Glasses and Melts
Linking Geochemistry and Materials Science

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Linking Geochemistry and Materials Science
Georges Calas, Grant S. Henderson, and Jonathan F. Stebbins

The Structure of Silicate Glasses and Melts
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Geochemical Aspects of Melts: Volatiles and Redox Behavior
Harald Behrens and Fabrice Gaillard

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Structure–Property Relationships in Industrial and Natural Glasses
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About the cover: This spectacular photograph of the August 30, 2006 eruption of the basaltic volcano Piton de la Fournaise, Réunion Island (France), illustrates the intense activity of volcanoes. Magma viscosity is a major parameter for modeling volcanic eruptions, and may be explained by melt structure and dynamics and ultimately by the atomic motion of melt components. Like several other volcanoes around the world, the Piton de la Fournaise is monitored by a volcanological observatory, built in 1979. Photo courtesy Thomas Staudacher and Institut de Physique du Globe de Paris/OVPF
The Mineralogical Society of America is composed of individuals interested in mineralogy, crystallography, petrology, and geochemistry. Founded in 1919, the Society promotes, through education and research, the understanding and application of mineralogy by industry, universities, government, and the public. Membership benefits include special subscription rates for American Mineralogist as well as other journals, 25% discount on Reprints in Mineralogy and Geochemistry series and Monographs, reduced registration fees for MSA meetings and short courses, and participation in a society that supports the many facets of mineralogy. For additional information, contact the MSA business office.

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The Mineralogical Society of Great Britain and Ireland, also known as the MinSoc, is the international society for all those working in the mineral sciences. The Society aims to advance the knowledge of the science of mineralogy and its application to other subjects, including crystallography, geochemistry, petrology, environmental science and economic geology. The Society furthers its objects through scientific meetings and the publication of scientific journals, books and monographs. The Society publishes three journals, Mineralogical Magazine (print and online), Clay Minerals (print and online) and the e-journal MINARIS Online (launched in January 2004). For full details on how to join the Society and its events and publications, consult the Society’s website at www.minersoc.org or contact the general office.

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

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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. By 1962, the CMS was incorporated with the primary purpose of stimulating research and disseminating information relating to all aspects of clay science and technology. The membership includes those interested in mineralogy, crystallography, geology, geochemistry, physics, chemistry, biology, agronomy, soils science, environmental, materials science, and industrial science and technology. The CMS holds an annual meeting, workshop, and field trips, and publishes Clays and Clay Minerals and the CMS Workshop Lectures series. Membership benefits include reduced registration fees to the annual meeting, discount on the CMS Workshop Lectures, and Elements.

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The International Association of Geochemistry (IAGC) has been a pre-eminent international geochemical organization for over 40 years. Its principal objectives are to foster cooperation in, and advancement of, applied geochemistry, by sponsoring specialist conferences and the activities organized by its working groups, and by supporting its journal Applied Geochemistry. The administration and activities of IAGC are conducted by its Council, comprising an Executive and ten ordinary members. Day-to-day administration is performed through the IAGC Business Office.

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The Société Française de Minéralogie et de Cristallographie, the French mineralogy and crystallography society, was founded on March 21, 1878. The purpose of the society is to promote mineralogy and crystallography. Membership benefits include the “bulletin de liaison” (in French), the European Journal of Mineralogy and non-Member rates, and reduced registration fees for SFMC meetings.

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

This issue of *Elements* was already on track when I joined the editorial team, but it is the first issue for which I’ve played the role of principal editor. The experience has been interesting and enjoyable, and in some respects a trip down memory lane. Unbeknownst to most, I seriously considered a career in glass science (in industry) after finishing my PhD. My doctoral research on silicate melts had exposed me to the glass-science literature, and I was fascinated not only by the breadth and challenges of the field but also by its technological relevance. I have no regrets about having stayed in academia, but the reflections triggered by working on this issue made me realize that my career choice was somewhat accidental, having hinged on a critically timed postdoc offer from the Geophysical Laboratory. I was also reminded while working on this issue of the varied employment opportunities available to individuals holding PhDs in mineralogy, petrology, or geochemistry (MPG). These musings—and my continuing role as an advisor to graduate and undergraduate students—led to thoughts about advising future scientists in a sociopolitical climate not favorable to the basic sciences.

Funding for basic geoscience research in the U.S. and worldwide is currently very limited. This situation inevitably affects the everyday lives and careers of those of us who depend upon funding from government agencies to conduct research. Unfortunately, it also affects students, both directly, because we depend on contracts and grants to support them, and indirectly, because they detect the stress to the system and develop concerns about their own career choices and employment prospects. In this difficult climate, our advice to students considering careers in the geosciences becomes particularly important, whether they are beginning undergraduates or PhD candidates nearing degree completion.

First and foremost, we in the geosciences must not abandon our enthusiasm for our field or our efforts to inspire and encourage young people, directly and by example, to enter our profession. Even fleeting exposure to the news media will drive home the message that environment and energy are prominent national concerns, and the challenges in these fundamentally Earth-science areas are with us to stay. There are many roles for well-qualified MPG graduates in academia, government, and industry in addressing these challenges, so employment prospects are reasonably good if individuals are flexible about the nature and location of their employment. That said, I don’t think we should sell our science as a ticket to a job; rather, we should encourage nascent scientists at the undergraduate level to “be all they can be,” but at the same time not mislead them about the realities of the job market. The inspiration side of the picture is vitally important, too, because students who are passionate about their chosen field will do better at every level. I’ve known a few undergraduates who became inspired long before they enrolled in university—either by a “life-altering” observation (the Jupiter system through a telescope; the perfection of a natural crystal) or by a big, unanswered question (Is there life beyond our world?). Such students are relatively rare, especially at a practical place like Rensselaer. The more-typical potential geoscientist might be a student who likes science in general but hasn’t yet been inspired. Perhaps here we can do our jobs best by teaching what we’ve learned about the Earth (and the methods we use) while at the same time emphasizing what we don’t know yet. This approach might help a student see a place for him- or herself in working on or solving the important unanswered questions.

By definition, graduate students in MPG have already chosen an area of specialization in science, so here the question is how to help them maintain their enthusiasm, maximize their opportunities, and generally be successful in their career paths. With my own students, I try from the outset to convey my personal belief that “success” comes in many forms, and that they don’t have to be clones of myself (in terms of career choice) to be successful in my eyes—or their own. What is important is that potential PhD recipients learn how to think and work independently, to evaluate their own work and that of others with a critical eye, to conceive and design new research projects, and to take the next step in an effort already underway. There is nothing unusual in these words (most PhD guidelines probably use similar language), but the skills acquired to achieve the stated objectives can be applied in a wide range of areas, well beyond the walls of academia. The effectiveness of these skills on the job market can be maximized by gaining interdisciplinary exposure during the graduate education process through cross-sectional coursework or research. For MPG students, glass science is not a bad option (as the articles in this issue make clear), and exposure to materials science in general is invaluable, especially if you can get the prefix “nano” on your academic transcript. If I were to presume to advise students (other than my own!) in advanced-degree programs, I would say something like this: Pursue your graduate career with passion, determination, and an intellectually adventurous attitude. If you’re interested in basic research, be aware of the limited funding opportunities for “nonapplied” science, but don’t be dismayed by the situation—it is likely to change, and even today people with good ideas who persevere do obtain funding. The approaching criticality of
What’s New?

Several societies have expressed interest in participating in *Elements* and we expect that at least three become participating societies in 2007. Watch the next issue for an announcement. Our line-up for 2007 is complete—we will publish a 2007 preview in the December issue—and we are now discussing potential topics for 2008. Suggestions and proposals are always welcome.

**Elements at IMA meeting**

The International Mineralogical Association held its quadrennial meeting in Kobe, Japan, last July (see pages 316 and 317). *Elements* was present in the exhibit hall, thanks to the hard work of Adrian Lloyd-Lawrence, executive director of the Mineralogical Society, and the help of several members of participating societies. We are grateful for the presence at the stand of Vicki Loschiavo (MAC), John Rakovan (MSA), Barb Dutrow (MSA), Herta Effenberger (EMU), and MinSoc members Michele Warren (Manchester University) and Mark Welch (NHM). Adrian made all the arrangements and managed the stand. He reports the following.

Part of the IMA conference was an exhibition held in the main conference centre. Participating in this display of stands were 28 organisations, from booksellers through instrument manufacturers to consultancy services. The *Elements* magazine consortium of eight participating societies mounted a stand which was managed by the Mineralogical Society. As anticipated there was much interest in this relatively new publication which has been highly acclaimed internationally, and over a hundred sample copies were taken by interested conference delegates.

**Multi-Society Catalogue**

With this issue of *Elements*, you will find enclosed our 2007 multi-society catalogue. Please keep it, or forward it to a colleague, a student, or your library. If each of you encouraged a colleague or a student to join one of the participating societies, the mineralogy-geochemistry-petrology community would double instantly. Imagine our impact! Membership in any of the participating societies includes a subscription to *Elements*. *Elements* offers participating societies a way to promote their publications to a wider audience than their own membership, and this year seven of the societies “bought” pages of the catalogue.

**Thanks**

To guest editors Grant Henderson, Georges Calas, and Jonathan Stebbins, and the authors who contributed papers to this issue; to the society news editors of the participating societies; and to the other contributors to this issue, Jean Bédard, Henry L. Ehrlich, Peter Heaney, Andrea Koziol, and Takamitsu Yamanaka.

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**Environmental Impact of the Nuclear Fuel Cycle**

**GUEST EDITOR: Rodney C. Ewing**

(University of Michigan)

As the world faces the consequences of global warming caused by the use of fossil fuels, there has been a resurgence of interest in nuclear power. However, there is no “silver bullet”, and each energy-producing system produces waste. This issue of *Elements* will explore the interface between mineralogy and geochemistry and potential means to reducing the impact of radioactive waste from the nuclear fuel cycle.

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**Nuclear power and the nuclear fuel cycle**

Rodney C. Ewing (University of Michigan)

**Uranium mineralogy and its impact on neptunium mobility under oxidizing conditions**

Peter C. Burns and Amanda L. Klingensmith

(University of Notre Dame)

**Spent nuclear fuel**

Jordi Bruno (Enviros, Barcelona)

**Nuclear waste glass**

Bernd Grambow (Subatech Laboratory, Nantes)

**Ceramic waste forms for actinides**

Gregory Lumpkin (University of Cambridge)

**Uranium mine and mill tailings**

Abdelsalam Abdelouas

(Subatech Laboratory, Nantes)
The medical community has wrestled with the moral implications of this issue to a far greater degree than have Earth scientists. In 1999, the British Medical Journal disallowed anonymous review entirely; the editors concluded that secret peer evaluation is “slow, expensive, profligate of academic time, highly subjective, prone to bias, easily abused, poor at detecting gross defects, and almost useless for detecting fraud.”\textsuperscript{1} Subsequent studies have supported the feasibility of open review while disagreeing with some of these particulars. A controlled trial involving signed and unsigned reviewers for the British Journal of Psychiatry found that “signed reviews were of higher quality, were more courteous, and took longer to complete than unsigned reviews.”\textsuperscript{2} BMJ itself observed that the open system “significantly increased the likelihood of reviewers declining to review,”\textsuperscript{3} but the journal noted that this route is always a recourse for those who fear the personal repercussions of a signed negative evaluation.

The practical strengths and weaknesses of total transparency deserve further exploration, but the arguments against secrecy really are more of a principled nature. Reviewers of manuscripts are accountable to two constituents. First and most obviously, authors surely have some right to evaluate criticisms of their articles in a context that includes the quality of the reviewer. Is an expert in molecular dynamical simulations quibbling with the experimental technique? Is an avowed proponent of an anoxic early atmosphere ravaging a contrary model? Even when criticisms are wholly valid, intrinsic reviewer bias or limitation rightly plays a role in the recipient’s self-analysis.

In addition, reviewers are accountable to their public. In the US, scientists receive about $35 billion each year for the performance of basic and applied research. We are individually privileged with the responsibility for disbursing these funds, albeit indirectly, through peer evaluation of the papers that build reputations and of the proposals that map out future research directions. Although these decisions may appear less dramatic than the impeachment of a president, the ramifications of our collective judgments are not trivial. From the quashing of a career to the suppression of an idea that may ultimately save or enhance lives, the wrongful rejection of a scientific inspiration damages our society.

Nature announced this past June that it is running a several-month trial of the open review process.\textsuperscript{4} Papers that have been distributed to confidential reviewers will be posted on an open website. Anyone may contribute comments on-line while the standard review process occurs. The hitch: only signed reviews will be accepted. Final assessment of the paper will include both the confidential reviews and the on-line evaluations. The approach may not work for the society journals managed by the sponsors of Elements. Nevertheless, it is refreshing that high-end publications perceive that traditional modes of scientific assessment are themselves fit subjects for testing.

Recently, a paper of mine was evaluated by the American Mineralologist. Each of the two reviewers had scrutinized the paper with a fine-toothed comb, and they each found errors that would have proved acutely embarrassing to me had they been published. Nevertheless, the tone of the reviews never strayed from the respectful, and each reviewer offered constructive suggestions for repair. In short, they provided exactly the kind of feedback that one hopes for, and I wanted to send a personal note in thanks for their commentary. Unfortunately, I couldn’t do that, because the reviewers had taken my own advice and elected not to reveal their identities.

Maybe this is an article about fraud in science after all, but of a type in which we all have willingly conspired. The measurement of courage is an inexact exercise. Kennedy observes that Edmund Ross “faced the accusation that he accepted office under one banner and yet deserted it in a moment of crisis for another.”\textsuperscript{5} Certainly there are instances when anonymous review is the best recourse, but in an age when transparency of information is the stuff of revolution, perhaps we should model ourselves more closely after those who pronounced their opinions publicly and bravely faced the aftermath.

Peter J. Heaney
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\textsuperscript{1} Nature 407, 612 (2000).
\textsuperscript{2} BMJ 323, 545 (2001).
\textsuperscript{3} BMJ 323, 546 (2001).
\textsuperscript{4} Nature 407, 612 (2000).
SCIENCE IN THE GARAGE

I enjoyed very much volume 2, number 3 of Elements, which was devoted to water on Mars. The timely and thorough reviews are invaluable to help students learn about these exciting new developments. I have recently completed an experiment that has some relevance to water on Mars. The rover Opportunity, which still functions magnificently on the surface of Mars, has been sending back data that suggest magnesium sulfates are present on the surface of the planet. When I heard this I wondered what phase you would obtain when you crystallize magnesium sulfate from a saturated solution at subzero Celsius temperatures? My unheated garage in Kingston, Canada, was just the right temperature in early January, so I bought some epsom salts at the local drug store and put a saturated solution and a petrographic microscope in the garage. After a few days I had grown crystals that obviously were not the orthorhombic 7 hydrate, epsomite. What’s more, the crystals had tapered edges that are very similar to the voids observed using the microscopic imager on Opportunity. The phase diagram predicts a 12 hydrate. I managed to transport a crystal, packed in snow in a cooler, from my garage across town to the diffractometer lab and into the NERC’s cryostat. The crystal structure solution showed that the crystals were in fact MgSO\(_4\)·11H\(_2\)O. What is most interesting and relevant to the Martian surface is that this compound melts incongruently to a slurry of one mole of MgSO\(_4\)·7H\(_2\)O and four moles of water with a very low latent heat of fusion. If there was a deposit of MgSO\(_4\)·11H\(_2\)O on the Martian surface, it could incongruently melt and rapidly evolve large amounts of water, which could explain some of the outwash features and chaotic terrain observed on Mars. Who says you can’t do science in your garage anymore? MgSO\(_4\)·11H\(_2\)O is predicted as a valid mineral species on Earth where magnesium sulfate crystallizes near 0°C. This work will appear in the November issue of Geology.

Ron Peterson
Queen’s University, Kingston, Ontario, Canada

REFERENCES


FÉLICITATIONS

J’en profite pour vous dire que le travail éditorial sur Elements est fantastique. C’est une des seules revues scientifiques que je lis en entier, du début à la fin. En fait, la raison principale pour laquelle je suis devenu membre de l’Association minéralogique du Canada est de m’assurer que je ne manquerais pas de numéro d’Elements. Bravo!

Dr. Yvan L’Heureux
Département de physique, Université d’Ottawa, Canada

IN PRAISE OF POLARIZED LIGHT MICROSCOPY

As the general secretary of the Russell Society, I am fortunate to be the recipient of a copy of Elements. In addition to the fascinating articles on the early Earth in the August 2006 edition, an interesting article by Dan Kile extolled the virtues of polarized light microscopy (PLM) and its decline in geoscience education. Perhaps the only benefit of this reduction in the teaching of PLM in colleges and universities has been the appearance of reasonably high-quality polarized light microscopes on the secondhand market; some of these microscopes have been purchased by members of the amateur mineralogical community. In the UK, and there are no doubt equivalent groups in other countries, a number of members of the Russell Society and the British Micromount Society have been wrestling with the intricacies of their microscopes and, whilst most of us have had little or no formal training in the use of PLM, some of our more-experienced members (Max Wirth and Don Blake) have summarised the ways in which PLM may be used in the process of mineral identification (usually as slides of ~30-micron mineral grains in epoxy resin). Using these summaries and the standard textbooks, together with micro-chemical techniques, the number of possibilities for an unknown mineral can be markedly reduced, and in some cases the process of mineral identification can be relatively straightforward. This approach can be of particular value to the amateur mineralogist as it can reduce the number of times that more sophisticated analytical methods need to be used. Bearing these points in mind, I agree with Dan Kile that it is important that PLM remains an active component of mineralogical, petrological and analytical courses so that specialists in this useful technique continue to be available to provide instruction and support for both professional and amateur mineralogists.

Frank Ince
Leicester, United Kingdom

ELEMENTS IN THE CLASSROOM

I received my Elements magazine this month and found it to be an exceptional volume! I wonder if it might be possible to purchase 30 individual copies of this issue, so that I may use it in my astrobiology class at the University of Hawaii.

Karen Meech, Director
University of Hawaii NASA Astrobiology Institute, USA

Editors’ reply: Yes indeed it is possible to order extra issues to use in the classroom. It was certainly envisaged by founding editor Rod Ewing that these collections of thematic papers would be ideal to use in the classroom. We are thrilled to see it happening.

Check our website

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Donald B. Dingwell received his BSc (1980) in geology and geophysics from the Memorial University of Newfoundland and his PhD in geology at the University of Alberta (1984). After two years as a Carnegie Research Fellow at the Geophysical Laboratory and one year at the University of Toronto, he became the assistant director of the newly founded Bavarian Geo-institute. In 2000 he was appointed to the Chair in Mineralogy and Petrology at the Ludwig-Maximilians-University of Munich. Dingwell’s principal research interest is the physicochemical nature of molten rocks and their impact on volcanic systems. For his scientific contributions, he has received awards and prizes from the German Mineralogical Society (DMG), the German Research Society, and the Mineralogical Society of America (MSA).

Harald Behrens is a researcher at the Institute for Mineralogy at the University of Hannover. After studying physical chemistry, he switched over to the fields of experimental petrology and geochemistry. One of his major interests is the interaction of volatiles with silicate minerals and melts. Structure and properties of glasses and melts, kinetic processes in magmatic and metamorphic systems, and weathering reactions of minerals and rocks are other research interests. Although he is working mainly as an experimentalist, more than 80 published papers demonstrate his ability to apply experimental studies to various problems in geoscience and materials science.

Georges Calas is a professor of mineralogy at the Université Paris VI and deputy director of the Institute of Mineralogy, Universités de Paris VI et VII, Institut de Physique du Globe de Paris and CNRS. He is affiliated with the Stanford Environmental Molecular Science Institute. His research focuses on how the molecular-scale organization of minerals, glasses and melts controls their properties. He applies his research in the Earth and environmental sciences and materials sciences by using a combination of solid-state spectroscopic methods, X-ray and neutron diffraction and numerical modeling. A former president of the Société française de Minéralogie et Cristallographie, he is a Fellow of the Mineralogical Society of America.

Fabric Gaillard has been carrying out research at ISTO, CNRS, Orléans, France, since January 2005. His current research interests center on volatiles and magmas, with specific applications to redox equilibria in the early solar system and the effect of volatiles on the geophysical properties of magmas. From 1998 to 2004, at Orléans and at the Bayerisches Geoinstitut, Bayreuth, Germany, he studied redox processes in silicate glasses and melts. With most of his work focused on the thermodynamic properties of redox equilibria involving iron in hydrous amorphous silicate and, later, on the transport properties of water-derived species and electrical conductivity as functions of pressure and temperature. His expertise is largely inherited from the continual experimental and conceptual developments at Orléans led by M. Pichavant, B. Scaillet and J. Roux.

Bruce Marsh is interested in all the physical and chemical aspects of the generation, extraction, collection, ascension, emplacement, and eruption of magma. He enjoys blending field geology with complementary laboratory experiments and theoretical analyses. At the same time, he maintains a keen appreciation of the people, history, and art of doing science in all fields of natural science and exploration. He was born and raised in the woods of the Upper Peninsula of Michigan and received his education in geology, geophysics, and geochemistry at Michigan State (BSc), Arizona (MSc), and Berkeley (PhD). He has been on the faculty at Johns Hopkins University since 1974. His present principal field areas are the McMurdo Dry Valleys of Antarctica and the Sudbury impact feature.

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Silicate melts are major components of magmatic activity and of its most spectacular expression, volcanic eruptions. The “hidden part” is even more fascinating, as silicate melts are directly involved in matter and heat transfer within the Earth and planets. Silicate glasses, often investigated as a frozen picture of their molten counterparts, are also materials of major importance in technology. Despite the difficulties in rationalizing physical and chemical properties of glasses and melts, due to an incomplete knowledge of their structure, major progress has been made recently in synthetic and natural systems. This issue of *Elements* reviews the properties of silicate glasses and melts from the molecular to the field scale. It includes insights into their technological applications and describes some recent advances this fast-evolving field.

**Keywords:** magmas, volcanology, geochemistry, glasses, silicate materials

**INTRODUCTION**

Silicate glasses and melts have been of interest to mineralogists, geochemists, and igneous petrologists for many decades. Silicate melts are essential components of igneous processes, participating actively in Earth differentiation, heat transfer and global geodynamics, and geochemical cycles. Melt viscosity can decrease some 20 orders of magnitude below that of corresponding solids, and timescales for transport properties are dramatically reduced in the presence of a liquid phase. In addition, melts relevant to volcanological processes contain various amounts of volatiles, mainly H$_2$O, CO$_2$, and sulfur-bearing species. Models for Earth’s formation propose a period of substantial melting of the planet during the later stages of accretion, due to the extremely high energies involved in a probable Moon-forming “giant impact” event. As properties of deep magmas must be experimentally constrained, researchers studying melts and glasses participate actively in current experimental developments in Earth sciences, such as in situ experiments at high temperature (T) and high pressure (P) and numerical modeling of complex systems. Many of these experiments are designed to aid in developing an understanding at the atomic level of the structure and dynamics of silicate melts under the P–T conditions of Earth’s crust and mantle. Current issues range from the conditions of formation of planetary systems to volcanological monitoring and Earth’s dynamics.

