ore Deposits.” A second invited talk, by S.-J. Barnes of Université du Québec à Chicoutimi (with S.A. Dare) was entitled “Contrasting Platinum-Group Element and Chalcophile Element Contents in Pyrrhotite, Pentlandite, and Chalcopyrite from Different Environments.”

Robert Linnen (University of Waterloo)

Carbonate-Hosted Ore Deposits

The session was held in honor of Frank Beales (1919–2004), who made many fundamental contributions to the understanding of Mississippi Valley Type deposits and their host rocks in the 1960s. The presentations addressed the genesis of carbonate-hosted deposits from Australia,
Water-rock interactions cannot be understood or quantitatively interpreted without the application of physical chemistry consisting of thermodynamics, kinetics, and quantum mechanics. In the period 1965–1985, applied geological thermodynamics reached a pinnacle of importance, with kinetics closely following. It would have been unthinkable then to graduate master’s and doctoral students in mineralogy, geochemistry, petrology, or any chemically related (or meteorologically related) aspects of environmental science without a course in thermodynamics. It is no longer true. Several years ago I taught an environmental geochemistry course for graduate students, and one student was extraordinarily upset because I had required everyone to know a few basic principles of thermodynamics. Hence, volume 70 in the Reviews in Mineralogy and Geochemistry series, entitled Thermodynamics and Kinetics of Water-Rock Interaction (TKWRI), is most welcome. As the editors state, “There is a compelling societal need to resuscitate the fields of thermodynamics and kinetics of natural processes.”

The TKWRI volume accompanied a short course held at the 19th annual Goldschmidt Conference in Davos, Switzerland, in June, 2009, and it was also an outgrowth of European summer courses offered by the editors of the volume at the request of students. As such, it contains a broad range of theoretical principles and applied examples. The range and thoroughness of each chapter is the strength of the volume, as with most volumes in this series. There are a few omissions, including the lack of a chapter on stable and radiogenic isotopes, the lack of discussion on geothermal fluids, the lack of uncertainty discussions when applying thermodynamics and kinetics to field data, and the limited discussion of the pros and cons of the different approaches to applying thermodynamic and kinetic theory to field data. I would also like to have seen more discussion on aqueous speciation codes, databases, and kinetics. It is unfortunate that we find the saturation index defined in logarithmic terms as \( \log K_c \) and in other chapters as \( \log \Omega \), i.e., the ion activity product divided by the equilibrium constant) and in other chapters as \( \log \Omega \).

The introductory chapter on thermodynamic databases by Oelkers is certainly appropriate, as it contains a summary of thermodynamic equations and the Helgeson-Kirkham-Flowers approach. Coverage of other databases is somewhat limited. No mention is made of the IUPAC Solubility Data Series, of the CODATA books on key values and calcium compounds, of the numerous contributions from Navrotsky’s lab, and of the voluminous OECD/NEA chemical thermodynamics series for actinides, nickel, zinc, and selenium, with more volumes in progress. I would have liked to have seen suggestions on how we can achieve greater collaboration among those making measurements of thermodynamic properties, the evaluators of the data, and those who apply the data to geochemical problems. Apparently there remains a lack of interest, funding, and prestige associated with such activities.

The remarkably clear and current reviews of the thermodynamics of solid solution–aqueous solution systems by Prieto and mineral replacement reactions, including numerous excellent examples, in the following chapter by Putnis were refreshing and stimulating to read. Prieto’s discussion of stoichiometric saturation is short and quite understandable, so you would not know there was some controversy over this subject several years ago.