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The structure of glasses and melts depends on their chemical composition. To a first approximation, a silicate glass or melt can be understood as a network of tetrahedra (Fig. 1a) bonded by non-bridging oxygens to network-modifying cations, such as Na\(^+\) and Mg\(^2+\), which depolymerize the silicate network. However, in the presence of trivalent tetrahedral cations, such as Al\(^3+\) and B\(^3+\), cations are charge compensators and then contribute to increasing the connectivity of the network. This connectivity, defined by the relative abundances of Q\(^3\) species, has a strong influence on the viscosity of silicate melts and other melt properties. The lack of periodic structure and disorder effects are a major limitation for the structural description of silicate glasses and melts. Figure 1b shows how disorder can act in the absence of a periodic structure: silicate tetrahedra are free to rotate, which causes a loss of information over the medium-range structure scale. Numerical modeling provides the possibility of describing the structure of multicomponent glasses. It confirms recent experimental observations that the structure of most glasses and melts, in contrast to silica and other network glasses, e.g. glasses of feldspar composition, is not simply the continuous random network illustrated in the majority of textbooks. Figure 1c represents the simulated structure of a borosilicate glass and illustrates the heterogeneous distribution of cations (Henderson et al. 2006).

A direct visualization of the existence of well-defined sites in silicate glasses is provided by the magnificent coloring of medieval stained glass: the optical absorption bands arising from crystal field effects indicate the oxidation state and site geometry of transition elements (Fig. 2).

**MELTS AND GLASSES**

Any liquid might become glassy if cooled rapidly enough. The glass transition is characterized by a change in thermodynamic properties (e.g. heat capacity), from solid-like to liquid-like values, with changing temperature. The glass transition temperature depends on thermodynamic and kinetic parameters (Wong and Angell 1976). Glasses provide a frozen image of the melt “structure” at \(T_g\); in the reverse direction, a glass gradually softens to a molten state above \(T_g\). This property is at the origin of glass making. Blowing the supercooled liquid remains a dramatic aspect of the glass craft industry. Figure 3 depicts the progressive cooling of an industrial silicate melt.

As a melt is cooled, its structure rearranges more and more slowly. At some point (if crystallization is avoided by slow kinetics), the rate of this ordering process can no longer keep pace with the rate of cooling. The melt falls out of equilibrium, forming a glass, with the melt structure “frozen in” at a certain “fictive temperature” (\(T_f\)). Faster cooling thus leads to a higher \(T_f\), allowing the melt structure to be sampled over a range in temperatures and studied conveniently and precisely at ambient temperature. This method is limited to the experimentally obtainable

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**GLOSSARY**

- **Amorphous material**: A solid that lacks a periodic crystalline structure, i.e. it lacks translational symmetry, or a liquid.
- **Bridging oxygen (BO)**: Oxygen atoms that are shared between two network formers.
- **Charge compensator**: A cation or anion that is in close proximity to another cation or anion in order to provide an overall neutral charge to a polyhedral unit, e.g. Na\(^+\) charge compensates Al\(^3+\) near [AlO\(_4\)\(^2\)] tetrahedra.
- **Clusters**: Small groupings of atoms or polyhedra that have some sort of directionality or non-randomness associated with them.
- **Disorder (structural)**: Applied to arrangements of atoms that cannot be described by well-defined bond angles and distances and/or random distributions of adjacent cations or anions.
- **Fictive temperature \(T_f\)**: The temperature at which a liquid was last in thermal equilibrium during cooling to form a glass. It therefore characterizes the thermal history of the glass and is higher for more rapid cooling.
- **Glass**: An amorphous material that exhibits the glass transition.
- **Glass transition**: A relatively narrow temperature region over which second-order thermodynamic properties, such as heat capacity and thermal expansivity of a glass, decrease from liquid-like to solid-like values.
- **Glass transition temperature \(T_g\)**: A specific point on the temperature curve of a glass property measured at a standard heating rate; often associated with a viscosity of 10\(^{12}\) Pa.
- **Intermediate cation**: Cations that may act as either a network former or a network modifier depending upon coordination number.
- **Magma**: A naturally occurring high-temperature melt, generally containing dissolved gases and often mixed with bubbles or crystals or both.
- **Medium- or intermediate-range order (MRO, IRO)**: Structural arrangement out to a radial distance that incorporates nearest neighbors. This arrangement can also incorporate polyhedral organization such as rings.
- **Melt**: Hot molten material found in magmas.
- **Network**: A three-dimensional structure composed of network formers. It may or may not be continuous, ordered or disordered.
- **Network former**: Cations that bond to bridging oxygens to form the network. They usually have coordination numbers of 3 or 4.
- **Network modifier**: Cations that disrupt the network and produce non-bridging oxygens. They usually have a coordination number of 6.
- **Non-bridging oxygen (NBO)**: Oxygen atoms that are bonded to only one network former.
- **Order (structural)**: Applied to arrangements of atoms that can be described by well-defined bond angles and distances and/or random distributions of adjacent cations or anions.
- **Polyamorphism**: Two liquids or glasses with the same composition but different structures.
- **Polymerization**: The bonding together of polyhedral units to form two- and three-dimensional structures.
- **Q\(^n\) species**: A network former that has 0 to 4 bridging oxygens \((n = 0–4)\) bound to the cation.
- **Short-range order (SRO)**: Structural arrangement out to a radial distance that incorporates nearest neighbors.
- **Topology**: The interconnections between atoms that describe the network.
range of cooling rates (six to eight orders of magnitude), which fixes the obtainable range of $T_f$ to generally only about 150 to 250K above the “normal” (slow cooled) $T_g$ (Dubinsky and Stebbins 2006).

An important property is the excess volume of silicate melts relative to their crystalline counterparts, as this property is crucial to magma ascent through the mantle and crust. However, at high pressures, the high compressibility of melts may lead to important density inversions. For example, perovskite may be neutrally buoyant in a chondritically derived liquid at the core–mantle boundary in a deep magma ocean (Miller et al. 1991).

Understanding melt thermodynamics is important, as the free energy is needed to calculate phase equilibria. However, changes of melt structure with increasing temperature are indicated by the observation that liquid-state heat capacities and thermal expansions are generally considerably higher than the solid-like values of glasses, requiring significant “configurational” components (Mysen and Richet 2005). These must be considered to develop accurate structure-based models of melt properties.

**The Dynamics of Silicate Melts**

Silicate melts are not static mixtures of silicate polymer species and cations, but contain dynamic, rapidly exchanging chemical environments, with bond-breaking and ionic exchange between structural units occurring on a timescale comparable with those of viscous flow and chemical diffusion. In particular, the Adam-Gibbs theory of relaxation allows a quantitative link to be made between the timescale for viscous flow and the configurational entropy of the melt (Mysen and Richet 2005). Silicate melts are viscoelastic liquids, with a finite relaxation time related to dissipation of the strain induced by chemical, mechanical or thermal stress. Relaxation time increases with decreasing temperature down to the glassy state.

A schematic diagram of an oxygen-diffusion mechanism is shown in **Figure 4A** (Farnan and Stebbins 1994). The diffusion mechanism is initiated when a non-bridging oxygen of the SiO$_4$ tetrahedron $A$ (probably with three other bridging oxygens) impinges on a tetrahedron $B$, where all oxygens are bridging oxygens (e.g. to tetrahedron $C$ among others). In this situation, $B$ transforms to an intermediate five-fold-coordinated species ($[^5]$Si, step 1). Diffusion occurs when $[^5]$Si dissociates, and an oxygen that was initially bonded to $B$ (e.g. green circle) is now associated with a neighboring tetrahedron such as $C$ (step 2). The increase of higher-coordinated species is consistent with increasing diffusivity in the liquid, which implies that viscosity decreases, since diffusivity and viscosity are inversely correlated. These atomic-scale mechanisms are at the origin of important transport properties, such as diffusivity or viscosity (Fig. 4a).

**IN THIS ISSUE**

In the articles that follow, the unique structures and properties of glasses, melts, and magmatic systems are further explored. Grant Henderson, Georges Calas and Jonathan Stebbins provide insight into the peculiar aspects of the atomic-scale structure of glasses and melts, including the major changes observed at high temperature and at high pressure. Harald Behrens and Fabrice Gaillard discuss the
influence of volatiles on the properties of silicate melts. They show how the speciation of these volatiles affects their solubility, the rheology and redox state of magmas, and the stability of minerals. The parameters controlling the transport properties of magmas, mostly diffusion and rheology, are addressed in the article by Don Dingwell. He brings attention to the major experimental and theoretical advances in viscous behavior and diffusion, which give a new perspective on magma migration and volcano dynamics. Bruce Marsh discusses the dynamic aspects of magmatic systems, setting this question in a historical perspective. Field studies, including investigations on the fascinating Sudbury complex, provide the real-scale validation of laboratory experiments and outline pertinent parameters, such as marginal solidification fronts and magma ascent. The final contribution presents examples of properties of industrial and natural glasses. Laurence Galoisy emphasizes the role of transition elements in defining glass coloration and stability, and in defining the formation conditions of volcanic and impact glasses.

Silicate glasses and melts play a critical role in many geological and technological processes. From the molecular to the planetary scale, they constitute a broad though still largely unknown universe, in which the mineralogist, the geologist, and the materials scientist must often find original ways to solve the many questions that are still open. This issue of *Elements* shows the rapid progress that has been made recently. We hope it will encourage young scientists to enter this fascinating field!

**ACKNOWLEDGMENTS**

We thank the authors of the articles presented in this issue, who give a synthetic and interdisciplinary view of the complex world of glasses and melts. Editors Pierre Tremblay and Bruce Watson are thanked for their efforts in bringing this issue together. This is IPGP contribution #2156.

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The Structure of Silicate Glasses and Melts

Grant S. Henderson,1 Georges Calas,2 and Jonathan F. Stebbins3

Much progress has been made in elucidating the complex structures of silicate glasses and melts. X-ray and neutron scattering, spectroscopy, and theoretical calculations now provide a reasonably clear picture of many aspects of the short-range structure of glasses (which approximates the melt structure at the glass transition temperature). Critical effects of redox conditions and volatiles on structure have been clarified. Qualitatively, links between structure and properties such as molar volume, entropy, cation partitioning, and viscosity have been established, but quantitative connections remain challenging. Effects of temperature and pressure on structure have been the subject of much recent work.

**Keywords:** melts, structure, properties, cations, heterogeneous, coordination, polymorphism

**INTRODUCTION**

Glasses and melts have unique physical and chemical properties, which vary as a function of temperature, pressure, and chemical composition. Understanding these properties requires an accurate structural description. The amorphous nature and complex chemical composition of glasses and melts do not allow the construction of a unique, crystal-like structural model. Nevertheless, despite the lack of periodicity and long-range order, glasses and melts retain a characteristic short-range order, which obeys basic crystal-chemical rules. However, only a limited amount of information exists about changes in glass structure with temperature or pressure. Obtaining this information requires a combination of experimental and theoretical approaches. The connections between structural observations and melt properties are less well known, even at the qualitative level, although progress has been and continues to be made. Melt structure, properties, and dynamics were reviewed a decade ago (Stebbins et al. 1995) and are discussed in detail in a recent book (Mysen and Richet 2005); we provide here only a few examples.

**DETERMINING THE STRUCTURE OF MELTS AND GLASSES: A COMBINATION OF STRUCTURAL METHODS AND NUMERICAL MODELING**

The structure of melts and glasses is primarily determined from diffraction (scattering) and spectroscopic methods. These techniques have benefited from the development of user facilities, such as synchrotron and neutron sources (see Elements volume 2, issue 1). Due to the lack of periodicity, neutron and wide-angle X-ray scattering result in one-dimensional information, but give access to interatomic distances, bond angles, and coordination numbers (Brown et al. 1995). Chemically selective spectroscopic methods, such as nuclear magnetic resonance (NMR) spectroscopy, X-ray absorption spectroscopy (XAS), optical absorption spectroscopy, and Mössbauer spectroscopy, are sensitive to the local geometry, site symmetry, and the nature of the chemical bonds (see Hawthorne 1988). We will focus mostly on XAS (see e.g. Brown et al. 1995; Henderson 2005) and NMR (Stebbins et al. 1995). Most methods that have been applied to glasses have now also been used to investigate melts at high temperatures, in spite of their associated experimental challenges and loss of sensitivity and/or resolution. In addition, there is an increasing number of structural studies of glasses and melts at high pressure.

Numerical simulations (ab initio and classical molecular dynamics (MD) and Reverse Monte Carlo (RMC) simulations) are also used to gain insights into the possible atomic-level structure of glasses. The advantage of these approaches is that they provide access to the melt structure and atomic mobility at temperatures and pressures not reachable with experimental methods. Furthermore, RMC simulations can improve the analysis of the theoretical results by allowing the extraction of three-dimensional atomic models from the data that are in quantitative agreement with experiment.

**Networks**

Decades of experimental evidence have shown that the tetrahedron is the basic structural unit of silicate glasses. The tetrahedra have a well-defined geometry and are linked to each other through their corners in a manner similar to the connection between tetrahedra in crystalline SiO2. Beyond adjacent tetrahedra, the medium- or intermediate-range structure contains rings of tetrahedra and other interconnected units whose exact structures are not well understood. The addition of a network modifier (such as an alkali oxide) results in the generation of non-bridging oxygens and distributions of Q species (see glossary p. 266) within the structure, which have been quantified by Raman and NMR spectroscopy (cf. Stebbins et al. 1995). The distribution of Qn species in silicate glasses is governed by equilibria in the precursor liquids:

\[ 2Q^n \leftrightarrow Q^{n+1} + Q^{n+1} \ (n = 3, 2, 1) \]
where the extent of the reaction depends on the type of modifier, temperature, and pressure. These distributions make important contributions to the overall order/disorder (i.e., entropy, hence free energy) of the melt, as does mixing or ordering among different types of network cations (e.g., Si, Al). Modifier cations interact with the silicate network in ways that are still poorly known. However, the local structural environments around many cations are now relatively well understood.

**The Peculiar Structural Organization Around Cations in Glasses and Melts**

In silicate glasses, an intriguing picture is given by the peculiar geometry of cationic sites, the relationships between modifier and “intermediate” cations and the glass network, and evidence of a non-homogeneous distribution of such cations. Cation site geometry is often well defined, but cation coordination numbers are generally lower in glasses than in corresponding crystals. Some cations resemble network formers by occurring in tetrahedra connected to the polymeric network: such is the case for tetrahedral Ni$^{2+}$, Zn$^{2+}$, and Fe$^{3+}$. Other cations such as Ca$^{2+}$ and Sr$^{2+}$ are 6- or higher-coordinated and act as network modifiers. An interesting case is presented by Zr$^{4+}$, which occurs in regular octahedral coordination in glasses with local charge compensation (Farges et al. 1991). This unusual coordination, encountered in alkali zirconosilicates, was previously suspected from Zr geochemistry (Watson 1979).

An unusual feature of glass structure is the frequent occurrence of 5-fold coordination (cf. Fig. 1A). For example, in silicate glasses, $^{91}$Ti coexists with $^{48}$Ti, their relative proportions depending on glass composition (Henderson and Fleet 1995). Five-coordination has now been recognized for a wide range of cations, including Mg$^{2+}$ (George and Stebbins 1998), Ni$^{2+}$ (Galoisy and Calas 1993), and Fe$^{3+}$ (see e.g. Jackson et al. 2005), as well as for network cations (Al and Si) in glasses quenched from high-pressure melts (Stebbins et al. 1995; Allwardt et al. 2005).

The same cation may be located in two or more different sites. This is more conveniently observed by symmetry-sensitive spectroscopic methods than by site-averaging diffraction methods. For instance, the presence of low-field-strength cations (i.e. K$^+$) can increase the mean coordination number of the coexisting cations. These can compete more effectively for oxygen ligands, in some cases clearly affecting partial molar volumes of melt components (Liu and Lange 2001). A similar effect has also been noted for five-coordinated Al in both ambient- and high-pressure glasses (Allwardt et al. 2005). The chemical dependence of cation speciation may directly affect mineral/melt partition coefficients, as well as mineral component activities and thus solubilities. In the specific case of transition elements, crystal field splitting energy is also dependent on glass/melt chemistry.

The medium-range organization of cations involves a heterogeneous distribution with a clear structural ordering revealed by cation–cation distances. This information may directly affect mineral/melt partition coefficients, as well as for network cations (Al and Si) in glasses quenched from high-pressure melts (Stebbins et al. 1995; Allwardt et al. 2005).

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**Oxygen Surroundings: A Sensitive Witness of Glass Structure**

Recently, a complementary view of glass structure has been obtained using methods that reveal the local structure around anions in glasses and melts, especially the all-important oxide ion. Two-dimensional, “triple-quantum magic-angle spinning” (3QMAS) NMR of $^{17}$O has been especially interesting, as it can directly quantify the extent of ordering (e.g. “aluminum avoidance”) among network components Si, Al, and B (Lee and Stebbins 2000) and of modifier cations around non-bridging oxygens. Another approach is oxygen K-edge XANES, which is proving to be useful where other methods are not available to directly measure network cation coordination, such as for Ge in alkali germanate glasses (Wang and Henderson 2004). Here, the electronic processes responsible for the oxygen XANES are strongly influenced by the cationic environment, and consequently the O K-edge XANES is sensitive to changes in the coordination geometry and environment of the cation bound to the oxygen.
FROM GLASSES TO MELTS

When glasses are heated through their glass transition temperatures (T_g ranging from about 450 to 800°C for most anhydrous silicates), values of the second-order thermodynamic properties increase abruptly. For example, increases in heat capacity at constant pressure (C_p) are typically 10 to 50% (cf. Angell et al. 2000). The glass transition marks the transformation from a disequilibrium amorphous solid to a metastable supercooled liquid. Because the heat capacity just below T_g is commonly near the classical vibrational limit of three times the gas constant R per mole of atoms, the “extra” C_p at higher temperature is thought to be the consequence of additional energy being added to change the structure of the liquid via the onset of dynamic bond breaking and an increase in disorder. When integrated up in temperature from T_g to stable melting points, this “configurational” contribution to thermodynamic properties is often large. For example, the enthalpy and entropy differences between diopside (CaMgSi_2O_6) and the corresponding liquid at the equilibrium melting point are about twice those between the crystal and the glass at T_g. While it has long been appreciated by those modeling the properties and phase equilibria of magma systems that data for liquids, not just glasses, must be included, it is perhaps less well appreciated that the inherent nature of this distinction is that the liquid structure must change significantly with temperature. Extrapolation from studies of glass structure to models of melts at high temperature is thus a key problem.

Perhaps the most intuitive connection between melt structure and critical thermodynamic properties is the entropy associated with structural disorder. Just as in models of site mixing in solids, we can imagine the mixing of various structural units in molten silicates, which gives rise to a configurational contribution to the entropy. Similar concepts connect the configurational components of the thermal expansivity and compressibility to the large, decidedly non-ideal-like effects of temperature and pressure on the densities of molten silicates (Richet and Neuville 1992).

Free energy is at the heart of calculations of magmatic phase equilibria; enthalpy is at the center of models of heat flow and transport. The configurational entropy bears obvious relations to these thermodynamic properties through the heat capacity, but a direct connection to a transport property such as viscosity is less obvious. Nonetheless, it has been known for some time that liquids with large heat capacity increases at T_g also show the most rapid decreases in viscosity just above T_g, as well as the most pronounced upward curvatures on plots of the logarithm of viscosity versus inverse temperature, i.e. “non-Arrhenian” behavior (Angell and Sichina 1976). The result is differences in viscosities at high temperatures that vary by many orders of magnitude from one magma composition to another. Remarkably, for silicate liquids a quantitative link between the configurational entropy and viscosity has been demonstrated for many systems via the “Adam-Gibbs” relationship (cf. Richet and Neuville 1992 and references therein). Thus, the structural basis of the configurational disorder and the effect of temperature upon it become critical to explaining and predicting a host of chemical and physical processes involving magmas.

STRUCTURAL MODIFICATIONS WITH TEMPERATURE

A simple alkali silicate melt such as Na_2SiO_3 might contain only Q^3 units. However, results from Raman (Mysen and Richet 2005) and 29Si NMR spectroscopy (Stebbins et al. 1995) demonstrate that the glass network is more disordered than this and is better described by reactions of the type 2Q^3 = Q^2 + Q^4. If these species mix randomly, they could account for as much as half of the entropy difference between glass and crystal at T_g. Further NMR studies on glasses prepared with varying cooling rates demonstrate that the reaction moves to the right at higher temperature, making an important (but by no means dominant) contribution to the configurational heat capacity (Majerus et al. 1995). In situ high-temperature Raman studies have confirmed this type of change and have greatly extended the temperature and compositional ranges explored (Mysen and Richet 2005). Temperature-induced changes in the networks of alkali silicate melts, possibly reflecting changes in ordering at intermediate length scales, have also been reported from in situ neutron diffraction (Majerus et al. 2004a).

The tetrahedral networks of magmatic liquids are dominated by interconnected SiO_4 and AlO_4 tetrahedra. Just as Si-Al order/disorder is a key variable in the thermodynamics and phase equilibria of crystalline feldspars and other minerals, it is likely to be important to the properties of melts, although most models of free energies have perforce assumed ideal and thus fully random mixing. Aluminosilicate melts often show anomalous heat capacities, suggesting a role for changes in Si-Al ordering (Mysen and Richet 2005). In Ca-, Li-, and Na-aluminosilicate glasses, 29Si and 17O NMR demonstrate that at least in melts at T_g, “aluminum avoidance,” although far from complete, can cause considerable ordering (Lee and Stebbins 2000). The increase in disorder with higher temperatures, which was predicted by statistical mechanical modeling, was recently quantitatively confirmed by studies of glasses with varying cooling rates and thus varying fictive temperature (Figs. 2a and 2b) (Dubinsky and Stebbins 2006). Increases in the randomness of mixing with temperature may account for as much as about half of the configurational heat capacity at T_g in aluminous melts such as NaAlSiO_4 but probably cannot explain their increases in C_p at higher temperature.