A reader might think that sorption could be covered in one chapter rather than three, but each chapter brings a different perspective. Kulik presents a substantial chapter on the basics of sorption thermodynamics and isotherms, the different models used for sorption theory, and some of the codes used with these models. For an introduction or refresher on sorption basics, this chapter is the place to start. Sherman presents the other side of sorption, summarizing what is known from recent studies using \textit{ab initio} calculations and some results from synchrotron spectroscopy of surface bonding. It would have been even more helpful to have a summary of all the synchrotron studies of aqueous species bonded to mineral surfaces. Numerous studies by Brown, Waychunas, Manceau, Sturchio, and their colleagues are never mentioned. The chapter by Schott, Pokrovsky, and Oelkers is one of the most ambitious in the volume. It integrates mineral dissolution/precipitation kinetics with mineral surfaces. Numerous studies by Brown, Waychunas, Manceau, Sturchio, and their colleagues are never mentioned. The chapter by Schott, Pokrovsky, and Oelkers is one of the most ambitious in the volume. It integrates mineral dissolution/precipitation kinetics with importance in water–rock interactions, organic-matter sorption, and the effects of organics on dissolution of silicate and carbonate minerals. Unfortunately, there are insufficient references to several metal–organic modeling efforts, especially the successful work of Tipping and colleagues who developed the WHAM model. The main problem with organics in water–rock interactions is that the subject is huge and really requires a separate volume.

A major area of water–rock interactions is weathering. Two chapters cover this field, a shorter one by Goddèriès, Roelandt, Schott, Pierret, and François on a generalized approach to weathering and its modeling, and a longer one by Brantley and White on regolith weathering. The former chapter presents an approach integrating climate, vegetative effects on weathering, and mineral dissolution rates within an input–output model embodied in the WITCH code, with applications to a small catchment and a large catchment (the Orinoco Basin). The sensitivity analyses performed by the authors on these catchments make an instructive and valuable addition to these methods. The latter chapter is written by two well-known researchers in this field who have worked on weathering processes for more than two decades. They delineate the range of approaches to modeling weathering processes from the simple to the complex and use an appropriate heuristic style in which they begin with the characteristics of real weathering profiles. As the latest synthesis by these two authors, it is a must-read for anyone attempting to do research on weathering.

Two complementary chapters complete this volume, bringing the application of thermodynamics and kinetics to its ultimate goal of interpreting water–rock interactions in terms of reactive-transport and geochemical modeling and networks. The first of these chapters is an introduction to reactive-transport geochemical modeling by Steefel and Maher, who use irreversible thermodynamics to present the physical aspects of transport (advection, diffusive, dispersive, and electrochemical) relevant to solute transport. In my opinion, this framework is the best possible one for a generalized and understandable approach for the purpose of teaching and learning reactive transport. A discussion on the “reactive” part of reactive transport follows, along with some helpful caveats concerning the pitfalls that lurk around every corner of this topic, and the chapter ends with several case studies. The volume concludes with the chapter by Zhu, focused on the geochemical reaction modeling that is largely missing from the previous chapters. It also goes full circle, bringing us back to solution speciation codes and their databases, and it connects with previous chapters through mineral dissolution/precipitation rates within the framework of geochemical modeling. It ends with some overviews of reactive-transport modeling and biogeochemical networks. I found the last chapter to be a most enjoyable read, and it should be read together with the previous chapter.

Anyone teaching or taking advanced courses in thermodynamics and kinetics in water–rock interactions should use this book if they hope to stay current.

D. Kirk Nordstrom, USGS, Boulder, CO, USA

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Principles of Igneous and Metamorphic Petrology, second edition, is a welcome update of the volume originally published in 1990, authored by Anthony Philpotts alone, which became the definitive reference for petrologists. The term “principles” in the title is the key here. The second edition covers nearly all aspects of petrology; there are thorough, in-depth treatments of everything from thermodynamics, heat transfer, kinetics, crystal growth and emplacement mechanisms to phase diagrams, petrography and isotopes. The flow is fairly logical – the chapters “Magmaic Processes” and “Igneous Rock Associations” build on material covered earlier in “Thermodynamics,” “Phase Equilibria” and “Crystal Growth.” What there is less of is geochemistry. Of course this is a separate topic in itself, and there are plenty of excellent geochemistry texts available. Nevertheless, modern petrology does rely heavily on geochemistry, and although isotopes, for instance, warrant a separate chapter, the application of trace elements to magmatic processes is limited. I don’t recall seeing a single normalised trace element (or REE) diagram, although for many, that may not be such a bad thing!