Increasing temperature causes important structural modifications for cations, such as site thermal expansion, local disorder, and enhanced rates of motion. A recent quantification of the thermal expansion in glasses has indicated values similar to those encountered in minerals (Calas et al. 2006), a confirmation that cations organize their own surroundings in glasses and melts. These effects are enhanced for alkalis due to a low ionic potential and large bond thermal expansion. In the melt and supercooled liquid, alkali motion is decoupled from the structural relaxation of the network without discontinuity through the glass transition (Majerus et al. 2004a). Despite these modifications, the modified random network model still prevails in silicate melts, as in the corresponding glasses. With the temperature-enhanced mobility of alkalis, some cations undergo coordination changes in melts and supercooled liquids: in this case, the glass can no longer be considered as a frozen image of a silicate melt. Recent in situ high-temperature studies have detected changes in the coordination numbers of transition metals and other cations between glasses and high-temperature melts. For example, XAS studies of nickel cations in a variety of glasses and melts have indicated a decrease in the Ni coordination number at higher temperature (Farges et al. 2001). In contrast, in situ NMR has suggested increases with temperature in the average coordination number and/or cation–oxygen bond distance for Na, Mg,
and Al in melts (George and Stebbins 1998), possibly as energetically less favorable, larger sites are explored by rapidly diffusing cations. Experimentally daunting, in situ structural studies of hydrous melts at simultaneous high pressure and high temperature have recently been carried out using externally heated diamond anvil pressure cells (Wilke et al. 2006). Some of these studies provide important new insights into the petrologically critical problem of temperature effects on water speciation in melts, which controls solubility and thus many eruptive processes (Behrens and Gaillard 2006).

**PRESSURE-DRIVEN TRANSFORMATIONS**

Pressure-induced structural transformations of glasses and melts are of major interest for understanding the geophysical properties of deep magmas. While modifier cations may also be affected, the most dramatic consequences of these transformations involve the silicate network. These may be at the origin of the densification of glasses and melts at high pressure, the latter having major consequences for magma transport and differentiation (cf. Stebbins et al. 1995 and references therein; Allwardt et al. 2005). The difficulty comes from the prediction of the changes in melts at high pressure and temperature (as opposed to recovered glasses) and from the partial reversibility of the pressure-induced coordination changes, particularly in glasses that are compressed at ambient temperature only. In situ measurements are thus especially important but are particularly difficult on high-temperature and high-pressure melts. Some structural modifications may be quantified using high-pressure XAS measurements on germanate analogs. The Ge coordination change in the tetrahedral framework of $\text{SiO}_2$–$\text{GeO}_2$ glasses depends on composition and occurs at higher pressure and over a broader pressure range as the $\text{SiO}_2$ content increases (Fig. 3). XAS data agree with a model based on a mixing of $\text{[4]}\text{Ge}$ and $\text{[6]}\text{Ge}$, in agreement with a kinetically hindered, first-order transformation at room temperature (Majérus et al. 2004b). Furthermore, 5-fold Ge ($\text{[5]}\text{Ge}$) appears not to be significant, although further work needs to be done.

“Polyamorphism,” implying a relatively abrupt structural change, is a widely discussed topic for silicate glasses and melts at high pressure (McMillan 2004). For example, $\text{SiO}_2$ glass appears to undergo polyamorphic transitions at 8 and 28 GPa (Inamura et al. 2004), with that at 8 GPa resembling the crystalline $\alpha$–$\beta$-cristobalite transition. Spectroscopic studies of glasses quenched from high-pressure and high-temperature melts are beginning to provide insights into mechanisms of structural changes in melts, although at best they record the structure at $T_f$ and may undergo some still incompletely known structural changes during decompres-
sion. NMR studies of alkali and calcium silicate glasses from pressures to 10 or 12 GPa clearly record increases in Si coordination (Stebbins et al. 1995); in aluminosilicates the recovered structural changes are dominated by the development of five- and six-coordinated Al (Lee 2004; Allwardt et al. 2005). Observed structural changes are often well correlated with measured density increases, providing a good prognosis for future structurally constrained models of melt properties (Ghiorso 2004; Stixrude and Karki 2005).

FINAL THOUGHTS

We have not addressed here many of the fascinating structural questions that have direct bearing on the behavior of melts in nature and in technology. For example, intermediate-range order, involving organization on nanometer and longer length scales, is still a major challenge but must be of critical importance to kinetics of crystal nucleation and diffusive transport. For the mechanisms that control dynamical processes such as viscous flow, only tantalizing experimental glimpses have been obtained for the simplest systems; an example is the role of transient, high-coordinated Si in bond exchange in alkali silicates (Stebbins et al. 1995). The structural understanding of component activities in melts, or the effect of melt structure on trace element partitioning, are long-lasting questions, which make a link between molecular-scale and global processes. For these examples and many others, development of new and improved experimental techniques and of new analytical capabilities, as well as the making of in situ high P and T measurements and the application of advanced theoretical methods, are providing major insights. The further development of such approaches can only benefit our understanding of these intriguing and complex materials.

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Geological Society Geology of Series

The Geology of England and Wales (2nd Edition)

Edited by P. J. Brenchley and P. F. Rawson

This second edition of The Geology of England and Wales is considerably expanded from its predecessor, reflecting the increase in our knowledge of the region, and particularly of the offshore areas. Forty specialists have contributed to 18 chapters, which cover a time range from 700 million years ago to 200 million years into the future. A new format places all the chapters in approximately temporal order. Both offshore and economic geology now form an integral part of appropriate chapters.

Most of England and Wales is formed from part of a single terrane, Avalonia, and its pre-Cambrian (Neoproterozoic) history is preserved in patches. However the time intervals from the Cambrian to the present day are well represented in our sequences and the Cambrian, Ordovician, Silurian and Devonian systems were all defined here. William Smith's map of England and Wales was the world's first geological map of a country and the British Geological Survey's copy is reproduced in the introductory chapter. This chapter, by the editors, consists of a broad overview aimed particularly at the non-specialist while guiding the reader towards the appropriate succeeding chapters. The volume concludes with a look at the future, from the short-term effects of climate change and sea-level rise to the position of our region in a possible plate tectonic configuration 200 million years hence.

While the authors have taken a 'dynamic' view of the evolution of the area over geological time, they have also ensured that the geological evidence on which the interpretations are based is reviewed thoroughly. Hence the volume provides a valuable resource for both Earth scientists and the broader community.
Dissolved volatiles can have tremendous effects on the physical and chemical properties of silicate melts. The most abundant volatile in terrestrial magmas is H\textsubscript{2}O. A few weight percent of added H\textsubscript{2}O can reduce melting temperatures of rocks by several hundred degrees and enhance the fluidity of magmas by orders of magnitude. Carbon dioxide and sulfur, although less abundant in natural magmas than H\textsubscript{2}O, often control the initial stage of magma degassing. The strong effect of volatiles on melt properties is related to the chemical bonding of the volatiles in the melt, which depends in particular on melt composition, temperature and oxygen fugacity. The oxygen fugacity, although very low at magmatic conditions, nevertheless has a large influence on the magma, determining the abundance and composition of minerals, fluid–melt partitioning and the physical properties of the melt.

INTRODUCTION

Elements and molecules that are easily released from a melt into a vapor or fluid phase are usually called volatiles. Knowledge of the distribution of volatile species between silicate melts and gases (or fluids) is crucial for understanding and modeling degassing of magmas and melts. The importance of volatile solubility in melts is most obvious for volcanic eruptions. Large amounts of volatiles can be stored in magmas deep in the Earth at high pressure. During ascent to the surface, the magma becomes increasingly oversaturated in volatiles and may release enormous volumes of gases, triggering a volcanic eruption. Injection of these gases into the troposphere or even into the stratosphere can have large environmental impacts on both local and global scales. Degassing of melts is of interest not only in the geosciences but also in materials sciences and technical processes. Making bubble-free glasses often requires fining of glass-forming melts at high temperatures. In industry, chemicals such as sulfate or arsenate are routinely added to silicate melts to create bubbles, which rise through the melt, and are then resorbed as temperature is lowered. Understanding these processes requires detailed information on the amount of volatiles that can be dissolved in silicate melts, how these volatiles are incorporated in the melt structure and how fast they can migrate through the melt.

The chemical and physical properties of melts and glasses are also strongly modified by dissolution of volatiles. In particular, dissolved H\textsubscript{2}O may have a tremendous effect on melt behavior, enhancing viscous flow (e.g. Schulze et al. 1996); on the diffusion of melt components (Chakraborty 1995); and on the modification of the crystallization sequence (Schmidt et al. 1997; Dall’Angol et al. 1999). The stability of minerals coexisting with silicate melts is strongly affected not only by the water content of the melt but also by the oxygen fugacity, \( f_0 \) (Fig. 1). Although values of magmatic \( f_0 \) are very low (much lower than 10\textsuperscript{-4} bar), they span a wide range that affects the oxidation state of heterovalent elements such as iron and sulfur. Osborn (1959) first recognized the petrological importance of melt redox state from studying the role of oxygen partial pressure on the differentiation of basaltic magma. Since then, many experimental studies have contributed to our understanding of oxygen fugacity as an important parameter controlling the properties and evolution of magmatic systems. However, what controls the variations of \( f_0 \) in magmas often remains difficult to elucidate. Control of the redox state of the melt is also crucial in various processes during the manufacturing of glass, e.g. fining of melts or coloring of glass.

In the following sections, we first outline the quantities of major volatiles that can be dissolved in silicate melts. Next we take a close look at how these volatiles are incorporated in the melt structure. Then attention is drawn to the effect of oxygen fugacity on the redox state of magmas. Finally we examine a special volatile, sulfur, which can be present in several oxidation states in natural magmas.

SOLUBILITY OF VOLATILES IN MELTS

Water and carbon dioxide comprise the most abundant volatiles in magmas, and their fraction in volcanic gases often exceeds 95%. However, sulfur, noble gases, nitrogen and the halogens fluorine and chlorine are also frequently found in volcanic gases in concentrations up to several mole percent. Although the concentration of these minor volatiles appears to be very small, they nevertheless determine the onset of degassing of magmas during depressurization when approaching Earth’s surface. Once volatile saturation is reached, all volatile species are partitioned between the magma and the vapor phase in proportion to their relative solubility and abundance (Carroll and Webster 1994).
The most direct information on the concentration of volatiles in natural melts is provided by melt inclusions trapped in minerals during growth in the magma (e.g. Wallace 2005). Indirect constraints can be obtained by comparing mineral phases found in erupted rocks with experimentally determined phase relationships, as shown in Figure 1. Additionally, emission of volcanic gases, which reflects migration and accumulation of volatiles within complex open magmatic systems (Wallace 2005), provides information on volatiles in magmas.

The potential of melts for storage of volatiles can be determined by experiments in which a melt is equilibrated with a fluid phase at given P–T conditions, and then the quenched glass obtained is analyzed by various techniques. However, this approach is usually limited to pressures up to 10 kbar because very volatile-rich melts often cannot be quenched to a glass. Furthermore, as shown by in situ observations using a hydrothermal diamond anvil cell, complete miscibility can be achieved for H₂O-silicate systems at high temperature and pressure (e.g. at 10 kbar and 1000°C for the system NaAlSi₃O₈–H₂O; Shen and Keppler 1997), and the term ‘solubility’ becomes meaningless.

The solubilities of one-component volatiles in silicate melts have been investigated intensively in numerous studies over the last few decades (for reviews see McMillan 1994, Blank and Brooker 1994, and Carroll and Webster 1994). H₂O has the highest solubility of all volatiles and, consequently, the largest effect on melt properties. At ambient pressure, technical silicate glasses (container or float glass) melted with air/gas or air/oil flame contain about 0.03 wt% water; if melted with oxycombustion, the water content can reach 0.045 to 0.065 wt%. Electrically melted soda–lime–silica glasses typically contain around 0.02 wt% water. Significantly larger amounts of H₂O can be dissolved in melts at high pressures, e.g. about 10 wt% H₂O in common natural melt compositions at 5 kbar. The solubility of CO₂ is typically more than one order of magnitude lower (Blank and Brooker 1994).

Pressure is the main factor determining the solubility of H₂O and CO₂ in silicate melts, while composition of the melt and temperature are subordinate (Fig. 2). At pressures up to ~2 kbar, water solubility varies approximately with the square root of pressure, reflecting the fact that most of...
the water is dissociated into two hydroxyl groups. At higher water pressures, water solubility increases more rapidly with further increase of $P_{H_2O}$ because molecular $H_2O$ becomes an important species (Zhang 1999). In contrast to $H_2O$, the solubility of $CO_2$ is proportional to the carbon dioxide pressure over a large range of pressures (Blank and Brooker 1994).

The solubility of mixed fluids in silicate melts is less well known. The partitioning of $H_2O$ and $CO_2$ between silicate melt and fluid has been investigated for melts from rhyolitic to basaltic compositions (e.g. Tamic et al. 2001; King and Holloway 2002; Behrens et al. 2004; Botcharnikov et al. 2006). Generally, increasing the $CO_2$ content of the fluid phase decreases the water content of the melt. However, for $CO_2$ solubility the relationship is not so simple, and often the $CO_2$ content of the melt remains constant or even increases when up to 30 mol% $H_2O$ is added to the fluid (Fig. 3). This indicates that modification of the melt structure by incorporated water enhances the solubility of carbon dioxide.

Based on the experimental solubility data, various attempts have been made to model the solubility behavior of volatiles (e.g. Holloway and Blank 1994; Papale et al. 2006). However, such models still have large uncertainties when applied to compositions and conditions that are not covered by experimental data. Apart from experimental or analytical problems, two main reasons explain the difficulty in developing general solubility models from the available experimental database: (1) the relative abundances of molecular species in the fluids (e.g. $CO$, $CO_2$, $H_2O$, $CH_4$, and $H_2$ can be major components in $C$–$H$–$O$ fluids) and their fugacities depend upon pressure, temperature and oxygen fugacity, the last of which is notoriously difficult to control in high-pressure experiments; (2) the solubility mechanisms of volatiles in silicate melts depend on the bulk composition of the melt as well as on temperature.

**STRUCTURAL INCORPORATION OF $H_2O$ AND $CO_2$ IN THE MELT**

Water and carbon dioxide dissolve in silicate melts in the form of at least two different species: an unreacted molecular species ($H_2O$ or $CO_2$) and a species formed by reaction between the molecular species and the silicate framework (hydroxyl groups or carbonate). The species may affect melt properties in different ways. For instance in aluminosilicate melts the formation of hydroxyl groups can depolymerize the silicate network and thus enhance viscous flow, whereas molecular $H_2O$ is the mobile species in diffusion (Zhang 1999).

Most of our knowledge of volatile speciation is based on infrared (IR) and nuclear magnetic resonance (NMR) spectroscopy on glasses at ambient temperature. The speciation of water in glasses depends mainly on total water content and less on anhydrous bulk composition. At the low water contents typically found in technical glasses (<0.2 wt%), OH groups are predominant and molecular $H_2O$ concentration is often below the detection limit. With increasing water content, the relative abundance of $H_2O$ molecules grows, and they become the dominant species above 3–5 wt% $H_2O$. In contrast, the speciation of $CO_2$ is independent of total $CO_2$ concentration but varies strongly with the anhydrous composition of the glass. In highly polymerized rhyolitic glasses, $CO_2$ is incorporated exclusively as molecular $CO_2$, whereas only carbonate is present in depolymerized glasses such as basalt (Blank and Brooker 1994). Glasses of intermediate composition, such as dacite, andesite and phonolite, contain both types of species. For both water and carbon dioxide, the relative abundance of the corresponding species in glasses does not depend significantly on pressure at least up to 8 kbar (Blank and Brooker 1994; Zhang 1999; Behrens and Nowak 2003; Nowak et al. 2003), implying that the volume of molecular species plus network oxygen is similar to the volume of the reacted species in the melt.

Significant controversy surrounds the question of whether volatile speciation data measured on glasses at room temperature are transferable to melts at high temperature. From relaxation theory it has been inferred that the volatile speciation measured in the glass at room temperature is equivalent to the volatile speciation in the melt at the glass transition temperature (Dingwell and Webb 1990). Based on this hypothesis, an approach was developed to study water speciation in silicate melts that involves annealing of glasses for a long time near the glass transition and then quenching to room temperature fast enough to prevent back-reactions (Zhang 1999). Quenching of the melt at a well-defined cooling rate from high temperature through the glass transition is another possibility (Behrens and Nowak 2003). However, both techniques yield speciation data only for melts in a small temperature range far below the liquidus temperature. In situ infrared spectroscopy using high-temperature and high-pressure cells has challenged our understanding of water speciation in silicate melts because this technique allows investigation of stable melts at high temperature (Nowak and Behrens 2001). In the case of rhyolitic melts, the in situ measurements give results that are consistent with those from studies on glasses (Behrens and Nowak 2003). Due to technical difficulties, however, only a few melt compositions (hydrous aluminosilicate melts with compositions similar to rhyolite) have been studied with the in situ technique to date.
Spectroscopic studies have shown consistently that with increasing temperature molecular H$_2$O is increasingly transformed into OH$^-$ groups in silicate melts (Fig. 4). General compositional trends are that molecular H$_2$O is stabilized in the melt with increasing ratio of alkaline to alkaline earth elements, whereas with increasing concentration of non-bridging oxygen (decreasing degree of melt polymerization) OH$^-$ groups are favored. From rhyolitic to andesitic composition. These effects cancel each other, and water speciation is very similar in these two melts (Botcharnikov et al. 2006).

**OXYGEN FUGACITY AND THE REDOX STATE OF THE MELT**

Elements such as iron and sulfur exist in silicate melts in different oxidation states, with the ratio of oxidized to reduced forms varying with temperature, melt composition and, in particular, oxygen fugacity. In the case of iron, the redox reaction can be expressed as

\[ 2 \text{Fe}^{2+} + 1/2 \text{O}_2 \leftrightarrow 2 \text{Fe}^{3+} + \text{O}^2- \]

A lot of work has been devoted to the experimental calibration and modeling of the equilibrium constants for redox reactions, in particular for Fe (e.g. Kress and Carmichael 1991; Gaillard et al. 2003a; Botcharnikov et al. 2005). On the basis of such calibrations, Carmichael (1991) concluded that the Fe$^{3+}$/Fe$^{2+}$ variations observed in the silicate melt fraction of lavas in various terrestrial geodynamic environments correspond to variations in $f_{O_2}$ of about 8 log units. He suggested that these variations probably apply to the source region as well. However, in interpreting magmatic $f_{O_2}$, one should keep in mind that magmas are produced at diverse temperatures and that changes in temperature impose changes in $f_{O_2}$. Therefore, petrologists usually express magmatic $f_{O_2}$ relative to a redox buffer (Fe/FeO, Ni/NiO) for which the temperature dependence of $f_{O_2}$ is similar to that of the magma. In Figure 5, some of the most common redox buffers are plotted in a T-$f_{O_2}$ diagram together with the T-$f_{O_2}$ domains representative of several magma types.

Despite the universal use of $f_{O_2}$, molecular O$_2$ is practically absent in magmatic fluids, and transfer of redox potential between fluid and melt operates via the transfer of other species. In hydrogen-free or hydrogen-poor magma such as mid-ocean ridge basalt, changes in magma $f_{O_2}$ can be imposed by complex cationic and electronic migrations (Cooper et al. 1996). In hydrous melts, molecular hydrogen and water are both extremely mobile in the melt, and the redox state of the melt can be locally established via the reaction H$_2$ + 1/2 O$_2$ $\rightleftharpoons$ H$_2$O (Gaillard et al. 2003b). The experimental control of $f_{O_2}$ in hydrous silicate melts has been achieved through technical developments based on the specific permeability to hydrogen of noble metals (Au, Au–Pd alloy, Pt) used as sample containers in hydrothermal experiments. Therefore, controlling $f_{H_2}$ in a gas pressure vessel allows $f_{O_2}$ to be controlled in the hydrous melt. The double capsule technique and the Shaw membrane, pioneered in the 1960s, are the classical methods to control $f_{H_2}$ in hydrothermal vessels (see Schmidt et al. 1997 and references therein). Most recent works have focused on the effect of water on the oxidation state of silicate melts and its impact on phase equilibria in magmatic systems (Fig. 1). Furthermore, the mechanism by which water affects the relationship between Fe$^{3+}$/Fe$^{2+}$ and $f_{O_2}$ has been the subject of several studies, with reasonably convergent conclusions (see Botcharnikov et al. 2005).

A challenging issue now is to understand the redox behavior of other heterovalent elements in silicate melts, in particular that of sulfur. In contrast to water and carbon dioxide, sulfur dissolves in silicate melts at magmatic conditions in at least two different oxidation states. At oxygen fugacities below the nickel/nickel oxide buffer, sulfide (S$_2^-$) is the predominant sulfur species, whereas at higher oxygen fugacities, sulfate (SO$_4^{2-}$) is formed (Carroll and Rutherford 1988). Some evidence derived from technical glass studies suggests that sulfite might also be present in silicate melts at intermediate oxygen fugacities, but the solubility of sulfite is probably much lower than that of sulfate and sulfate (Beerkens 2003). Minor sulfur species could also include radical anions such as S$_2^-$ or S$_4^-$ (Winther et al. 1998).

**Figure 4** Fraction of molecular H$_2$O in rhyolitic melts at various temperatures in comparison to the quenched glass
Redox conditions for terrestrial magmas in comparison with some oxygen buffers used for experimental control of the oxygen fugacity. Abbreviations: HM = hematite + magnetite, NNO = nickel + nickel oxide, IW = iron + wüstite, EPM = Earth primitive magma (magma ocean). The quartz-fayalite-magnetite (QFM) buffer, not shown on this diagram, is ~0.8 log units below the NNO buffer. Dashed lines show the equilibrium H$_2$O fraction in H$_2$–H$_2$O gas mixtures for given T and f$_{O_2}$. The Earth primitive magma ocean (EPM), saturated in metal iron, is the most reduced and is in equilibrium with H$_2$–H$_2$O gas containing 8% water. Komatites, the oldest lavas found on Earth, have redox conditions between IW +1 and NNO (Canil 2002), which correspond to a gaseous mixture containing 60 to 99% water. MORB displays moderately reducing conditions also upper bounded by the NNO buffer, whereas arc magmas, derived from subduction, are the most oxidized terrestrial lavas and also the most water rich (Carmichael, 1991). Such increase in oxidation state of magma with time, correlated with an increase in water content, is a fundamental issue that has motivated numerous experimental studies.