The real quality of this book lies in its authoritative character and depth of coverage. This is enhanced by the integration of research-based information from journals. There are 26 pages of carefully selected references, as up to date as 2007. The text is complemented by crisp, clear diagrams and photographs, including some taken from publications. These are all in black and white, but this detracts little from the quality and doubtless saves some cost. After all, this is not a coffee table book, but rather a volume which will likely be well thumbed and littered with “stickies” and other place markers by students and professors alike. The copious use of photomicrographs is an important feature, and they are a reminder of the critical need for careful microscope examination before time and resources are diverted to quantitative analyses and modelling. The photomicrographs are complemented by colour versions on the book’s website and by a companion petrographic guide by the main author. The text does not shy away from quantification and includes some challenging end-of-chapter numerical problems (sufficiently challenging that I would like to have had access to all the solutions!). The introduction of now widely used computational tools, such as MELTS and THERMOCALC in igneous and metamorphic petrology, respectively, adds to the rigour of the book.

For me, one of the excellent aspects of the book is the clever integration of different perspectives of petrology – for instance, the illustration of alkali feldspar phase relations, which is typically simply achieved through an X–T section, is shown as a three-dimensional sketch with X–T sections along varying X<sub>Na2O</sub>. These diagrams are accompanied by two photomicrographs to show how hypersolvus and subsolvus textures relate to the phase diagrams. Similarly, the Di–Ab–An phase diagram is accompanied by a photomicrograph showing how the curved plag–cpx grain boundary formed by progressive crystal growth reflects the phase diagram. This is typical of the innovative approach in many of the diagrams. Double-diffusive convection, for instance, is illustrated by combining cartoon magma chambers with photos of appropriate tank experiments, and the finger-like protrusions along the periphery of the Shonkin Sill are illustrated by analogy with a photo of a fried egg (along with an explanation of the viscosity control, lest this seem simply frivolous!).

Compared with the first edition of Principles, the main change (other than the addition of author Jay Ague) is in the physical quality of the book itself, which is perhaps related to the change of publisher to Cambridge University Press. The pages are of thicker, better quality paper (my copy of the first edition is impressively yellowed despite being less than 20 years old). The basic structure is quite similar – the chapter titles in the igneous section are unchanged, while those in the metamorphic section are restructured, reflecting the addition of Ague’s expertise and perspectives. The metamorphic section (which, as an igneous petrologist, I am less qualified to assess) is markedly enhanced by a wealth of additional images – field photographs, photomicrographs and line drawings – compared with the first edition. Overall there are an additional ~170 pages compared with the first edition, and the updates certainly make the second edition a worthwhile purchase. These updates include, for instance, Wark and Watson’s ‘Ti in quartz’ geothermometer, an updated compilation of diffusivities, crystal size distributions (CSDs) backed up with all the necessary theory, a 2005 InSAR image of the East African Rift showing the spectacular deformation accompanying recent eruptions, and the recently discovered ultrahigh-pressure terranes.

The book is designed as an advanced text and will certainly succeed in challenging even the brightest graduate students. The fact that it covers both metamorphic and igneous petrology may not increase its chances of adoption, as few instructors will be as competent in both subjects as the advanced level of presentation requires. Even at schools where advanced igneous and metamorphic petrology are taught as a single course, it is usually done by more than one instructor, each of whom has his or her own favourite texts. That won’t stop this volume from being an essential reference for professional/academic petrologists and geochemists.

Are there weaknesses in the book? In a sense it is a “classical” petrology text. The description of rock classifications and associations harks back to the era of Carmichael, Turner and Verhoogen, and the authors miss the opportunity to fully integrate the excellent fundamentals presented with plate tectonic environments, which, as we now recognise, dictate nearly all aspects of magmatism. Igneous practitioners will need to keep a copy of Wilson’s Igneous Petrogenesis (unfortunately now quite dated) alongside Philpotts and Ague to achieve the ideal mix of modern petrology–geochemistry–plate tectonics. Nevertheless, at less than $100, Principles of Igneous and Metamorphic Petrology is a “must-have” for any self-respecting petrologist.

Jon Davidson, University of Durham, UK

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<td>March 24–27</td>
<td>24th International Congress on Earth Sciences (ICE)</td>
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<td>21st International Conference on Crystallography</td>
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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.
Most readers would probably be very pleased to have just a mineral named after them, but Ove Balthasar Bøggild (1872–1956) must have been particularly popular with his peers, because he had a feast of things named after him. Bøggild was Professor of Mineralogy at the Mineralogical Museum of the University of Copenhagen, Denmark. His middle name (often spelt Belshazzar) is rather striking. The Old Testament story of Balthasar’s vast feast tells how, before a thousand guests, wives and concubines, the hand of God wrote on the wall, in a mysterious script, the awesome words ‘Thou art weighed in the balances, and art found wanting’. The phrase ‘the writing on the wall’, for obvious impending doom, has entered everyday speech. Much later, the early Christian church decided that one of the Three Wise Men was called Balthasar. Perhaps this was what was in the minds of Ove’s parents as they thought of names for their newborn son!

Bøggild is the man at the right of my monochrome picture, taken at Ivittuut (formerly Ivigtut) in southwestern Greenland in 1900, with his Greenlander crew. The man at the left is N. V. Ussing, who did pioneering and perceptive work on the exotic Ilimaussaq intrusion. Bøggild is nattily attired in a pork-pie hat and a wing collar. What else would one wear in the sub-Arctic summer? Ivittuut is best known as the only locality at which the important mineral cryolite has been mined (see Elements 5: 64), but the small granite and pegmatite body is the type locality of no less than 17 minerals, of which 6 have yet to be found elsewhere. Bøggild became the leading expert on the minerals of Greenland, publishing his 625-page Mineralogia Groenlandica in 1905, when only 33. The mineral Bøggildite, Na₂Sr₂Al₂(PO₄)F₉, from near the contact of the cryolite ore body, was named by the manager of the mine in 1952, to mark Ove’s 80th birthday.

He was an extremely skilful and careful crystallographer, and the microstructure in intermediate plagioclase feldspars that gives rise to the beautiful play of iridescent colours known as ‘labradorescence’ is now called the ‘Bøggild intergrowth’. He wrote a short book on this phenomenon, On the Labradorization of the Feldspars (1926), and showed, using optical goniometry, that it was caused by a planar feature. Because we can use electrons for microscopy, we now know that the iridescence is caused by coherent scattering of light by lamellar intergrowths of two plagioclases with different refractive indices, with a periodicity between 80 and 250 nm. The periodicity increases systematically with anorthite content, and the colour of the iridescence obeys Bragg’s law and changes from blue to red. Bøggild was the first to demonstrate that the common feldspar microcline is triclinic, using optical goniometry with astonishing accuracy on a single crystal of microcline from Greenland. He realised that microcline is usually macroscopically monoclinc, because of repeated fine-scale ‘tartan’ twinning.

But the thing for which I most envy Ove Bøggild is on a completely different scale. He has a fjord named after him, O. B. Bøggild Fjord. It is in the far north of Greenland, exactly on the 83rd parallel, almost as far north as it is possible to get on land. Its waters are permanently frozen, and the surrounding hills are draped by innumerable glaciers and small ice caps. The winter night is four months long, but during the four-month day that is its summer, little clumps of flowers, and even modest meadows, burst into life. Pure white, fluffy hares, unafraid, will run long distances to investigate the strange bipedal creatures that briefly and very infrequently invade their solitude. If I had the choice of being immortalized by a mineral name, a mineral intergrowth, or a fjord, I’d definitely go for the fjord!

Ian Parsons
University of Edinburgh, UK
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Oxygen isotope compositions of Ordovician to Early Silurian conodonts and brachiopods. Coloured band is SHRIMP II-derived data from conodont biocarbonate, compared to earlier calcite brachiopod and conodont data.

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