Models predicting sulfur speciation and solubility in silicate melts are already available (O’Neill and Mavrogenes 2002; Morretti and Ottonello 2005; Scaillet and Pichavant 2005), but more experimental data are required to improve these models. The narrow f$_{O_2}$ domain in which sulfur speciation shifts from $S^{2-}$ to $S^{6+}$ contrasts with the smooth variation in Fe$^{3+}$/Fe$^{2+}$ ratio with f$_{O_2}$ (Fig. 6). This characteristic of the redox behavior of sulfur in melts, coupled to its speciation in the fluid as H$_2$S, S$_2$ or SO$_2$, will be one of the major tasks of future studies.

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Transport Properties of Magmas: Diffusion and Rheology

Donald B. Dingwell*

The transport of magmas in the Earth is a phenomenon of first-order importance to the physical, chemical, and climatological evolution of our planet. Volcanism, in particular, can have dramatic impact on human lives, not only as an immediate environmental hazard but also as a longer-term influence on climate. The transport properties of magma—that is, physical flow in response to stress and diffusion of dissolved components as a result of chemical gradients—have been the subject of intensive study in recent decades. Nevertheless, the complexity of these physical and chemical responses requires an even more generalized picture of magma transport than is currently available. The emerging view of magma transport incorporates melt dynamics, non-Newtonian flow, brittle failure, and the fundamental nature of the glassy and liquid states.

KEYWORDS: rheology, viscosity, diffusivity, volcanism, glass transition

INTRODUCTION

The transport properties of magmas lie at the very core of their relevance to the Earth Sciences. Indeed, it is the very mobility of magmas that enables them to play a special role not only in whole-Earth differentiation but also in defining the physical properties of partially molten regions and illuminating deep-Earth chemistry. Moreover, when magmas interact energetically with the atmosphere or with seawater—as during explosive subaerial or subaqueous volcanism—the resulting gases and reactive particulates become important agents in the chemistry of the atmosphere and oceans. In summary, Earth would be a VERY different place without magmas. Building upon a long history of investigations, research in recent years has made major strides in the understanding of transport properties of molten silicates (melts), which are the essential physical components of magma. These insights are the result of new experimental technologies and theoretical approaches as well as advanced techniques in modeling and simulation of melt properties. Here, several recent advances in research on melt transport properties are highlighted and placed in the context of existing knowledge.

MELTS, GLASSES, MAGMAS

At the outset, it is essential to recall the definitions of the terms “melt,” “liquid,” “glass,” and “magma” (Dingwell and Webb 1990). The term “melt” implies an origin by melting. It is useful to apply the term to the molten state over the entire range of its behavior, which can span the glassy and liquid states. The physical attributes of a “liquid” are that (1) it possesses a Newtonian viscosity (i.e., the strain rate is proportional to the applied stress through the viscosity), and (2) its rigidity modulus is zero (i.e. it has no shear strength). Perhaps the most obvious consequence of such attributes is the ability of a liquid to adopt, under the influence of gravity, the dimensions and shape of the space or container in which it is confined. These attributes dominate and control the development of experimental strategies used to investigate liquids in the laboratory. Further, they determine the transport response of molten rocks within the Earth and terrestrial planets (magma transport), as well as at their surfaces (volcanism). The term “glass” refers to a non-crystalline material that exhibits a solid-like response to stress. It is thus clearly distinguished from the liquid state, with glassy behavior occurring at lower temperatures and shorter timescales than liquid behavior. The transition from liquid to glassy behavior is theoretically possible for any melt, and it is of tremendous importance in both the experimental investigation of melts and their behavior in volcanism. Finally, the definition of “magma” has been approached in the literature from different directions. One choice is to describe the physical state of the system in terms of its essential character, that is, the presence of a melt phase. Thus we can define magma as a “melt-bearing geological.” The magma is usually multiphase, containing a melt and one or more populations of individual crystalline phases, agglomerations of these and inclusions of one phase (fluid, melt or crystal) in another (Fig. 1). The magma may also contain bubbles (or vesicles) of one or more fluid phases. The fluid phases are typically extremely low in viscosity relative to the melt and exhibit chemical compositions rich in so-called volatile elements and compounds. The magma may also be composed of more than one melt phase. The presence of two coexisting melt phases can be due to the mingling, during transport, of two previously separate magmas or separate parts of a zoned magma chamber. During their physical mingling, the two melts are commonly in the process of chemical mixing via chemical diffusion. However, the two coexisting melts may also be generated by the unmixing of a single melt due to phase equilibrium constraints. In the latter case, the two liquids will mix by nucleation and then grow by means of chemical diffusion. In all cases of multiphase magma, the potential exists for a further complexity of the state of the system due to significant chemical diffusion gradients in one or both of the phases adjacent to a phase boundary where reaction (growth or dissolution of a phase, chemical re-equilibration
of two phases) is occurring. Given the slow kinetics of many silicate reactions and the dynamic pressure- and temperature-history of most magmas, such reactions during cooling and ascent/eruption are the rule rather than the exception.

According to a distinct and more restricted definition, magma must possess rheological properties that allow it to be readily transported from the place it originated as a partial melt in the Earth’s crust or mantle. This definition is distinct because it is based (at least qualitatively) on rheology and not on state. It is more restricted because the agent of efficient rheological transport relative to the crystalline Earth for a magma is the melt phase. Thus, a magma is a melt-bearing geometrical in which the amount and distribution of melt allow its rheological response to be distinct from that of what remains of the crystalline protolith—the precursor to melting. Thus, the two aspects lying at the very heart of magmatism are the melt phase and its rheological impact.

THE ATOMISTIC BASIS OF TRANSPORT IN MELTS

The exchange of individual atoms on sites within a phase is ubiquitous in matter at high temperature. The diffusive exchange involved is the mechanism whereby the structure and properties of a liquid respond to perturbations in its state, for example, temperature and pressure changes. The diffusive rearrangements in the liquid serve to re-equilibrate the liquid to its new state. Thus diffusion lies at the center of the establishment of equilibrium. This adjustment to a new physical state has been called relaxation (Dingwell 1995). One speaks of the relaxation of the liquid to the new set of structures and properties in equilibrium with a changed set of intensive parameters. Given the above, it should perhaps come as no surprise that the relaxation of silicate liquids is likely controlled by diffusion of individual Si and O atoms in the liquid matrix.

How do we know this? First, it has long been observed that the diffusion rate of Si in silicate liquids is inversely proportional to the viscosity. This correlation is a clear indication that Si mobility and melt viscosity are somehow linked. Second, in high-temperature, low-viscosity liquids, the self-diffusion of oxygen exhibits essentially the same inverse correlation with melt viscosity (Shimizu and Kushiro 1984). The third observation central to this assertion involves motional averaging in spectroscopic investigations of high-temperature silicate liquids. Specifically, various nuclear magnetic resonance experiments, based, for example, on the nuclei $^{29}\text{Si}$ and $^{17}\text{O}$, have identified a motional averaging of the signal of so-called “Q species” (essentially the next-nearest-neighbour statistics of tetrahedral cations expressed by the number of bridging oxygens per tetrahedron; see glossary page 266). The motional averaging, considered in the context of the intrinsic relaxation frequencies employed for the nuclei, yields diffusion coefficients for the cations that can be used to calculate relaxation times (Stebbins 1995). The evidence from these diffusion data matches nicely the macroscopic evidence for the relaxation of melt properties (shear stress, volume, and enthalpy relaxation). Therefore the Q species exchange (diffusion of Si and O) defines both the structural and viscous relaxation timescales. Conclusion: viscosity reflects diffusion of Si.

The above conclusion appears to cast doubt on the existence of polymeric structures in silicate liquids. Large flow units and polymeric species whose lifetimes are significant on the timescale of viscous flow are precluded, so the very nature of the silicate melt structure is inconsistent with a polymeric structure. The viscoelastic properties certainly do not illustrate polymeric behavior. This is despite the continuing success of application of polymer theory to the solution properties of silicate liquids (Moretti 2005)—an apparent paradox.

The mobilities of the cationic and anionic constituents of silicate melts exclusive of Si and O have a long history of investigation. Sufficient data have been available over a decade to begin to elucidate one of the most central aspects of cationic mobilities in silicate melts, namely, their relationship to Si diffusivity and thereby to viscosity. Essentially, the diffusion behavior of cationic components can be divided into two types—extrinsic and intrinsic (Dingwell 1990). Extrinsic diffusivities have a magnitude and temperature dependence very similar to those of Si. They are interpreted to be the consequence of matrix mobility affecting the timescale of cationic diffusive jumps. In this domain, all diffusivities are relatively tightly clustered and may be roughly approximated by the calculation of melt viscosity. One may think of extrinsic diffusivities in terms of diffusion in a liquid where the diffusing cation senses the mobility of the melt matrix (Si–O bonds) on its own diffusive timescale. Intrinsic diffusivities are quite another story. At very high viscosities and low temperatures, the individual diffusivities of most cations and anions are much higher than the Si diffusivity (Watson 1994; Chakraborty 1995). Their temperature dependences are also quite different and significantly smaller than that of Si. As a result there is no apparent connection between viscosity and diffusivity in the intrinsic regime. This can be seen as diffusion in a solid (this is a glass), where the mobility of the matrix is so low that no changes occur on the timescale of diffusive jumps of the cation. In principle, all intrinsic diffusivity curves approach the extrinsic regime with increasing temperature. Practically speaking, small, highly charged cations and large anions tend to diffuse more slowly and thus have a wide temperature range of extrinsic behavior, whereas light, low-charge cations and anions exhibit a very wide temperature range of extrinsic behavior.
range of intrinsic behavior. The transition from intrinsic to extrinsic can be inferred from published data for certain cations where sufficient data are available. One of the most striking and perhaps counterintuitive hallmarks of the difference between extrinsic and intrinsic diffusivities involves their isothermal composition dependence. Intrinsic diffusivities increase with melt silica content, whereas extrinsic diffusivities decrease with increasing silica content. In the former case concepts such as ionic porosity and free volume have been employed to explain the trends, whereas in the latter case the viscosity is almost certainly the underlying factor.

**RELEVANCE AND USE OF THE GLASS TRANSITION**

In discussion of liquid-like versus solid-like behavior, of liquids versus glasses, of viscous versus elastic response, and of flow versus failure, a central theme lies at the heart of the nature of the glassy state—the glass transition.

The glass transition, portrayed in Figure 2, is the transition from liquid-like to solid-like behavior (or vice versa) for a molten silicate. Its position in temperature-time space can be calculated from the value of the Newtonian viscosity using the Maxwell relations. At the glass transition, silicate melts behave as a simple approximation to a Maxwell body (a spring and viscous dashpot in series). The bulk of magma transport occurs under conditions represented in the upper and left side of the glass transition (i.e. in the liquid state). Nevertheless, the glass transition region is certainly encountered by magma in volcanic processes (Dingwell 1996). It is also commonly encountered (sometimes unknowingly) in experiments in the laboratory (Dingwell and Webb 1990). It forms the basis for much of the glass-production industry.

We normally think of magmatism and volcanism as processes accompanied by monotonous cooling. As a result, the path that likely comes to mind when examining Figure 2 is that of a more-or-less constant cooling or quench rate (represented by a horizontal line from left to right). In fact, transects of the glass transition are possible in both directions with respect to temperature (a horizontal line in Fig. 2). Also, transects are possible in both directions with respect to cooling rate and therefore relaxation time (a vertical line in Fig. 2). Furthermore, multiple transects of the glass transition, in which the system may be liquid-like, then glassy, then liquid again, and finally returns to the glassy state, are almost certainly the case in nature (Gottsman and Dingwell 2002). In a volcanic system, an encounter with the glass transition can have catastrophic consequences in the form of explosive volcanism. It deserves more attention in magma and volcano dynamics (see below).

**MULTICOMPONENT MODELING FOR NEWTONIAN VISCOSITY**

Magma transport generally occurs under conditions of driving stresses that yield a purely viscous response of the magma. The viscous response of the magma, which is dominated by the presence and nature (chemistry, fraction, distribution) of the melt phase, is likely to involve a purely Newtonian role for the melt phase. For this reason, the bulk of the experimental investigation into the rheology of silicate melts has been performed within the Newtonian regime, where the ratio of stress to strain rate is a constant defined as the viscosity.

Equally important, as noted above, is the observation that the mapping of the limits of the Newtonian regime of melt viscosity is the key to determining the location of the glass transition. Thus it is essential for evaluating the likelihood and consequences of the onset of non-Newtonian melt viscosity in nature, laboratory, and industry.

Silicate melts exhibit a complex, fundamentally nonlinear relationship between chemical composition and viscosity (Richet 1984). Further, the temperature dependence of Newtonian melt viscosity is not only nonlinear, but also non-Arrhenian (that is, nonlinear in reciprocal absolute temperature). The pressure dependence of melt viscosity is also complex, with viscosity decreasing or increasing with pressure depending on chemical composition and absolute pressure range (Dingwell 1998).

Despite almost a century of experimental investigation, the Newtonian rheology of silicate melts remains a very active field of research. In fact, major steps forward, driven largely by geoscientific research, have been made in recent years. Perhaps foremost amongst these has been the realization that the complete description of melt rheology requires the application not only of techniques suitable for the determination of viscosity in equilibrium liquids at superliquidus temperatures, but also very different techniques for the determination of viscosity of supercooled, metastable liquids at temperatures far below their melting point (Richet and Bottinga 1995).

Nevertheless, in a long-established field of investigation it is certainly legitimate to ask the question “What is new?” In essence, the frontiers of investigation of Newtonian rheology have brought us to the point where the database permits, for the first time, an intensive and competitive body of
modeling approaches to best describe the chemical dependence of melt viscosity. A quarter century elapsed between the first attempts at modeling multicomponent melt viscosities in geochemistry and the second flurry of activity. During the past few years, much has been written on the philosophy of the approach, the critical examination of assumptions, the appropriate propagation or errors, the analysis of variance and covariance, and the choice of completely independent and heterogeneous sources of data for input. This has led to an active field of research on the modeling of melt viscosity. In addition to models based on direct viscosity determinations, models based on indirect sources of viscosity data have been proposed. Examples include the derivation of viscosity from experiments on complex processes, such as bubble growth in melts, and the incorporation of viscosities derived from glass transition temperature determinations involving volume and enthalpy relaxation (Dingwell 1995).

This conjunction of metastable liquid investigations, indirect sources of viscosity data, unconventional parameterizations, and sophisticated modeling approaches have made the prediction of viscosity far more rigorous.

How well are we doing? The fundamental features of volatile-bearing melt viscosities are emerging in a clear and accurate way. One example is presented in Figure 3, where the temperature-dependent viscosities of hydrous rhyolites are portrayed. Clearly identifiable trends in activation energy and non-Arrhenian nature (curvature) are observed as a function of water content in this parameterization (Hess and Dingwell 1996). In turn, the trends generate questions on the fundamental energetics of silicate melts and the inferences they permit regarding the nature of bonding in liquid silicates. The greatest theoretical progress along these lines applied to molten silicates may have resulted from an approach based on configurational entropy considerations. Here, it is the configurational entropy that is seen as the quantitative (inverse) monitor of the size of the regions that relax to accommodate viscous flow. Parameterization of the temperature and composition dependence of viscosity on this basis has led to encouraging simplifications for simple systems, such as linearization of the temperature dependence of viscosity of diopside (Richet and Bottinga 1995). Progress is, however, being held up by limitations on thermodynamic data. Thus, the state-of-the-art with respect to multicomponent melt viscosity models is currently reflected by empirical models whose reproducibility for viscosity is less than one half a log unit over a range of more than ten log units (Giordano et al. 2006). Figure 4 illustrates the situation for anhydrous multicomponent melts of volcanic relevance.

**VOLCANO DYNAMICS**

The glass transition plays a central role in volcanism. The presence of volcanic glass shards in ash flows, in lava flows, and as suspended fine particles in the stratosphere is a clear indication that high-temperature magma, rich in a liquid phase, has been converted into a collection of solid phases, including a glass. The liquid-to-glass conversion is thus a common occurrence, dominating the fate of intermediate to silicic liquids during eruption. This transition is also possible in more basic liquids, as evidenced by naturally occurring basaltic glass shards. We are conditioned to extract information on the origin of rocks from their crystalline mineral assemblages. The structures, stability, chemical compositions and partitioning, state of crystalline ordering, and parageneses of their inclusions all provide tools to decipher the history of the rocks. But what can we do with the glassy phase? In a petrological sense, what is it good for? The chemistry of the melt, as recorded in glass, is of course a critical component in the understanding of chemical partitioning and source conditions (Carmichael and Ghiorso 1990). The distribution of the phases also tells us something of the state of stress in the rock at some part of its history. But the glassy phase itself, and its physical state in particular, is also a source of information on the history of the rock. The glassy phase contains information on the latest phase of magmatic activity in the entire cycle from melting to eruption. It tells something of the eruption itself. The key to extract this information is the recognition of one simple consequence of the kinetic nature of the glass transition. Because the glasses are generated at a “phase boundary” that is purely kinetic in nature, the products of the
process—the glasses—are in a physical state that is path dependent. This has enormous predictive implications, both in experimentally generated glasses and in natural volcanic glasses. The path dependence of the glassy state can be stated in a different way. The thermal history of the transition into the glassy state (the last transect of the glass transition) is recorded in the glass. The glass possesses a thermal memory. Perhaps the simplest expression of the thermal history recorded in glasses is the fact that the density of a glass of a given chemical composition can vary, depending on the way in which the glass transition was accessed. The most common variable controlling the density of the glass is the cooling rate across the glass transition. Glasses quenched more rapidly are less dense. The state of the glass can be well approximated by an order parameter termed the “fictive temperature.” The fictive temperature of the glass is defined as the temperature at which the extrapolation of the temperature dependence of the physical property of the glass (e.g. density) to higher temperature intersects the temperature-density relationship of the equilibrium liquid. The fictive temperature became of practical importance in the 1930s because of the direct relationship between density and refractive index and the obvious importance of the latter for the production of optical glass. The fictive temperature of the glass essentially captures its point of departure from the liquid state, i.e. its falling out of metastable equilibrium with decreasing temperature during the quench that led to its production.

The thermal history of the glass thus yields a cooling rate determination for the rock in which it occurs. This cooling rate corresponds to the temperature range of the glass transition. The information can be obtained in several ways. First, the quenched state of the glass, reflected in its density, refractive index, and other properties, can be exactly determined and related to a value of the fictive temperature by comparison with samples formed under known cooling rates. Second, the quenched samples can be mildly reheated, and the temperature-dependent properties such as density can be measured; then the resultant temperature-dependent property of the glass can be extrapolated to higher temperature in order to obtain the fictive temperature and thus the cooling rate. The third technique, the one which has turned out to be most robust, involves the reheating of the glass across the glass transition and the recording of the hysteresis, or path-dependence, in the return of derivative thermodynamic properties (expansivity, heat capacity) to the supercooled/metastable liquid state. This technique has proven remarkably useful in the study of the thermal histories of volcanic glasses (Wilding et al. 1995). The variation in cooling rates obtained to date for volcanic glasses ranges over six orders of magnitude—from one million K/sec to several K/day. The extremes measured to date are represented by limu basaltic glass shards from the ocean floor (fastest cooling rate; Potuzak 2006, pers. comm.) and welded airfall pantelleritic glasses from an active volcanic caldera complex (slowest cooling rate; Gottsmann and Dingwell 2002). With this technique, a new branch of geospeedometry in volcanic terrains has been initiated which, if combined with other mineral-based geospeedometers in the future, could provide unprecedented insight into the cooling dynamics of volcanic terrains.

I will close with one example of the astonishing turn of thinking that has accompanied the most recent application of our new picture of magma rheology applied to rocks. During the past decade, the picture of explosive fragmentation in volcanic systems has been increasingly dominated by a series of sequential but overlapping physical processes,

![Figure 4](https://example.com/figure4.png)

**Figure 4** (A) Viscosity–temperature relationships of volcanic melts. (B) The goodness of fit of a recent multicomponent viscosity model tested for 44 natural volcanic melt compositions. (C) The compositional space ranges over virtually the entire range of natural volcanic melts at the Earth’s surface. Missing as yet is the combination of the influence of water and the fully multicomponent compositional base, combined with a stable plus metastable liquid data base enabling a non-Arrhenian approach. Colours refer to individual melt compositions as well as viscosity data for individual compositions.
such as volatile saturation, vesicle nucleation and growth, and foaming and fragmentation, which together produce volcanic pumice and ash. The core of this analysis has been the application of the glass transition as the material switch in generating explosive volcanism (Dingwell and Webb 1990). Major advances have been made in the experimental and simulation analysis of this picture, which is our best scenario for the development of major Plinian eruption events (Alidibirov and Dingwell 1996; Papale 1999; Spieler et al. 2004). Recalling, however, the theoretical possibility of multiple crossings of the glass transition, careful field-based analysis of modern glassy rhyolitic lava flows has led to speculation that multiple switching from liquid to glassy behavior in extruding rhyolitic systems may be the rule (Tuffen et al. 2003; Gonnerman and Manga 2005) (Fig. 5).

These scenarios have stunning implications for the behavior of rhyolites during eruption, implying as they do that the transport of highly viscous magma during effusive rhyolitic eruptions may be controlled by fracture and healing within the magma body itself rather than by simple viscous flow. The development of this idea has led to the postulates that the near-ubiquitous flow banding of rhyolitic obsidian records such history and that the events may well be significantly seismogenic! I can think of no more revolutionary twist to the story of magmas than the concept that their own rheology may periodically force their behavior into a regime more akin to the rocks they form than the liquids they come from.

**REFERENCES**


**FIGURE 5** Flow and fracture coexisting in space and time within a magma are recorded by flow banding in rhyolitic obsidians. The rheological consequences of this intimate relation between liquid and glassy behaviors have the potential to revolutionize our picture of magma transport in silicic eruptions. See Tuffen et al. 2003 for label definitions. Reproduced from Tuffen et al. 2003.
Dynamics of Magmatic Systems

Bruce D. Marsh*

An intimate physical and chemical interplay between crystals and melt in magmatic systems gives rise to a vast diversity of igneous rocks and the very structure of terrestrial planets. Yet the actual physical means by which this happens is unclear. The long-standing notion of crystals nucleating, growing, and settling ad infinitum from the interior of large pools of magma to eventually form continental rocks is foundering. Processes operating at the smallest scales within marginal solidification fronts and in mingling crystal slurries throughout highly integrated, vertically extended mush columns give rise to planetary-scale effects.

Keywords: magma dynamics, planetary differentiation, solidification fronts, crystallization, magma evolution, Sudbury melt sheet

INTRODUCTION

Ever since volcanoes were recognized as emitters of molten rock, the subsurface structure and intimate workings of magmatic systems have been a subject of mystery and fascination. Aristotle suspected that Stromboli’s prolonged agitation might be due to enflamed coal at depth. With the gradual recognition of the meaning of dikes, sills, and plutons, all the disciplines of igneous petrology or magmatology were born. The basic problem of understanding the physical and chemical evolution of magma is that so very little of any magmatic system, active or extinct, has ever been seen; or if it has been seen it has not been recognized for what it is. The science of magmatism has thus developed along the lines of those parts of magmatic systems offering easiest access to examination. These areas of study have developed into mature, highly technical and quantitative fields of research and thought, now so erudite that it is often not easy to move freely through the literature of these adjoining fields. And researchers in each field have a distinct view of what magmatic systems are and how they function to achieve the perceived ends. One whole class of volcanologists, for example, is mainly interested in the physical aspects of magma delivery, degassing, vesiculation, mechanical fragmentation, and eruption. The chemical compositions of the volcanic products are not necessarily of much interest or meaning to this puzzle. Other volcanologists are primarily interested in the chemistry of the products, and some of these only in the nature of the chemical variations from one lava to the next, which might reveal the processes leading to the observed chemical diversity. Still others are interested only in the most primitive compositions that might reveal the ultimate parental magma or perhaps shed light on the evolution of the mantle itself. Each discipline, in concert with the research results gained, jures up detailed conceptualizations of the nature of the underlying system. Volcanologists, plutonists, sill people, dike people, and layered intrusionists each have strict ideas of the general magmatic system to which their rocks are attached. In spite of this method of scientific inquiry having achieved major advances over the past two hundred years, in the drive to increasing detail, major, seemingly insurmountable problems have arisen, forcing the need for an overarching conceptualization useful to all branches of magmatic study.

HISTORICAL PERSPECTIVE

The vast diversity of igneous rocks on Earth’s surface, the striking compositional bimodality between ocean basins and continents, and the gross planetary structure itself have always driven the need to understand the origin and evolution of magma. From the earliest melting experiments using gun barrels, James Hall recognized in 1798 the temperature-dependent sequence of appearance of minerals during crystallization (see Dawson 1992). The discovery of the technique of making thin sections by H.C. Sorby and the splendid development of petrography by Zirkel and Rosenbush allowed intimate visual access through microscopy to boundless natural experiments exemplified in plutonic and volcanic rocks. Coupled with analytical advances in rock chemistry, this led to the clever insight of Fouque (1879) that the physical separation or fractionation of feldspars from Santorini lavas might produce silica enrichment. And by the end of the nineteenth century, the general nature of magma crystallization was known so well that Cross, Iddings, Pirsson, and Washington laid out a recipe (CIPW norm), accurate to this day, for the crystallization of any rock given its chemical composition. Little to nothing was yet known of the actual phase equilibria involved, but the kind and modal amount of each mineral phase were well predicted. The endless confusion over the equivalence of volcanic and plutonic rocks due to differing degrees of crystallization was erased. The scene was now set for Norman Bowen. Magmatology at the beginning of the twentieth century was exceedingly well developed based on field relations and petrography. The insights and understandings into physical processes leading to the diversity of rocks were masterful. But two important conditions led to a major revolution. First, with a few notable exceptions, the existing generation of petrologists faded into retirement. Second, devoid of the concepts of physical chemistry and physics of fluids, the field was at an impasse. The lightning rod was Bowen, who

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began systematic experimental investigations on silicate phase equilibria. Prior to this time the volumetric preponderance and compositional contrasts of basalt and granite were suspected to be due to eutectic-like "pole" compositions separated by a major thermal divide. Magmas naturally crystallized to one side or the other. Bowen rapidly found no pole compositions but, instead, a continuum of sliding compositions for most minerals and host magmas. The most primitive MgO-rich, SiO$_2$-poor mantle rock could be genetically connected to SiO$_2$-rich continental granite through the progressive separation of ever-lower-temperature minerals. Thus was born—in the days of Darwinian awakening and the Scopes monkey trial—the concept of a "liquid line of descent" connecting one magma to another through an endless chain of crystal fractionation. The physical separation of crystals from solutions to fractionate composition was a widely known, commonly used technique in physical chemistry. Madame Curie had used it extensively to discover polonium, actinium, and radium. H.A. Harker also actively used this principle to explain comagmatic sequences of rocks (Wilson 1993). But it was Bowen who put it on firm ground, as it has remained to this day. He did this not just by conducting experiments. He was a first-class geologist with a keen analytical mind. He marshaled experiments, principles, and field relations to build an unassailable theory of the evolution of all igneous rocks. He carefully and quantitatively evaluated all competing mechanisms (e.g. Soret diffusion, gas fluxing, magma mixing, etc.) and showed them to be ineffective. Bowen (1915) is a must read, and his 1928 tract, *The Evolution of the Igneous Rocks*, remains an unsurpassed masterpiece. Bowen nucleated a century of research into every possible way that minerals can be separated on a phase diagram from the host melt to yield the desired chemical offspring. The physical process has always been the same: crystals grow in magmas and settle out under the action of gravity, leaving behind a chemically refined melt (Fig. 1). The dictum has become McBirney’s Adage: “When in doubt, settle it out.” It is abundantly clear from the most meager mass balance considerations that the separation of crystals and melt gives rise to the diversity of igneous rocks. There is no other process so pervasively operative. But how this actually happens is much less clear. These doubts were around even in Bowen’s day. Indisputable field evidence showing granites grading imperceptively into metasediments and gneisses gave rise to a generation of debate on the “Granite Controversy.” Bowen himself saw the difficulty of generating silicic magma from basalt: the needed late-stage differentiate is interstitially distributed in barely connected pockets at high degrees (80–90%) of crystallinity. He thought that perhaps tectonic action might squeeze out the melt, but relative to solidification the rate is much too slow. Most petrologists to this day still think that basaltic magmas simply go on and on growing and fractionating crystals in the centers of pools of magma to yield rhyolite. The mystery of this process, along with others, has forced igneous petrology to rethink its foundations.

**SOLIDIFICATION FRONTS**

Oddly enough, from the earliest times an abundance of field evidence seemed to suggest strong and pervasive crystal fractionation. Many straightforward intrusions, like the Shonkin Sag Laccolith in Montana and the Palisades Sill in New Jersey, show thick layers of coarse crystals on the floor and relatively thin basaltic upper margins. A reasonable scenario for solidification, still in use today, was put forth in 1898 by USGS chemist George Becker. He postulated that laccoliths crystallize like over-chilled bottles of wine: just as crystallizing wine becomes richer in alcohol, coarse crystals grow on the walls of the magma chamber, and the remaining melt becomes progressively richer in silica. Laccoliths and magma chambers being so large, they cool much faster at the roof, nucleating and growing dense populations of crystals that settle and collect on the floor. With the discovery of large exquisitely layered bodies like Skaergaard, Stillwater, and Bushveld, the following mantra was adopted: a crystal-free magma, instantly injected, commences cooling at the roof, nucleating and growing crystals that are deposited on the floor by periodic cascading convective currents; eventually the floor cumulates reach the encased in marginal solidification fronts within which all crystallization occurs. The chemically fractionated residual melt is trapped within the front and is normally inaccessible to extraction and eruption.

![Magma Chambers](image-url)

**Figure 1** (A) The classical concept of a magma chamber where crystals nucleate, grow, and settle from the interior to chemically fractionate the residual melt. (B) The same magma chamber encased in marginal solidification fronts within which all crystallization occurs. The chemically fractionated residual melt is trapped within the front and is normally inaccessible to extraction and eruption.
thin roof crystallites, “sandwiching” a thin horizon of silica-rich differentiate. It seemed to work. But in these big systems, critical parts of the geologic picture are always missing. Where are the feeders? How was the magma emplaced? All at once? Crystal free? Did convection occur?

In smaller systems, where the full picture was better known, things were not so clear. Many sills and laccoliths show no internal sorting or structure of any kind. These can be dismissed as being too small for slow cooling and effective crystal fractionation. But the Shonkin Sag Laccolith, one of the best examples of layering, is only 70 m thick. In contrast, many 300–400 m thick basaltic sills are featureless, whereas others of this size show remarkable internal ordering. On broader scales, in higher-volume volcanic systems like Hawai‘i and along ocean ridges, crystal fractionation and the production of siliceous material should abound. In fact, little is found. At Kilauea, for example, compositionally primitive (picritic) magmas charged with olivine crystals evolve chemically by dropping out olivine. Their composition evolves from ~25% MgO and 49% SiO$_2$ to 7% MgO and ~52% silica, and then suddenly stops changing. Crystal fractionation ceases. Nothing approaching rhyolite (~70% SiO$_2$) or even dacite (~65% SiO$_2$) appears. The same is true at ocean ridges. Only in large immobile systems, like Iceland and Galapagos, are significant volumes of rhyolite formed. Why?

A fundamental obstacle to understanding magmatic processes, as mentioned already, is that large pools of active magma are inaccessible to long-term examination. The closest approximation is the Hawaiian Lava Lakes. Steep-sided basins in the landscape suddenly filled with lava to depths of over 100 m have furnished isolated pools where magma can be examined throughout solidification. Once a lava lake fills, a crust begins forming. When the crust in Makaopuhi Lava Lake became strong enough, T. L. Wright and co-workers had the foresight to drill progressively into the magma as crystallization proceeded (e.g. Wright and Okamura 1977). The value of this work to understanding magmatic processes cannot be overemphasized. What happens during solidification is quite straightforward. A flood of lava carrying a mass of large olivine crystals pools to form a lake. After a brief (days to weeks) period of instability, a crust forms on top and bottom and advances steadily inward. Some of the large olivines are caught up in the initially rapidly advancing top crust, but as the rate of cooling slows with crust thickening and as crust advancement lessens, the olivines escape wholesale and settle to form a thick cumulate pile on the floor. The lower solidification zone suddenly becomes much thicker than the top one. Crystallization proceeds in the upper and lower, inward-advancing solidification fronts, exactly along the lines predicted from heat conduction calculations. The hottest part of the system is located inward from the solidification fronts. This inner melt is devoid of crystals and remains so until the arrival of the solidification fronts, when solidification begins. [The same sequence (i.e. loss of crystals, etc.) occurs for magmas generated in the crust through basalt underplating.] With no cooling in the center, there can be no crystallization and certainly no crystal fractionation. The melt composition is constant. Tiny crystals falling from the leading part of the upper solidification front are reheated and dissolve back into the magma.

The mystery of cumulate piles of crystals, thin upper solidifica-
tion zones, and featureless bodies is solved. The answer simply revolves around the presence or absence of large crystals (phenocrysts) in the initial magma. The Shonkin Sag Laccolith was formed from magma laden with ~35 vol% phenocrysts, and the Palisades Sill arose from repeated injection of phenocryst-bearing magma (Gorring and Naslund 1995). Thick featureless sills, like the massive Peneplain Sill (350 m x 100 km) in the McMurdo Dry Valleys, Antarctica, formed from phenocryst-free magma, and the underlying Basement Sill is pervasively layered because its magma was laden with large orthopyroxene crystals (Marsh 2004). The corollary of this simple phenocryst axiom is that large exotically layered intrusions form from prolonged trains of deliveries of varieties of magma, some exceedingly laden with phenocrysts, some devoid of phenocrysts. As a large body requires more deliveries to build it, the probability is then greater that some deliveries will be phenocryst rich. The rich and varied nature of the deliveries themselves is due to the diverse magmatic environments, structural instability, style of dynamic loading and unloading, and spatially integrated nature of the underlying magmatic mush columns within which the deliveries are spawned (Marsh 2004). In size of magmatic bodies, it’s not slow cooling, but the number and nature of magmatic deliveries that lead to exoticism. The style of cooling has little to do with the outcome. All sheets of magma cool in a similar manner, regardless of depth of burial. Modest variations on this theme arise from the shape of the container holding the magma—boxes with slanting walls, tunnels, and slots each have discernable influences on filling, layering, and cooling. But how then does differentiation take place?

The most obvious means of differentiation is by massive crystal settling during emplacement. The loss of the phenocryst load, which overall can give the magma a primitive bulk composition, suddenly produces an abundance of relatively fractionated crystal-free melt. This is punctuated differentiation. It is dramatic, but limited in scope. Now the chemical evolution of the magma stalls. Further crystallization proceeds only in the solidification fronts, which encase the entire body (Fig. 1). The evolution of the body is tracked by the behavior of the solidification fronts (Fig. 2), which are defined by a bundle of isotherms contained between the solidus and liquidus, the beginning and end of melting. The hotter the isotherm the faster it advances, thickening the solidification fronts with time. In magmas of the upper
Compositions plotted on a phase diagram form a differentiation array that progresses to a point and suddenly stops (Fig. 3). From phase equilibria alone there is no obvious explanation for the truncation of differentiation. The key to deciphering this stop rests in the dynamics of solidification fronts and especially the realization that temperature is always tied to space or position in the magma. A movement in temperature and composition space on a phase diagram is a movement in position space in magma. Dropping below the liquidus is equivalent to entering the solidification front where differentiation is greatly restricted if not curtailed. This also explains the conundrum at Kilauea over the inability of lavas erupted from the summit to differentiate beyond ~7 wt% MgO and ~52% SiO₂. Olivine-laden magma stalling anywhere during ascent drops its load of crystals and fractionates to the composition defined by the leading edge of the solidification front (i.e. the liquidus), which for these tholeiitic magmas is at the magic composition of ~7 wt% MgO and ~52% SiO₂. This also explains the truncation of differentiation. The key to explaining this stop rests in the dynamics of solidification fronts and especially the realization that temperature is always tied to space or position in the magma. A movement in temperature and composition space on a phase diagram is a movement in position space in magma. Dropping below the liquidus is equivalent to entering the solidification front where differentiation is greatly restricted if not curtailed. This also explains the conundrum at Kilauea over the inability of lavas erupted from the summit to differentiate beyond ~7 wt% MgO and ~52% SiO₂. Olivine-laden magma stalling anywhere during ascent drops its load of crystals and fractionates to the composition defined by the leading edge of the solidification front (i.e. the liquidus), which for these tholeiitic magmas is at the magic composition of ~7 wt% MgO and ~52% SiO₂. This also explains the truncation of differentiation.

**SUDBURY: THE ULTIMATE MAGMATIC EXPERIMENT**

A massive ~12 km meteorite hit Earth 1.85 billion years ago. Within two minutes, it penetrated the entire continental crust and formed a transient cavity ~30 km deep and ~90 km in diameter. Within five minutes, the transient cavity relaxed to form a multi-ring crater ~200 km in diameter filled with 3 km of superheated magma. Unlike magmas generated deep within Earth, which are always at or below the liquidus, impact-generated melts can reach almost any temperature. For the Sudbury impactor the temperature may have in places reached ~2500°C, well beyond the point of vaporization of typical silicate melts, i.e. ~2000°C. The impactor itself vaporized, but the main body of the melt at ~1700°C was much cooler, although still strongly superheated relative to the liquidus at ~1200°C. All solids in the melt vanished. The stage was then set for the ultimate magmatic experiment: a large sheet-like (3 km x 200 km) volume (~30,000 km³) of magma free of crystals had been emplaced instantaneously. What happened?

Impacts are marked by massive fragmentation (brecciation) of the target rocks. At Sudbury, flash melting of these breccias produced a heterogeneous initial magma reflecting the nature of the local crust. Blobs, globs, and dollops of slightly different compositions formed a confused magmatic emulsion due to slight density and viscosity differences reflecting chemical composition. Emulsions operate much like sedimentation, except at Sudbury, parcels rapidly rose and fell depending on chemical composition. In a short time (months to years) the impact emulsion separated into two massive layers, one silica rich (~70% SiO₂) and one silica poor (~55% SiO₂). Through instant melting all the various compositional components of the local crust were allowed to cleanly reorganize into two massive layers. After rapidly (tens of years) dissipating the superheat by vigorous thermal convection, which also served to further homogenize each layer, solidification fronts migrated inward from the top and bottom. Two essentially uniform layers of rock formed the final product. There is now no sign of layering and very little sign of differentiation. Thus, instantaneous injection of crystal-free magma does not form exotically layered, well-differentiated intrusions. The Sudbury testimony is clear: no phenocrysts, no layering. This is the Null Hypothesis (Zieg and Marsh 2005).

**CONTINENTS**

Continents are ultimately differentiates of basalt (e.g. Davidson and Arculus 2005). There is no way around it. There is no indication from meteorites that granitic rock was any part of the original solar debris forming Earth, to be sorted and collected, like at Sudbury, through meteorite impacts into continents. Basalt comes from partial melting of the underlying primitive mantle during convection through a phase boundary, the mantle solidus. But the main problem is that basalt does not physically fractionate directly into silicic continental building blocks. There are two principal physical routes to the formation of continents, and both involve solidification fronts.

Roof solidification fronts in basaltic magma commonly thicken to the point of becoming structurally unstable, failing under the action of gravity by tearing internally (e.g. Marsh 2002). Forming well within the solidification front,
the tears fill with local residual interstitial melt, which is enriched in silica (~60–65% SiO$_2$) and other continent-like components. These isolated silicic segregations are scattered at specific horizons and can only be amassed or collected by wholesale disruption of the solidification front itself. During the earliest stages of Earth formation, it is likely that magma oceans prevailed and solidified much like lava lakes. Because of the scale and steady heavy meteorite bombardment, the upper solidification front continually foundered and remelted in the underlying superheated magma, freeing the silicic segregations; these steadily collected, almost like lint, on the surface. This runaway process might well have rapidly produced the first continental vestiges (Fig. 4). Additional processes (e.g. erosion, sedimentation, metamorphism, etc.) are needed to transform these differentiates into continental material (e.g. Rudnick 1995), but the mechanism described above is perhaps the critical physical process required to bridge the basalt differentiation impasse. From a purely chemical perspective, solidification front instability is indistinguishable from normal fractional crystallization.

The key to this physical process of producing primordial crustal material is the recycling of the solidification front, which is unavoidable in any major magmatic system stationary long enough to undergo substantial reprocessing. All major oceanic volcanic systems of this nature produce highly silicic material. Iceland, Rapa Nui (Easter Island), and the western Galapagos Islands are good examples. At Iceland, lying athwart the Mid-Atlantic Ridge, about 18% of the surface rocks is highly silicic. Periodic jumps of the oceanic ridge into older parts of Iceland promote reprocessing, and the silicic lavas are full of telltale signs (e.g. clots of leucocratic silicic rocks) of this process (e.g. Gunnarsson et al. 1998). Volcanic centers like Hawai’i are too mobile to allow any significant reprocessing—once the system is built it becomes extinct, moves on, and a new center is built. The Moon is similar. Although strongly differentiated, there is no sign whatsoever of granitic rock on the Moon because there has been no protracted magmatism to reprocess the initial crust.

**MUSH COLUMNS, CRYSTAL CARGO, AND GRANULAR PROCESSES**

The traditional approach to understanding the chemical evolution of erupted magma is to assume a source rock, generate the magma through partial melting, and move it to a near-surface magma chamber where crystal fractionation achieves the final product. The magma gains its chemical identity through “source” and “high-level” generic crystal fractionation and contamination processes, and the spatially and temporally protracted intervening path from depth to near surface is, per force, unneeded and ignored. An increasing abundance of evidence in near-surface and erupted magma reveals, however, that the most important part of the life cycle of magma is what happens during ascent, when a series of physical processes buttressed by chemistry operate. The magnitude of the load of large crystals, carried by the moving magma and critical to punctuated differentiation when the magma tarries during ascent, is proportional to the local transport flux. Playing the role of suspended sediment in a surging river at flood stage, the crystal cargo also acts as a tracer to the dynamics of ascent and emplacement or eruption. In fissures and dikes this crystal slug forms a central tongue or swarm, which is deposited on the floor of a sill after the magma in the dike stalls and moves horizontally into the sill (Simkin 1967). This Simkin Sequence is a key link between the dynamics of magma in dikes, sills, layered intrusions, and major volcanoes. The regional distribution of phenocrysts in sills reflects the point of infilling and recharge. Local magma ponding and successive avalanching of crystal slurries produces distinct layering through granular sorting. Mechanical
processes produce the basic layering, which is then buttressed by diffusive chemical processes. The Dais section of the Basement Sill in the McMurdo Dry Valleys, Antarctica (Fig. 5) exhibits this critical relationship. The cargoes of crystals themselves also have a rich story to tell.

The provenance or ultimate source of the individual crystals often reflects contributions from deep wall rock, deep older cumulate deposits cognate to the system, and crystals freshly nucleated and grown in transit. At any level, the magmatic system consists of a “carrier” magma containing varying proportions of these genetic contributions. None of the crystal ensembles are fully at chemical equilibrium, but each locally reacts with the magma to produce, in detail, assemblages of older crystals armored by overgrowths, crystals dissolving and regrowing, and fresh crystals growing in magma of changing composition. Detailed microsampling of individual nearby (within a centimeter) crystals reveals strong compositional and isotopic diversity (e.g. Dungan and Davidson 2004; Davidson et al. 2005), indicating a multidimensional magmatic mush column open and highly integrated from source to surface and operating under the temporal pulse of volcanism (Marsh 2004).

CONCLUSION

The ultimate challenge to understanding the dynamics of planetary magmatism is the quantitative perception of a unified process accurately combining dynamics operating on the smallest spatial scales in solidification fronts with the spatial structure and rhythms of volcanism operating on the largest scales. Processes operating between crystals and melt at the smallest scales within solidification fronts and in mingling slurries give rise to planetary-scale effects. Regardless of the system, there is every indication of a single broad magmatic style operating under various themes.

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FIGURE 5 The Dais section of the Basement Sill, McMurdo Dry Valleys, Antarctica. The 450 m section exhibits an extreme variation in composition, ultramafic (~mantle) at the base and dioritic (~continental) at the top. Rich modal layering on many scales is due to the mechanical sorting of large pyroxenes and tiny plagioclases, producing layers of orthopyroxenite and anorthosite. This sorting is reflected in strong chemical variations (see CaO–MgO inset) over short (5–15 m) distances (after Marsh 2004).
The structure and properties of both natural and industrial glasses are influenced by the presence of small amounts of specific elements. Selected examples illustrate the roles of various elements in controlling properties such as coloration, stability, and optical and thermal properties, as well as the effect of redox state of multivalent elements (Ni, Fe, Zn, Zr, Mo) on chemical properties.

**INTRODUCTION**

Natural glasses form on Earth during rapid cooling of melts ranging in composition from basalt to rhyolite. They also form upon impact of extraterrestrial objects on Earth (as in the case of tektites) and as a consequence of impacts or volcanic activity on the Moon and rocky planets. Whatever their origin, natural glasses and their synthetic analogs provide key insights—through study of their structure and properties—into the melting processes that shape our planet and our neighbors in the solar system. Multivalent elements present at low concentration play a role in the geochemical environment and redox state that prevailed during glass formation, and also in the subsequent history of the host glass.

Early humans used natural glasses such as obsidian for specific purposes, such as cutting tools or arrowheads. For more than 7000 years, glass has played an important role in the everyday life of humans and in the evolution of technological materials. In recent times, silicate and borosilicate glasses that exhibit a wide range of properties and are used in a number of industrial applications (e.g. glassware, packaging, building, optical devices) have been developed. Today, it is possible to “tune” a number of glass properties by varying the composition and fabrication conditions, something not attainable with crystalline phases. The typical compositions of the most widely used industrial glasses have not changed much from antiquity to modern times. However, their properties have been greatly improved not only by the modern technologies of fusion, fining and glass fabrication, but also by the addition of small amounts of elements that play specific roles. This paper provides some snapshots of our understanding of glasses through an examination of the role of selected elements—present at levels ranging from a few parts per million to a few per cent—in the structure–property relationships of natural and industrial glasses.

**GLASS COLORATION: THE CASE OF NICKEL**

Most glasses lacking impurities, defects, or crystalline nanoparticles are colorless and do not absorb visible light. However, the natural raw materials used in the glass-making process (sand, sodium carbonate, and calcium carbonate for soda-lime glass) may contain small amounts (<1%) of iron-bearing crystalline phases that can give rise to a pale brown or green tint related to the redox state of iron in the glass. Progress in achieving colorless, transparent glasses has been made by selecting high-purity raw materials.

In many areas of the glass industry, however, colored glasses are required, e.g. perfume packaging, tableware, and in the restoration of stained glasses. Glass color has many origins: (1) the presence of specific coloring elements, such as transition elements, which play a role at the microscopic scale in the glass structure; (2) dispersed nanophases, such as gold (Au°), colloidal copper oxide (Cu°), and cadmium selenium sulfide (CdS,Se); and (3) coatings of metallic or semiconducting materials on the glass surface. Transition elements are particularly efficient coloring agents in glasses, even at low level (a few per cent or lower); they can produce a wide range of colors and hues depending upon the transition element present, its redox state, and its local environment in the glass structure. The color-causing process is related to the electronic transitions, induced by absorption of light in the visible region, between two d orbitals of the cation for which degeneracy has been removed by the presence of anionic ligands in a specific geometry. For example, Fe^{2+} in six-fold coordination (represented as [6]Fe^{2+}) can produce blue or green hues, and [4]Fe^{3+} a yellow/brown color.

The range of colors that can be produced by the presence of a single transition element with a single redox state at low concentration is perhaps best illustrated by nickel (Ni^{2+}). Depending on its local environment (site) in the glass structure, nickel imparts a wide range of colors to glass (Fig. 1). When Ni^{2+} is diluted in the glass structure, only the nature of the cation playing the role of charge compensator can change the glass coloration from brown to purple (variation of the ratio [4]Ni^{2+}/[5]Ni^{2+}), regardless of the glass composition. The nickel concentration has no influence on the glass color (Galoisy and Calas 1993a, b).

As for other transition elements (see, for example, Henderson et al. 2006), five-fold coordination is the predominant coordination for Ni^{2+} in most silicate, borate, and borosilicate glasses and induces a brownish coloration (Galoisy et al. 2005). However, in glasses with high concentrations of
low-field-strength cations (such as K\(^{+}\)), Ni\(^{2+}\) is predominantly in tetrahedral coordination, and the glass takes on tints from blue to purple. \(^{[5]}\)Ni\(^{2+}\) in glass seems to be indicative of the associative/dissociative reactions occurring in the melt above \(T_g\), which are associated with the viscous flow and the chemical diffusion that characterize silicate melts (Farnan and Stebbins 1994). Because Ni\(^{2+}\) is tetrahedrally coordinated in melts (Farges et al. 1994), \(^{[5]}\)Ni in glass is probably a transient species, formed during the quench of the melt via the association of a fifth oxygen to the four oxygens surrounding Ni\(^{2+}\). The geometry of the Ni sites in the glass explains the structural dependence of the glass color.

**THE KEY ROLE OF CATIONS IN GLASS STABILITY**

The stability of glass is an important property that is promoted by inhibiting nucleation and crystallization in response to a physical or chemical change (e.g. heating). Stability is determined mainly by the glass structure, which is in turn determined by its composition. In some instances, nucleation may be desired, and Zr and Zn at low concentrations are used sometimes in industrial glasses as nucleating agents. Interestingly, however, these cations have different structural roles in oxide glasses: depending upon their local environment, they can act as agents for the nucleation and crystallization of specific phases or, in contrast, as a means to increase glass stability.

**The Influence of Zn\(^{2+}\) Charge Compensation and the Local Environment of Zr\(^{4+}\) on Stability and Chemical Durability of Glasses**

The redox state of Zn in glass is Zn\(^{2+}\). In alkali-bearing glasses, Zn\(^{2+}\) usually shows a marked preference for tetrahedral sites with, for example, Na\(^{+}\) compensating for the charge deficit of the ZnO tetrahedra. In this case, Zn\(^{2+}\) is associated with the network-forming SiO\(_4\) tetrahedra and stabilizes the glass structure. In alkaline earth silicate and aluminosilicate glasses, in the absence of alkalis, Zn has a nucleating role (Dumas and Petittau 1986). When no alkali is available for charge compensation, Zn\(^{2+}\) appears to be located in octahedral sites. In Mg-aluminosilicate glasses with a low Zn concentration (cordierite composition with 3 wt% ZnO), the measured Zn–O distance (using EXAFS spectroscopy) does not enable discrimination between \(^{[6]}\)Zn\(^{2+}\) and \(^{[6]}\)Zn\(^{2+}\). However, heating to \(860^\circ\)C for two hours leads to crystallization of gahnite (ZnAl\(_2\)O\(_4\)), in which Zn\(^{2+}\) is in 6-fold coordination, suggesting that a significant proportion of Zn\(^{2+}\) exists in the glass at room temperature. In this case, the presence of Zn\(^{2+}\) destabilizes the glass structure and promotes crystallization of gahnite.

In complex borosilicate glasses, there is strong competition among the different cations for the charge-compensating alkali and alkaline earth elements (Cormier et al. 2000). A recent study has shown that Zn\(^{2+}\) is in 4-fold coordination and corner-linked to the SiO\(_4\) polymeric network in these glasses (Le Grand et al. 2000). Zn\(^{2+}\) thus competes favorably for charge compensation by alkali or alkaline earth elements versus other cations, such as tetrahedral boron (\(^{[4]}\)B), Al\(^{3+}\), and highly charged Zr\(^{4+}\). The improvement of the mechanical and thermal stability of low-Zn borosilicate glasses containing low-field-strength cations (e.g. Na, K, Cs, Rb) may be explained by the network-forming role of Zn\(^{2+}\) in these glasses. The presence of Zn\(^{2+}\) decreases the effective modifying cation concentration, as more alkalis are involved in compensating its charge. The structure-reinforcing effect of Zr\(^{4+}\) may also arise from the specific location of Zr tetrahedra within the glassy network, i.e. incorporated into small rings such as rigid 4-membered rings. In addition, Pauling’s rules limit the possibility of Zn–O–Zn linkages due to the resulting underbonding of oxygen atoms, which explains the absence of Zn-rich clusters.

The case of zirconium is somewhat different. Zirconium is a highly charged cation (Zr\(^{4+}\)) existing mainly in three different crystalline compounds in the glasses: in 6-fold coordination in zircon (ZrSiO\(_4\)), in 7-fold coordination in zirconia (ZrO\(_2\)) and in 6-fold coordination in zirconosilicate crystals. Depending on the site occupied by Zr\(^{4+}\) in the vitreous matrix, the role of the cation will be very different and induce different properties in the glass. Zr\(^{4+}\) is used in the glass-ceramics industry as a nucleating agent (in the absence of alkali in the starting glass), with zirconia being one of the major phases in the resulting glass-ceramic (Meneghini et al. 2004). The presence of zirconia in the glass reinforces the thermal and mechanical resistance of the glass. In borosilicate glasses containing 2% ZrO\(_2\), Zr\(^{4+}\) is in 6-fold coordination, compensated by alkali and alkaline earth cations (Galoisy et al. 1999). The stability of these glasses to alteration in water has been explored with a view to their possible use as high-level nuclear wasteforms. When subjected to static flow conditions, the glass is altered to a gel formed at the interface between glass and water. Zirconium takes part in the polymerization of the gel and retains the local atomic environment occurring in the glass (\(^{[6]}\)Zr). The presence of this stable gel phase protects the glass from further degradation. On the other hand, under dynamic flow conditions, the coordination number of Zr increases (\(^{[7]}\)Zr) in the gel, and subsequent crystallization of a dense ZrO\(_2\) phase affects the chemical stability of the gel, defeating its protective role. This example illustrates the fundamental role of a small amount of zirconium in these glasses in determining alteration behavior.
SPECIFIC ROLE OF IRON AND SULFUR IN INDUSTRIAL AND NATURAL GLASSES

Iron and sulfur can affect the thermodynamic, chemical and physical properties of both natural and industrial oxide glasses.

Five-fold Coordination of Iron in Industrial Glasses: Influence on Optical and Thermal Properties

In industrial glasses, specific oxides determine various properties, such as melting point, mechanical characteristics, chemical resistance, and color. In terms of energy savings in the heating and cooling of buildings (reduction of interior heat build-up or improvement of comfort by reduction of solar radiation) and protection against harmful UV rays, iron is one of the most important elements because small amounts (0.1 to 2% Fe oxide) absorb selectively in both the IR and UV domains, depending upon oxidation state (Ushino et al. 2000). Ferrous iron absorbs around 1000 nm (10,000 cm\(^{-1}\)) and 2000 nm (5000 cm\(^{-1}\)) in the near IR to visible domain (Jackson et al. 2005), while Fe\(^{3+}\) absorbs around 400 nm (25,000 cm\(^{-1}\)) in the near-UV domain (Fig. 2A). Jackson and co-authors showed that Fe\(^{2+}\) is predominantly in 5-fold coordination in soda-lime glasses. However, both Fe\(^{2+}\) and Fe\(^{3+}\) can exist in three different types of sites (4-, 5-, and 6-fold coordination) in varying proportions, and each site induces specific optical transitions that influence the transmission window. Iron can thus be used to modify the above-mentioned properties to optimize the glass transparency in the visible region and avoid both IR and UV influences. Precise determination of the redox state of iron is thus fundamental to the improvement of these important properties of glasses (Chopinet et al. 2002).

Chemical Properties of Extraterrestrial Glasses: Redox State of Iron

Knowledge of the redox state of iron is important in petrology for establishing thermodynamic models for multicomponent melts and magmas. However, when both Fe\(^{2+}\) and Fe\(^{3+}\) are present in natural glasses, determination of the structural environment of iron in each redox state is difficult. For this reason, the redox state of Fe is characterized mainly using synthetic glasses prepared under controlled conditions (Gaillard et al. 2003). The resulting information can then be applied to natural glasses, including extraterrestrial examples such as tektites and lunar glasses, for which the Fe redox state can provide important insight into the specific conditions of formation.

The first reported application of this type is the redox state of iron in tektites in relation to its local environment. Tektites are natural green glasses with a high SiO\(_2\) concentration (>70 wt%) that are found in large but well-defined dispersion fields on Earth’s surface. Historically, the origin of tektites has been controversial. They were first believed to be of lunar origin, but it is now widely accepted that they result from melting of terrestrial rocks during hypervelocity meteor or comet impacts (Montanari and Koeberl 2000). The oxidation state and the coordination number of iron and aluminum in tektites have been widely investigated in order to understand the combined effects of temperature, pressure, and oxygen fugacity (f\(_{O_2}\)) on the local structural environment of these cations in such glasses (Dunlap et al. 1998; Giulii et al. 2002). Early studies showed iron (present at 2 wt% or less) to be mostly divalent (<10% Fe\(^{3+}\)) but controversy remains over the coordination number (4 or 6). Recently, other types of studies involving Mossbauer spectroscopy and molecular dynamics calculations (Fig. 2A) appear to favor a continuous distribution of sites between 5-fold coordinated Fe\(^{2+}\) and Fe\(^{3+}\) in tetrahedral sites (Rossano et al. 1999; Rossano et al. 2000). The inferred geometry of the 5-fold site is a trigonal bipyramid similar to [Ni\(^{2+}\)] in glasses (see previous section). The high temperature of formation is probably responsible for the predominantly ferrous state, as the impact melt ejected into the upper atmosphere would have no time to equilibrate with the reduced total air pressure, given relatively slow diffusion. The geometry of the site ([Ni\(^{2+}\)]) may be related to the high speed of quench for these glasses. In a silicate liquid in which oxygen atoms are mobile, the sites around cations are in a state of perpetual destruction and reconstruction. The 5-fold site could be transient, indicating that the glass structure is a result of chemical interactions between the elements in the liquid, as shown previously for [Ni\(^{2+}\)].

The second example pertains to lunar glasses that show two distinct colors (green and orange). In these glasses, iron and titanium are present at approximately 5 and 20 wt%, respectively. The green color of the glass is readily attributed to the redox state of iron being mainly Fe\(^{2+}\), due to the absence of significant atmosphere on the Moon. The orange color of some lunar glasses was at first very enigmatic. Early on it was suggested that water played a role in the formation of these glasses by inducing some Fe\(^{3+}\), which gave rise to the orange coloration. Analyses revealed, however, that the phenomenon responsible for the color is a charge transfer between Fe\(^{2+}\) and Ti\(^{4+}\). No water is present on the Moon to induce a local change of iron oxidation state (Bell et al. 1976).
Sulfur and Iron as Indicators of the Conditions of Formation of Volcanic Melts

Sulfur is an important component of volcanic gases, occurring dominantly as \( \text{SO}_2 \) and \( \text{H}_2\text{S} \). It can exist under redox states varying from \( \text{S}^2- \) to \( \text{S}^6+ \), depending on redox conditions in the host magma. Basaltic melts produced in subduction zones are enriched in sulfur and water relative to magmas from ocean ridges or plumes. As a consequence, large amounts of sulfur are released during explosive eruptions of arc volcanoes. Primary basaltic glass inclusions (40 to 80 \( \mu \)m) trapped in olivine crystals at various active volcanoes (Stromboli and Vesuvius, Italy; Piton de la Fournaise, Réunion Island) contain \(- 1100 \) to 2950 ppm S (Fig. 3). These vitreous inclusions provide information on the composition of magmas before major release of sulfur and water. Total S is mainly dissolved as sulfate (\( \text{SO}_4^2- \)), along with minor sulfate (\( \text{S}^{IV} \)) and sulfite (\( \text{S}^{VI} \)). The presence of these latter two species can lead to the possibility of partial equilibrium between \( \text{S}^{IV} \) and \( \text{S}^{VI} \) in melts. The presence of sulfite might explain part of the production of \( \text{SO}_2 \)-rich gas during the ascent of magmas (Métrich et al. 2002). Another way to assess the redox state of magma is the determination of the redox state of iron in the same basaltic glass inclusions. The \( \text{Fe}^{\text{III}}/\Sigma\text{Fe} \) ratio is an indicator of the oxygen fugacity prevailing in the melt before the eruption. The \( \text{Fe}^{\text{III}}/\Sigma\text{Fe} \) value in glasses from arc basalts has shown that oxidizing conditions dominate (in contrast to mid-ocean ridge basalts, which are relatively reduced), a fact consistent with the increased proportion of sulfate in arc basalts.

FROM CLUSTERS TO PHASE SEPARATION: MODIFICATION OF GLASS PROPERTIES

In this section, the importance of organized domains (clusters) around impurities at a microscale will be emphasized and the resulting glass properties described.

Unusual Colors of Glasses

In minerals, the crystal field stabilization energy for \( \text{Ni}^{2+} \) is highest for 6-fold coordination with oxygen (\( \text{Ni}^{2+} \)), as in garnierite (Burns 1993). Six-fold coordination of Ni is in fact typical of crystalline materials, but is rarely found in common oxide glass compositions (see above).

Under special circumstances, however, \( \text{Ni}^{2+} \) is stabilized in glasses. In low-alkali borate glasses doped with \(- 2 \) wt\% NiO, for example, the presence of large \( \text{BO}_4^3- \) structural units induces the presence of Ni-enriched domains in which \( \text{Ni}^{2+} \) is in 6-fold coordination. These clusters are ordered up to the medium-range scale (\( \text{X}\text{A}_{\text{A}} \)), with collinear, edge-sharing \( \text{NiO}_6 \) octahedra (Cormier et al. 1999). This phenomenon occurs at Ni concentrations in the 0.1 to 2 wt\% range; it does not affect the transparency of the glass and gives it a bright green color (Galaisy et al. 2001) (Fig. 1).

In borosilicate glasses doped with \(- 2 \) wt\% NiO, a bright orange color is observed for sodium or potassium contents of about 10 mol\% (Galaisy et al. 2005). In these glasses, \( \text{Ni}^{2+} \) has been observed, for the first time, with three different coordination states (4, 5 and 6). The orange coloration of these glasses is also independent of the Ni concentration, which varies from 0.5 to 2 wt\%. The low alkali content can explain the various environments: \( \text{Ni}^{2+} \) is probably associated with the borate units of the glasses as low alkali content favors 6-fold coordination in borate glasses, while \( \text{Ni}^{2+} \) and \( \text{Ni}^{3+} \) are probably associated with the \( \text{SiO}_2 \) network as no 6-fold-coordinated Ni can occur in silicate glasses. These hypotheses are supported by the separation between the silicate and borate networks in the borosilicate glass structure (Lee and Stebbins 2002).

Stability of Industrial Borosilicate Glasses Containing Iron or Molybdenum

The practical interest in borate and borosilicate glasses in the glass industry stems from the influence of boron on the properties of the glass (low melting temperature, resistance to thermal shock, low thermal expansion), which make these glasses useful for optical, medical, and more specialized technical applications (e.g. Babal® and Pyrex® glasses). The presence of iron (\( \text{Fe}^{2+} \) and \( \text{Fe}^{3+} \)) as an impurity in the natural raw materials used in the glass-making process can influence some physical properties of the glass, such as durability. Babal® glasses [(100-X)(0.30BaO 0.50B\(_2\)O\(_3\) 0.20Al\(_2\)O\(_3\)) XFe\(_2\)O\(_3\)], with X up to 10 mol\%, have been synthesized and studied using different techniques, including XRD, EPR, Raman, and dissolution rates. As had been observed previously for the addition of CaO in borate glasses, an increase in Fe\(_2\)O\(_3\) induces conversion of boroxol rings into structural units such as diborate, tetraborate, and pentaborate groups. Increasing Fe\(_2\)O\(_3\) also leads to formation of iron clusters that reduce the glass network connectivity. These structural modifications cause a dramatic decrease in the chemical glass durability (Tadeu do Reis et al. 2003).

Molybdenum is a nucleating agent used in the glass-ceramics industry to control the phase separation of glasses (McMillan 1979). Mo\(_{6+}\) has low solubility in alkali or alkaline earth borosilicate glasses and is responsible for the formation of the so-called “yellow phase” containing crystalline alkali molybdates, which are sometimes observed in high-level nuclear waste glasses. Because of the solubility of these compounds in water, the presence of such phases may decrease the chemical durability of the nuclear waste glass. Mo\(_{6+}\) has been shown to be in 4-fold coordination in these glasses, but, in contrast with Zn\(^{2+}\), Mo\(_{6+}\) has no connection with the SiO\(_2\) polymeric network; rather, it is located in the alkali-rich domains of the glass structure (Calas et al. 2003). This siting may explain the preferential crystallization of
mo

lloys, a phenomenon also consistent with the fact that Na- and Ca-molybdate phases are found in molten and glassy states, respectively. The presence of the two different phases is the result of competition for charge compensation. At high temperature in the molten state, boron is mainly in 3-fold coordination, and alkalis are thus available to compensate the charge deficit of the 4-fold-coordinated MoO₄⁶⁻. This explains the formation of a good sodium molybdate phase. In contrast, in the glassy state around Tₐ, boron is mainly in 4-fold coordination, and its charge is compensated by alkalies. Only an alkaline earth such as Ca⁡⁺⁺ will then be available to charge compensate [⁴⁰⁺¹⁰⁴ Mo]⁶⁺, and calcium molybdate phases will result (Cormier et al. 2000).

CONCLUSION

The study of both natural and industrial glasses is at an exciting stage in its history, and lessons learned from one can often be applied to the other to great advantage. The study of impurities in geological glasses can help elucidate the conditions of formation of these materials from their parent melts. The need for diversification of industrial glasses has grown as their use in everyday products and processes has expanded, e.g. in tableware, automobile parts, building and insulating materials, communications, and medical applications. Understanding the structural and chemical complexity of glasses is important to explain the remarkable variations in their chemical and physical properties, and the structural role of impurities is particularly complex. The examples highlighted above underscore the importance of studying glass structure at the submicroscopic scale. The great variety of local atomic environments around cation “impurities” provides an example of the heterogeneity of the vitreous structure at that scale. Key properties, such as durability, stability, coloration, and chemical resistance of the glass, can be dramatically influenced by the structural role and variation of the redox state of these cations, as well as by their competition for charge compensation. Observational studies of glass microstructure and corresponding properties—in addition to the use of models from molecular dynamics—are promising ways to explore and develop new glass compositions for future applications in the glass industry.

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I must admit that it is a pleasure to see so many questions and objections that are set out in PPP. Are we on the cusp of a paradigm shift? Will the students of 2056 look back on the Great Plume Debate as the moment when “modern” mantle plume advocates now need to provide counter-arguments to the serious objections that are set out in PPP. Are we on the cusp of a paradigm shift? Will the students of 2056 look back on the Great Plume Debate as the moment when “modern” mantle plume hypothesis can sometimes reconcile data with theory, the adulated hypothesis thus becomes essentially untestable, and plumes thereby become indefinable.

Many of the papers in PPP address the issues of whether or not “hotspots” are anomalously hot in contrast to normal MORBs and of the relative importance of excess temperature versus fertile source composition as an explanation for the larger melt volumes of “hotspots” (or “hotspots” as some would state it). For the Hawai’ian case (as for many other examples), there seems to be no compelling argument for hotter temperatures, and many geochemists have already proposed the participation of non-periodotitic source components to explain the larger magmatic fluxes and particular geochemical and mineralogical characteristics of these magmas. For Iceland, there is an ongoing debate about the temperature issue, which seems to hinge on how the composition of the “primary” melt is calculated, a matter about which there is no consensus as yet. The excess-volume argument for Iceland is addressed creatively in PPP by proposing that a large slab of Caledonian-age oceanic crust trapped in an orogenic suture zone is being recycled (i.e., the dominant Iceland source is not peridotite). That there is much discussion on this topic is no surprise, since the problem of hotspot magma genesis is extremely intractable, with the nature of the calculated melt and residue compositions being critically dependent on assumptions about source composition and melting processes. For that matter, there is little consensus on how MORB or arc magmas form either.

The basic data documenting the trends and age progressions of putative volcanic plume tracks are also considered in much detail in PPP. This phenomenological critique of the assumptions underlying the plume hypothesis is extremely effective. Data from several ocean basins and some continents show that most hotspot-type volcanism does not define coherent age-progressive tracks (contrary to popular belief), commonly exploits older linear structures (in many cases repeatedly), may occur synchronously at widely dispersed sites (right across Africa, e.g.), with age-spikes that can be correlated to documented plate-boundary reorganizations or collisional events. In a similar vein, the evidence for radiating dike swarms associated with plume-driven continental breakup is critically reexamined. Many apparent radiating patterns turn out to be composite structures, with directions controlled by an older tectonic grain or with several generations of intrusions constituting the pseudo-radial pattern.

Alternative plate tectonic explanations have been suggested for many volcanic features attributed to “hotspots,” including crack propagation, reactivated and incipient plate boundaries, membrane and extensional stresses, gravitational anchors, reheated slabs, decompression melting of heterogeneous mantle, leaky transform faults, etc. Many of these models are discussed in PPP and a variety of plausible alternative explanations for the data are provided. The diversity of proposed mechanisms suggests that there is more than one way to induce mantle melting, which may thus produce a concomitant diversity in the types of hotspots seen on Earth.

One anomaly in PPP is the near-absence of debate about how plume intensity may have varied with time. Archaean komatiites are widely considered to have been hotter than modern MORB and are generally interpreted to have formed from plumes, with a minority view assigning some types of komatiite to a subduction environment. Here, too, there is a vigorous debate in the literature, which is only barely touched on in PPP. Another anomaly is the near-absence of dissenting voices. Although the pro-plume viewpoint is abundantly represented in the literature, it would have been nice to see a couple of summary papers by the most devoted defenders of the hypothesis. Despite the strong anti-plume case that is made in PPP, I can’t help but feel that somewhere in the bathwater there might be a viable baby. Perhaps plumes are not as ubiquitous as is commonly assumed, but given our profound ignorance of the deep mantle it seems premature to categorically reject the possible existence of active plume-like instabilities. On the other hand, uncritical acceptance of the plume hypothesis to explain linear volcanic chains will never again be possible for anyone who takes the trouble to read PPP. Plume advocates now need to provide counter-arguments to the serious objections that are set out in PPP. Are we on the cusp of a paradigm shift? Will the students of 2056 look back on the Great Plume Debate as the moment when “modern” mantle plume dynamics originated? Whichever viewpoint ultimately prevails, PPP will remain an important milestone in the evolution of thought on mantle plumes by focusing and triggering debate on this important issue.

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The chapters in Molecular Geomicrobiology reflect the great advances made in the last few years in our understanding of microbial roles in mineral formation, mineral diagenesis and degradation. They reinforce expectations of further rapid progress in the field. They also clearly demonstrate how important the extensive collaboration of environmental microbiologists, molecular microbiologists, geochemists, mineralogists, organic and inorganic chemists, as well as specialists in each of these fields, has become to geomicrobiology. Such collaboration provides the complementary expertise in different fields and the special instrumentation in the laboratories of these experts that are needed to attain a desired research goal.

The volume was prepared for a short course entitled MolecularGeomicrobiology, sponsored by the Mineralogical Society of America, the Geochemical Society of America, the US Department of Energy, and NASA Astrobiological Institute, and held at the University of California Berkeley, December 3–4, 2005 prior to the fall AGU meeting in San Francisco.

Depending on their scientific background, different readers of this volume may find some chapters of greater interest than others, but that should in no way discourage them from perusing the other chapters. All chapters include a wealth of references, with emphasis on the most recent literature pertinent to the topic of the chapter. All authors make clear that much remains to be discovered and that molecular geomicrobiology is a work in progress.

Among the topics treated in this volume are the following: a consideration of how genetics can be applied to geomicrobiology and geobiology in general; electron transport phenomena in microbial redox interaction with certain metals of mineralogical interest in the environment; siderophore interaction with iron-bearing minerals in marine environments; iron cycling in a geomicrobial context; nanoscale mineral particles, some of their properties, and aspects of microbial formation of and interaction with such particles; the role of the organic-mineral interface in the formation of biominerals by prokaryotic and eukaryotic microbes; speculation about the transition from abiotic to biotic catalysis in the origin of life; the evolution of carbon and nitrogen cycling in the Precambrian and beyond; advances in the use of biomarkers to construct the tree of life; the use of biomolecular techniques in studying population dynamics in extreme environments; and examples of the use of genomics and proteomics in geomicrobiology.

For instructional purposes, this volume would have benefited from a glossary of special terms; and examples of the use of genomics and proteomics in geomicrobiology.

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In Ending in Ice, Roger M. McCoy, emeritus professor of physical geography at the University of Utah, recounts the life and accomplishments of Alfred Wegener. Of course, the name is familiar to Earth scientists and intertwined with the term “continental drift” (we learn that “drift” was not the best translation of Wegener’s term Verschiebung; “displacement” would have been a better term). But how did an astronomer/meteorologist with no background in geology and geophysics come to publish on what was at the time a revolutionary idea in Earth sciences? As a climatologist, Wegener became interested in past climates and started examining fossil evidence worldwide with his father-in-law, Wladimir Köppen (who published a classification of climates still in use today). He became intrigued by the similarities of nonmarine Paleozoic fossils in Africa, Brazil, and India and started digging for more evidence.

Others before him had postulated that continents might once have been joined into a single supercontinent and had drifted into their present position, but Wegener was the first to compile extensive geological, geodetic, and paleontological data in support of the idea. He first presented his concept in 1912 at a meeting of the Geological Association of Frankfurt. His book The Origin of Continents and Oceans was published in German in 1915. The subsequent three editions were extensively revised and new data added. The third edition (1922) was translated into French, Spanish, and English in 1924. Once the English version became available, the hypothesis became more widely known. In 1926, the Royal Society and the Association of Petroleum Geologists convened special sessions to discuss the theory. For lack of a plausible mechanism to move the continents, the idea was heavily criticized and abandoned. It would not be until the 1960s that new evidence would lead to the birth of plate tectonics.

Born in Berlin in 1880, Wegener first worked as an astronaut, then as a meteorologist. In 1906, he was invited to join a Danish expedition to Greenland. This expedition initiated his other lifelong scientific interest: the climate of Greenland. Why was there so much interest in Greenland’s climate at that time? Air travel was expected to become commonplace in the near future, and many routes would pass over Greenland. McCoy provides a gripping account of the harsh conditions and complex logistics of the 1929–1930 expedition led by Wegener. This expedition was the first to establish a station in the middle of Greenland at Eismitte with the purpose of collecting climatic data in winter. Establishing that station was the undoing of Wegener. He died tragically of exhaustion returning to the coast from Eismitte.

In the final chapters, McCoy summarizes the advances that eventually led to the acceptance of plate tectonics. As such, it provides an excellent summary of how all the pieces of the puzzle came together in the 1960s. Such historical accounts are invaluable for putting progress and changes in paradigms in perspective. Wegener’s story illustrates what holds true for many scientific breakthroughs: people deny it is true at first; then they deny it is important; then they credit the wrong person. So before shooting down the next new idea that comes along, think twice.

Many archival photographs and an index add to the enjoyment and usefulness of the book, which reads like a novel.

Pierrette Tremblay
Québec City
2006 STUDENT TRAVEL GRANTS

With support from donors and the National Science Foundation, GS is pleased to announce the 39 students who have been awarded travel grants to the 2006 Goldschmidt Conference in Melbourne, Australia. Each received a $1000 travel grant with the top ten (*) receiving an additional $100. Congratulations students!

Rich Abell (University of Bristol)
Rasmus Andreasen (Dartmouth College)
Lisa Baldini (University College Dublin)
Judith Barrett (Manchester Metropolitan University)
Frank Black (University of California Santa Cruz)
Madalyn Blondes (Yale University)
Alexander Bradley (Massachusetts Institute of Technology)
Aaron Celestian (State University of New York at Stony Brook)
Kirsty Crocket (University of Bristol)
Andrew Cyr (Purdue University)
Lois Davidson (University of Leeds)
Carolyn Dykoski (University of Minnesota)
Juyoung Ha (Stanford University)
Pamela Hill (University of California Los Angeles)*
Ulyana Horodyshyj (Rice University)
Fang Huang (University of Illinois at Urbana-Champaign)
David Johnston (University of Maryland)*
Sang-Tae Kim (McGill University)
Rhesa Ledbetter (Idaho State University)*
Harris Mason (State University of New York at Stony Brook)
David McGee (Tulane University)*
John Moreau (University of California Berkeley)
Alison Olcott (University of Southern California)*
Frederick Parthey (Massachusetts Institute of Technology)
Julie Pett-Ridge (Cornell University)*
Céline Pisapia (Centre de Recherches Pétrographiques et Géochimiques)
Cara Santelli (Woods Hole Oceanographic Institute)
Anat Shabar (University of California Los Angeles)
Sheri Simmons (Massachusetts Institute of Technology)*
David Singer (Stanford University)
Aaron Slowey (Stanford University)
Daniel Smith (University of Leicester)
Amanda Souders (Memorial University of Newfoundland)
Ryan Tapper (University of Delaware)*
Dominique Tobler (University of Leeds)
Katharine Tufano (Stanford University)
Xianfeng Wang (University of Minnesota)
Diana L. Washington (Washington State University)*
Aaron Zimmerman (Colorado State University)*

2006 GEOCHEMICAL SOCIETY AWARD RECIPIENTS

2006 V.M. Goldschmidt Award
- Susan Solomon, National Oceanic & Atmospheric Administration
  Presented August 2006 at the Goldschmidt Conference, Melbourne, Australia

2006 F.W. Clarke Award
- Alexis S. Templeton, Scripps Institute of Oceanography
  Presented August 2006 at the Goldschmidt Conference, Melbourne, Australia

2006 C.C. Patterson Award
- Fred T. MacKenzie, University of Hawaii
  To be presented August 2007 at the Goldschmidt Conference, Cologne, Germany

2006 A.E. Treibs Award
- Bernd Simonett, Oregon State University
  To be presented September 2007 at IMOG 23, Torquay, United Kingdom

2006 Organic Geochemistry Division Best Paper Award
- Mirela Dumitrescu and Simon Brassell, Indiana University
  “Biogeochemical assessment of sources of organic matter and paleoproduction during the early Aptian oceanic anoxic event at Shatsky Rise, ODP Leg 198;” Organic Geochemistry 36: 1002-1022
  Presented August 2006 at the Gordon Research Conference on Organic Geochemistry, Plymouth, New Hampshire, USA

2006 Gast Lecturer
- John Eiler, California Institute of Technology
  “Clumped isotope geochemistry”
  Presented August 2006 at the Goldschmidt Conference, Melbourne, Australia

2006 Ingersoll Lecturer
- Robert C. Aller, State University of New York at Stony Brook
  “Tropical deltaic systems as unsteady diagenetic reactors, global C incinerators, and reverse weathering centers”
  Presented October 2006 at the GSA Annual Meeting, Philadelphia, Pennsylvania, USA

2006 Geochemical Society Fellows
- William H. Casey, University of California Davis, USA
- Bor-mining Jahn, National Taiwan University, Taiwan
- Brian Popp, University of Hawaii, USA
- Jacques Schott, Université Paul Sabatier, France

2006 GEOCHEMICAL SOCIETY AWARD RECIPIENTS

FUTURE MEETINGS

Goldschmidt 2007, Cologne, Germany

www.goldschmidt2007.org
17th Annual Goldschmidt Conference, August 19–24, 2007
Organizing Committee: Herbert Palme, Albrecht Hofmann, Carsten Münker, and Sumit Chakraborty

AGU Fall 2007 Meeting, San Francisco, USA
December 11–15, 2006
Visit http://www.agu.org/meetings/fm06/ to review pre-planned sessions for the upcoming fall AGU meeting. GS is co-sponsoring several sessions with the Volcanology, Geochemistry and Petrology Section of AGU.

AGU Joint Assembly, Acapulco, Mexico
May 22–25, 2007
The GS is a co-sponsor of the upcoming AGU Joint Assembly meeting to be held May 22–25 in Acapulco, Mexico. Consider submitting a proposal for a session! The session proposal deadline is September 22. Information and submission of proposed sessions can be found at: www.agu.org/meetings/ja07/?content=program
A New Look for the Geochemical Society

After long and careful deliberation we are pleased to announce that the winner of our logo design contest is Marijo Murillo of Merced, California, USA. More details and the winning design will appear in the December issue of Elements.

2006 Committee Changes

Everything that we do as a society is impossible without the enormous efforts of our volunteers. It is with sincere thanks that I announce the volunteers who have stepped down this year:

- Organic Geochemistry Division (OGD) Secretary: Trudy Dickneider
- Board of Directors Nominations Committee: Victoria Bennett (chair), Ronald Frost
- Program Committee: Daniel Cherniak (chair)
- V.M. Goldschmidt Award Selection Committee: John Valley
- F.W. Clarke Award Selection Committee: Laurie Reisberg (chair), Bernard Boudreau
- C.C. Patterson Award Selection Committee: Robert Aller (chair), Bernhard Wehrli
- GS/EAG Fellows Selection Committee: Cindy Lee (chair), Sigurdur Gislason, Henry Elderfield, Guenter Lugmair

Below are our 2006 committee changes and additions. Welcome aboard!

- Board of Directors
  OGD Secretary: Josef Werne, University of Minnesota
- Board of Directors Nominations Committee
  Chair: Martin Palmer
  New Members: Lisa Pratt, Alan Matthews
- Program Committee
  Chair: Tracy Rushmer
  New Member: Robert Seal
- V.M. Goldschmidt Award Selection Committee
  Chair: Samuel B. Mukasa
  New Member: Christopher Martens
- F.W. Clarke Award Selection Committee
  Chair: Randall Cygan
  New Members: Doug Hammond, Christian Koeberl
- C.C. Patterson Award Selection Committee
  Chair: Brian Popp
  New Members: Candace Martin, Rick Wilkin
- GS/EAG Fellows Selection Committee
  Chair: Douglas Rumble
  New Members: David Rickard, Stuart Wakeham

For a complete list of committee members go to www.geochemsoc.org/aboutgs/personnel.html

Membership via Melbourne Goldschmidt

Delegates attending the Melbourne Goldschmidt who paid the non-member rate will receive a 2007 Geochemical Society membership as part of their registration. As a courtesy to these people and to welcome them to GS, their 2007 membership will also include the October and December 2006 issues of Elements.

A 2007 Geochemical Society membership include the following benefits:

- A 2007 subscription to Elements magazine (6 issues)
- Access to the quarterly newsletter Geochemical News (4 issues)
- A 25% discount on publications by GS, most MSA publications, Elsevier book orders, and Wiley/Josey-Bass
- Conference discounts to the GSA annual meeting, the spring and fall AGU meetings, and the Goldschmidt Conference
- Registration discounts on RiM&G short courses

Additionally, members may take advantage of these journal subscriptions at reduced prices:

- 2007 Geochimica et Cosmochimica Acta subscription (24 issues per year, plus the “Goldschmidt Abstracts” issue)
- 2007 GCA entitlement subscription (on-line access to GCA issues from 1995 to date through Elsevier’s Science Direct)
- 2007 Geochemistry, Geophysics, Geosystems (G-cubed) entitlement subscription

2007 Membership Drive

By now you may have received an e-mail or postal notice reminding you to renew. If you have not done so, please take a moment to renew your membership to the Geochemical Society by logging onto our website at www.geochemsoc.org/join/. Here you may either renew online or download our 2007 membership form. I thank you for your 2006 membership and look forward to serving you in 2007.

Seth Davis
Business Manager

GEOCHEMICAL SOCIETY RELATED QUESTIONS OR COMMENTS?

Send them to the Geochemical Society Business Office:

Seth Davis
Geochemical Society Business Manager
Washington University/EPSC
One Brookings Drive, CB 1169 Saint Louis, MO 63130-4899 USA
E-mail: gsoffice@geochemsoc.org
Tel.: 314-935-4131 Fax: 314-935-4121
www.geochemsoc.org

THE GEOCHEMICAL NEWS

Spotlight on Stanford University’s Environmental Molecular Science Center in the July issue of G.N.
One of the major challenges to young scientists is finding an academic job. Despite the founding of the European Union, this challenge is made surprisingly more difficult by the different regulations, requirements, and job titles in each European country. In an attempt to clarify the job-hiring process, we will periodically publish on job opportunities in Europe.

**OBTAINING AN ACADEMIC POST IN FRANCE**

The academic job system in France is so complex that even many of its natives find it confusing. Most have no idea how the government goes about hiring the educators for the halls of higher learning. Academics in France are employed by its universities, by the national ‘normal’ schools (École Normale Supérieure, ENS) and by the Centre National de la Recherche Scientifique (CNRS).

**University Faculty**

University faculty are either temporary or permanent. Temporary faculty can be hired towards the end of their thesis year for a maximum duration of two years. These posts, termed Attachés Temporaires d’Enseignement et de Recherche (ATER), provide employment during a brief period between finishing a thesis and finding a permanent job. Other individuals who are either working on their thesis or who are already employed outside the university sector can also teach at the university; these Chargés de Cours (CC) teach courses on an as-needed basis for many years if they and the university desire. These posts are roughly equivalent to assistant or temporary lecturers in the British system.

Full-time permanent university faculty have two job titles: Maître de Conférences (MCF) and Professeur. An MCF post is roughly equivalent to a position as Associate or Assistant Professor in the United States or Lecturer in the United Kingdom. A Professeur is equivalent to a Full-Professor in other countries. The starting salaries of MCF and Professors are approximately 1700 and 2500 Euros per month after social charges, but before taxes. The tenure process in France is different from other countries. The first year as a permanent academic in France is an ‘internship’ year. After one’s first full year as either MCF or Professor, the university grants the equivalent of tenure if the local committee and/or department have no qualms about the choice. If an MCF is promoted to Professor at some point (more about that process below), the Professor does not need to go through this tenure process again. One additional distinction of the French system is that promotion from MCF to Professor is not direct. To be promoted an MCF must apply for an available Professor post and compete against other candidates as though he or she were applying for the first time.

The application process differs markedly from those of many other countries. The national committee, Le Comité National Universitaire (CNU), is divided into over 70 sections, each representing a major field of academic study. The sections for the geosciences are sections 35 (Structure and Evolution of the Earth and Planets) and 36 (Solid Earth: Geodynamics of Terrestrial Reservoirs). Before one is allowed to apply for any of these academic posts, the interested candidate must be ‘qualified’ by this committee. The candidate must register towards mid-October via the Internet to announce his/her intention to request qualification to the CNU section. The candidate is then required to submit a dossier composed of several parts by early January to two reviewers selected by the CNU. Qualification applications and instructions are available on the web at http://www.education.gouv.fr/ personnel/default.htm. In order to register for qualification the candidate must create an account on ‘Antares’. A list of candidates who have successfully qualified is announced at the end of January or in early February.

In general, to be qualified for academic posts, one needs a completed PhD, publication of one to three papers, and some teaching experience. To be qualified to apply for Professor posts, one generally needs at least ten published papers, teaching experience, and to have completed an habilitation, if available, in the country of his or her origin. An habilitation is different from a thesis in that it delineates an established field and program of research demonstrating not only the ability to do research and publish in one’s field but also the capacity to direct doctoral and post-doctoral students. Those with foreign PhDs are not obligated to furnish proof of an habilitation, but it is considered good form to have the habilitation when applying for a Professor post.

The list of available posts is published on the Internet during February and March on the same website as the Antares module. As the qualification dossier deadline will have been the previous fall or winter, candidates will have needed to anticipate their interest in any post and submit a qualification dossier before the posts are published! Only after one is qualified can one apply for any job available in the country and in the desired section. This application is sent directly to the university offering the post. The university reviews the applications and then selects a number of candidates to interview, usually between three and five. Each candidate is interviewed for 15 to 20 minutes and all are interviewed on the same day by the same recruitment committee. The recruitment committee classifies their top candidates. Candidates are expected to attend the interviews, called auditions, on very short notice and at their own expense. Commonly, candidates are notified less than a week in advance of their audition. A given candidate can travel from one end of France to the other within a matter of days in order to participate in the auditions. Any candidate not present for his or her interview is immediately removed from the pool of candidates.

After the local hiring committees have announced their choices, each candidate must again connect to the Internet and acknowledge their preference for a job. Candidates are given final notice of hiring in early June.

**CNRS Posts**

CNRS posts are somewhat less complicated to obtain than MCF and Professor posts. There are two levels of CNRS posts: Chargé de Recherche (Research Scientist) and Directeur de Recherche (Research Director). These posts are roughly equivalent to junior and senior faculty posts and have starting salaries similar to those of the MCF and Professor posts in France. As is the case of university posts, CNRS posts are divided into sections among scientific disciplines. The bulk of Earth scientists are employed in section 18 (The Structure, History, and Modeling of the Earth and Planets) and section 20 (Earth Surface and Interfaces). Applications are made directly to the CNRS by e-mail. A website explaining the recruitment procedure is available at: www.sg.cnrs.fr/drehchercheurs/ concoursch/default-fr.htm

Applications are due in early January and must include a curriculum vitae and a detailed research project. The research project is usually written in collaboration with the laboratory where the candidate plans to work once recruited by the CNRS. This typically requires the candidate to be in close contact with this laboratory several months prior to the application.
deadline. It is extremely rare that the CNRS recruits candidates that are not supported by one of its laboratories.

Over the past several years, sections 18 and 20 recruited on average six to eight new scientists per year, from a pool of approximately 100 applicants for each section; the level of competition is high. Recruitments are generally made at one of three levels: Chargé de Recherche level 2, Chargé de Recherche level 1 and, more rarely, Directeur de Recherche. The Chargé de Recherche level 2 post is a lower-level position than the Chargé de Recherche level 1 post.

Until recently, the level 2 posts were restricted to scientists who had not yet reached the age of 32. As is the case of MCF and Professor posts, recruitment is based on a 15-minute interview, and candidates are expected to attend the interviews at their own expense. As in the case of MCF and Professor posts, CNRS posts become permanent after a short trial period, and promotion from Chargé de Recherche to Directeur de Recherche requires an application process similar to that of the original recruitment.

S. Callahan and E. H. Oelkers
Toulouse, France

POST-MEETING REPORT: 3rd WORKSHOP ON HIGHLY SIDEROPHILE ELEMENTS, DURHAM, UK

The 3rd International Workshop on Highly Siderophile Elements was hosted in the Department of Earth Sciences, Durham, UK, on July 4–7, and was organized by Ambre Luguet, Graham Pearson and David Selby. The format of the workshop was broadened from the previous two incarnations and included HSE behaviour during low-temperature processes. The 45 delegates were treated to summaries of the most recent developments in HSE geochemistry, in systems ranging from experiments on siderophile element behaviour, atmospheric PGE fluxes, mantle peridotites, magmatic ore bodies and basalts through to foraminifera and the dating of oil formation. The workshop provided a forum for interaction among experimental petrologists, mineralogists, trace element and isotope geochemists and economic geologists and highlighted the powerful insights highly siderophile elements have to offer in wide-ranging areas, such as atmospheric chemistry, climate change and the evolution of planetary bodies. True to the spirit of the workshop atmosphere, the lively, broad-ranging and extensive discussions spilled over into drinks in the Undercroft bar and dinner in the Senate Room of Durham’s Norman castle, now a student college. The workshop was generously sponsored by Thermo Electron, New Wave Research, Anton Paar and IUGS-SECE. The proceedings will be published in a special issue of Chemical Geology, the official journal of EAG, and will appear next year.

Delegates having pre-dinner drinks at the Durham Castle

THE EUROPEAN ASSOCIATION FOR GEOCHEMISTRY INVITES YOU ALL TO GOLDSCHMIDT 2007 “Atoms to Planets”

The 2007 Goldschmidt Conference will be held in Cologne, Germany, on August 19–24, 2007. The Goldschmidt Conference is the premier annual meeting in geochemistry and mineralogy. In addition to its usual sponsors, the European Association for Geochemistry and the Geochemical Society, the Cologne meeting is co-sponsored by the German Mineralogical Society. This meeting will cover the full range of geochemistry, from cosmochemistry to mineralogy and the origin of life. Sessions are planned on the following themes:

- Analytical Geochemistry
- Atmospheres and Oceans (including Climate Change)
- Biogeochemistry and Geomicrobiology
- Computational Geochemistry
- Cosmochemistry
- Crystal Chemistry and Crystallography
- Environmental Geochemistry and Mineralogy
- Experimental Geochemistry and Mineralogy
- Fluid–Rock Interaction
- Geochemistry and Mineralogy of Surfaces
- Igneous Petrology
- Isotope Geochemistry and Geochronology
- Metamorphic Petrology
- Mineral Deposits and Economic Geology
- Mineralogy
- Organic Geochemistry
- Planetary Geochemistry
- Sedimentary Geochemistry

Cologne has just over one million inhabitants and is the fourth-largest city in Germany. Founded by the Romans, Cologne is the oldest of the major German cities and is still characterized by its 2000 years of history. The metropolis on the Rhine annually attracts many millions of visitors.

To get further information on the 2007 Goldschmidt Conference, please visit the website

www.the-conference.com/gold2007
The International Association of GeoChemistry (IAGC) is planning to celebrate its 40th anniversary in conjunction with the Goldschmidt Conference (see below for more details).

Mel Gascoyne
Manager, IAGC Business Office and Newsletter Editor

IAGC 40th ANNIVERSARY CELEBRATION AND SYMPOSIUM

Next year is the IAGC’s 40th birthday. A special celebration to recognize this anniversary will be held at the University of Cologne, Germany, on Saturday, 18 August 2007, immediately prior to the 2007 Goldschmidt Conference.

This special event will consist of a day-long scientific symposium and an evening anniversary celebration and awards ceremony. The symposium will begin with a series of retrospective vignettes by former IAGC presidents and IAGC Ingerson Lecturers and will be followed by technical presentations highlighting the research interests and activities of current IAGC officers, councilors, and members. The contributions from the symposium will be published in a special issue of *Applied Geochemistry* dedicated to IAGC co-founder Professor Al Levinson, who passed away in December 2005.

The evening event will consist of an anniversary reception. This event will honor IAGC past presidents and other important figures in IAGC history. The recipients of the inaugural set of IAGC Awards—the Vernadsky Medal, the Ebelman Medal and the Hitchon Award—will be announced, but the awards will be formally presented later in the week during the Goldschmidt Conference at the joint society awards ceremony. Certificates of Merit recognizing special service to IAGC will be presented at the anniversary celebration.

The chair of the organizing committee for the IAGC 40th Anniversary Celebration and Symposium is Jochen Hoefs. Any IAGC members wishing to join the committee or otherwise volunteer to assist with the organization and implementation of the event should contact Prof. Dr. Hoefs by e-mail (jhoefs@gwdg.de).

Russell Harmon
IAGC Vice President

IUGS, IYPE AND EPISODES

Recently, IAGC has been contacted by Dr. Godfrey S. Nowlan, chair of the IUGS Publications Committee, to promote *Episodes*, its official quarterly journal (www.iugs.org). *Episodes* covers developments of regional and global importance in the Earth sciences and is distributed worldwide in four issues (March, June, September and December) each about 80 pages long. Articles cover a wide range of Earth sciences, and authors are from all over the world. The content is of interest to a broad audience of professional Earth scientists with diverse cultural and linguistic backgrounds.

*Episodes* welcomes thoughtful contributions in the topical areas listed above. Please consult the *Episodes* website for submission guidelines (www.episodes.org) and direct further inquiries concerning preparation and submittal of manuscripts and illustrations, special requirements, and pre-press processing to the *Episodes* staff, whose contacts are listed on the website.

Recent and current issues of the journal can be viewed online at www.episodes.org/. The printed version of the journal can be obtained for the annual subscription price of US$24.00. A subscription order form is published regularly in the journal, and you can also subscribe by contacting the editorial office by mail at P.O. Box 823, 26 Baiwanzhuang Road, Beijing 100037, China or by e-mail at episodes88@yahoo.com

The 12th International Symposium on Water–Rock Interaction (WRI-12)
August 13–18, 2007
Kunming, China

The first circular is out (see website www.wri12.org), and the second circular is due out in October 2006, with abstracts due in December. A list of conference topics can be found on the website.

Russell Harmon
IAGC Vice President

The International Year of Planet Earth (IYPE) was registered in March this year by Proclamation of the United Nations General Assembly. By June 2006, national committees had been created in 15 countries (Australia, Austria, Germany, India, Ireland, Italy, Japan, Malaysia, Mongolia, Namibia, New Zealand, Peru, Sweden, Switzerland and UK), and 20 other nations were well advanced in launching similar committees. Geoscience activities will be led by the International Union of Geological Sciences (IUGS). Geoscientists worldwide have been invited to contribute to and participate in this largest-ever global event for the geosciences, which will span 2006–2010. More information can be found at www.yearofplanetearth.org

The IAGC, as an affiliated society of IUGS, is proposing to hold a special session as part of IYPE activities at the next International Geological Congress in Oslo, 2008. This session will comprise two sections:

- a historical review of geochemistry and its applications
- a series of presentations on future developments in geochemistry and how geochemistry may be used to solve environmental and other problems

It is proposed that the proceedings of this special session be published in book form by Elsevier (which publishes the Association’s journal, *Applied Geochemistry*).
The three facets of the IAGC mission are (1) to foster the use of the tools and techniques of chemistry to advance the understanding of Earth and its component systems for the benefit of mankind and modern society; (2) to contribute to the advancement of geochemical research throughout the world, including both fundamental geochemical research aimed at understanding the global Earth system and applied geochemical research that addresses problems of particular relevance to the welfare of mankind and society; and (3) to promote international and educational cooperation in geochemistry through outreach activities, including sponsoring international scientific meetings related to geochemistry, disseminating new knowledge and fostering communication in geochemistry across the international scientific community. The IAGC sponsorship of a symposium entitled ‘Frontiers in Analytical Geochemistry’ at the 32nd International Geological Congress, held in Florence, Italy, in August 2004, provided an opportunity for IAGC to accomplish all of these objectives.

Across many areas of science, the frontiers of research are moving rapidly forward as a result of fast-paced and revolutionary advances in technology, particularly as regards emerging applications for in situ, spatially resolved analysis across a broad spectrum of organic and inorganic geochemistry. This symposium was an open forum to discuss the development of new techniques and progress in established technologies, which are providing new ways to advance our understanding of many geological and environmental processes. It was apparent during the symposium that the tremendous advances in both new and established analytical techniques are rapidly pushing down the limits of detection, allowing the detection and accurate quantification of a growing number of geochemical and isotopic tracers in smaller and smaller samples. Exciting new methods have recently been developed whereby geochemical investigations can be carried out within a spatial context that takes into account the microstructural relationships of analysed materials. The important messages coming from the symposium presentations and the papers from the symposium recently published in May 2006 as a special issue of the IAGC journal Applied Geochemistry (vol. 21, no.5; see contents in side bar) are that analytical geochemistry is continually providing new tools for the ever-more-detailed characterisation of geomatials at higher levels of spatial resolution and that vast new territories in every aspect of Earth and environmental sciences are potentially available for exploitation through exploration of the new frontiers in analytical geochemistry.

Russell Harmon
IAGC Vice President

Frontiers in Analytical Geochemistry
An IGC 2004 Perspective

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MAC-SPONSORED SPECIAL SESSIONS AND SYMPOSIUM AT MONTREAL 2006

The Mineralogical Association of Canada sponsored three special sessions and one symposium at Montreal 2006, its annual meeting held jointly with the Mineralogical Association of Canada, from May 14 to 17. Here are some highlights.

**Alkaline Igneous Systems: Dissecting Magmatic to Hydrothermal Mineralizing Processes**

This highly successful symposium attracted over thirty oral and ten poster presentations and ran for all three days of the conference. It was organized by David Lentz (University of New Brunswick), André E. Lalonde (University of Ottawa), Stefano Salvi (LMTG, Toulouse), and Jeanne Paquette (McGill University). Keynote speakers included I.V. Veksler, G.N. Eby, A.N. Mariano, and A.E. Williams-Jones. The program was complemented by the MAC short course Melt Inclusions in Plutonic Rocks, organized by James Webster (AMNH); by a three-day post-meeting field trip to the Montreign Hills, led by Nelson Eby (University of Massachusetts), David Lentz and Adrian Park (University of New Brunswick), and Serge Lavoie (NIOCAN); and by a one-day pre-meeting field trip to Mont Saint-Hilaire, led by Charles Normand (UQAM) and Peter Tarassoff (Redpath Museum). The presentations by this international group demonstrated that melt and fluid inclusion research is a common thread in discerning the relative roles of magmatic and hydrothermal processes from the deep mantle source regions to the near-surface formation of many ore deposits associated with alkaline magmatic systems.

Veksler (GFZ Potsdam) presented new experimental studies on immiscible silicate and carbonatite melts, using new rapid-quench centrifuge methods. Roger Mitchell (Lakehead University) and Bruce Kjarsgaard (GSC) used experimental equilibria to test hypotheses on crystallization of natrocarbonatite. The remaining day focused on more primitive parts of these magmatic systems and included several case studies on the source and fractionation history of specific settings. On the second day, Nelson Eby provided an overview of the Montreign (Canada) and Chilwa (Malawi) alkaline provinces, highlighting areas of current and future research in these interesting regions. The remainder of the second day evolved into presentations with ore deposit formation themes, highlighted by the keynote address on REE and Y deposits by Anthony Mariano (consultant) and James Hedrick (USGS). The final day included a particularly informative presentation by Carol Frost (University of Wyoming) on the new classification of alkaline rocks; it is part of a new IGCP project 510 started last year (www.igcp-510.org/) The remaining talks focused on the petrogenesis of mineralization associated with various alkaline complexes, with an excellent keynote talk entitled “Rare-Metal Mineralization in Alkaline Igneous Rocks: The Role of Hydrothermal Processes” by A.E. Williams-Jones (McGill University) and S. Salvi (LMTG, Toulouse).

Papers on talks presented at the symposium are currently being solicited for publication in a special issue of The Canadian Mineralogist. This special issue will be edited by Roger Mitchell, Anton Chakhmouradian (University of Manitoba), and Dave Lentz and will honor the fundamental contributions of Professor John Gittins (now Emeritus Professor, University of Toronto) to the field of carbonate petrology. We were very lucky to have John attend the meeting too. He, Roger Mitchell, and Keith Bell (Carleton University) initiated a lot of interesting discussion. Thanks gentlemen!

**Advances in Micro- and Nanoscale Analysis and Characterization of Earth Materials**

The objective of this full-day session, organized by Alan Anderson (St. Francis Xavier University) and Penny King (University of Western Ontario), was to introduce new and classic analytical techniques to geoscientists who share a common need to examine their samples at the nano- and microscale. Twelve different techniques were featured with application to a wide range of geological research topics, such as dissolution of uranium minerals, zircon geochronology, structural and chemical analysis of glasses and melts, mineral exploration, and radiation damage in minerals.

The advantages of sample preparation using a focused ion beam (FIB) and nanoscale characterization of materials using transmission electron microscopy were emphasized in a keynote address by Dr. Richard Wirth of the GeoForschungZentrum, Potsdam. Four other presentations demonstrated the capabilities of synchrotron radiation for spectroscopic analysis of glasses, fluid inclusions, and samples at extreme pressures and temperatures in a diamond anvil cell.

The session attracted a large and eclectic audience. The participants also learned about some new instrumentation in Canada and made the contacts needed to access these state-of-the-art laboratory facilities.

**Abstracts of all talks presented at the meeting are available at:**

The special session “Earth’s Mantle: New Insights from Diamonds and Xenoliths,” organized by Maya Kopylova and Don Francis (McGill University), opened with an invited talk by Dr. L. Barron on the parentage of alluvial diamonds. Dr. Barron uses new techniques, such as diamond strain birefringence and Raman spectroscopy, to gauge the remnant pressure exerted on mineral inclusions by diamond entainment. These techniques enable one to reconstruct a diamond’s P–T path and thus distinguish between different P–T regimes of diamond formation, such as cold subducted slabs, cratonic upper mantle, and the lower mantle. Based on these methods and on the mineralogy of garnet, alluvial diamonds of southeast Australia were proposed to originate from a buried ultrahigh-pressure terrain.

The session continued with several talks on the redox state of mantle processes, such as melting and metasomatism. A novel conclusion was reached in the talk by Canil, Johnson, and Mihalynuk. The authors estimated the oxygen fugacity of formation of ophiolite peridotite using the variation of Sc and V as a proxy, and found it to be independent of the degree of melting. Such a pattern is inconsistent with closed-system behavior of oxygen, in which the redox state of the residue reflects their degree of depletion because Fe\(^{3+}\) is more incompatible than Fe\(^{2+}\). On the contrary, the observation supports melting in a system that is open to oxygen, in which oxygen fugacity is buffered externally, presumably by a mobile fluid.

Several presentations were devoted to inclusions in diamonds. Kopylova and Hayman showed that Fe-rich ferropericlase in Rio Sorisso diamonds may be enriched in Fe due to an origin at the base of the lower mantle in equilibrium with the post-perovskite phase. Donnelly et al. and De Stefano et al. presented new data on diamond inclusions in the Diavik and Jericho kimberlites, which are mainly peridotitic at Diavik and eclogitic at Jericho.

Many talks dealt with the petrology of peridotite and eclogite xenoliths in rocks ranging from the Muskox kimberlite (Schulze, Valley, and Hetman) to the Kirkland Lake kimberlite (De Hoog and Schulze) and the Cape Verde basalts (Shaw). A talk by Stachel et al. posed a provocative question: should we abandon one of the main paradigms of diamond exploration? Traditionally, exploration targets with harzburgitic (G10) garnets were considered more prospective than targets with Iherzolitic garnets. Stachel et al.’s study of diamondiferous garnet xenocrysts from Diavik demonstrates that Ca metasomatism is not destructive to diamonds, and therefore Iherzolitic garnets from refertilized former harzburgites may also coexist with diamonds in the mantle. The session was well attended and enjoyed by all participants.

Maya G. Kopylova
University of British Columbia

**Earth’s Mantle: New Insights from Diamonds and Xenoliths**

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**Metamorphism, Crustal Fluids, and Experimental Petrology: A Tribute to George Skippen**

Dan Marshall (Simon Fraser University), Fred Ford (Inco), and Jo-Anne Goodwin-Bell (Carleton University) convened this special session to honor George Skippen, who recently retired from Carleton University. Keynote speaker Greg Dipple from the University of British Columbia gave a talk entitled “Physical Consequences of Mineral–Fluid Carbon Exchange: Examples from Metamorphism, Mineral Deposits, and Carbon Sequestration.” The talk was an excellent blend of classic and modern metamorphic petrology. Professor Dipple did an exemplary job of summarizing Skippen’s early work on carbonate metamorphism. He then built upon that work to explain how he and his group, working on CO\(_2\) sequestration, have used metamorphic petrology to study carbonate reactions in mine tailings and how they propose to use those reactions as a partial solution to the ever-increasing global greenhouse gas budget.

Other talks in the session comprised an eclectic mix of metamorphic topics, including classic metamorphic phase relations (Ford), mapping (Goodwin-Bell), and the algebraic manipulation of metamorphic components (Gordon). The chairs, speakers, and audience did a wonderful job keeping the session entertaining and on time. Thus the group was able to move to a local “fluids lab” to continue the session.

They enjoyed a 50-year perspective on George’s contributions given by Dave Watkinson (a friend and colleague of Skippen’s) from Carleton University.

Dan Marshall
Simon Fraser University

From left to right, the guest of honor, George Skippen, and session chairs Ian Hutcheon, Richard Moore, Terry Gordon, and Fred Ford

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**CALL FOR NOMINATIONS FOR THE 2007 MINERALOGICAL ASSOCIATION OF CANADA AWARDS**

**YOUNG SCIENTIST AWARD**

This award is given to a young scientist who has made a significant international research contribution in a promising start to a scientific career.

- The scientist must be 40 or younger at the time of the award.
- The scientist must be a Canadian working anywhere in the world or a scientist of any nationality working in Canada.
- The research area includes mineralogy, crystallography, petrology, geochemistry, mineral deposits, and related fields of study.

**PAST-PRESIDENTS’ MEDAL**

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

**BERRY MEDAL**

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

**PINCH MEDAL**

The Pinch Medal is awarded every other year since 2001 to recognize major and sustained contributions to the advancement of mineralogy by members of the collector-dealer community. This medal is named for William Wallace Pinch of Rochester, New York, in recognition of his enormous and selfless contributions to mineralogy through the identification of ideal specimens for study and through his generosity in making them available to the academic community.

**DEADLINE:** December 31, 2006 (October 30 for the Pinch Medal)

Check our website for additional details:

[www.mineralogicalassociation.ca](http://www.mineralogicalassociation.ca)
NOTES FROM LONDON

Countdown to ‘Frontiers 2007’
It is now less than five months until the 28 February 2007 deadline for submission of abstracts and conference registration. We are hoping this meeting will be an international forum to highlight much of what is new in research in the mineral sciences. A full listing of 21 symposia and their convenors appeared in the June issue of Elements and is also available on the conference website at www.minersoc.org/Frontiers2007.html. If you haven’t already done so, now is the time to register your interest in making a presentation with one of the session convenors. We have tried to keep registration fees low for this three-day conference, and for members of the supporting societies the registration fee is only £195.00. Students are particularly welcome and will be charged only £50.00. Accommodation is available at Fitzwilliam College for £44.06 (incl. VAT) per night.

New Awards Committee Established
Council has been concerned for some time about the small number of candidates put forward for the Society’s two medals. The Schlumberger Medal is awarded to recognize scientific excellence in mineralogy and its applications, and the Max Hey Medal recognizes excellent ongoing research carried out by young scientists (normally under 35 years) who are members of the Society. Nevertheless the calibre of candidates put forward in recent years has been outstanding. A new awards committee is now established under the chairmanship of Prof. Michael Carpenter of Cambridge University. The committee will in addition comprise six members appointed by the special interest groups. The aim is that each member will serve for three years, but in order to avoid the simultaneous retirement of the entire committee, appointments are being staggered initially so that some members will only serve one or two years. The benefit of the new structure is that the chair will have no vote and so will be free to actively search for suitable candidates. Also, members of the committee will not be eligible to propose candidates, allowing them to cast their votes impartially. It is also hoped in due course to appoint overseas members to the committee to widen the net. The work of the committee will be largely undertaken by e-mail and telephone, thereby lessening the need to meet in person. The first medallists to be chosen by the new committee will be for the 2007 awards.

New Council Members
At the Council meeting of 15 June, Dr Kathryn Goodenough (British Geological Survey, Edinburgh Office) and Dr Michele Warren were elected as ordinary members of Council to serve from 2007 to 2009. Kathryn studied Earth sciences at Worcester College Oxford under Dave Bell, Keith Cox, Steve Moorbath and John Reavy. She studied the alkaline igneous rocks of the Gardar Province of SW Greenland for her PhD at the University of Edinburgh under Brian Upton, Ian Parsons and Adrian Finch. She has carried out extensive studies of the highland rocks of Scotland and recently began mapping the Oman-UAE ophiolite complex. Since 2002 Kathryn has contributed significantly to the work of the Volcanic and Magmatic Studies Group as group secretary. Michele Warren received a BA in natural sciences from Cambridge University before going on to the University of Edinburgh where she completed her PhD research on ab initio lattice dynamics. She has been secretary of the Mineral Physics Group since 2004. Michele is now a lecturer at Manchester University where she pursues her research interests in surface processes and phase transitions in minerals.

We are also pleased to welcome to Council in recent months appointees from the special interest groups – Kathryn Linge of Kingston University (secretary of the Geochemistry Group), Simon Harley of Edinburgh University (chair of the Metamorphic Studies Group), Jon Davidson of Durham University (chair of the Volcanic and Magmatic Studies Group) and Karen Hudson-Edwards of Birkbeck College, London (chair of the Environmental Mineralogy Group).
WINNERS OF THE 2006 SOCIETY MEDALS

The Schlumberger Medal 2006 to David Vaughan

David Vaughan is a very worthy recipient of the seventeenth medal in this series, which is awarded for excellence in the mineral sciences. David has published over 200 papers, most of which are focused on or related to mineralogical research. At Manchester University he established the Williamson Research Centre for Molecular Environmental Science, a premier UK research centre open to all members of the UK’s mineral community. David’s major research contribution has been to provide a much greater understanding of the electronic structures of minerals, thus enabling rationalization and prediction of physical properties, crystal structures and the behaviour associated with dissolution and oxidation. A pioneer in the research field now termed ‘mineral physics’, David undertook the first studies of complex silicates and sulphide minerals by high-pressure Mössbauer spectroscopy. He has published several books, including a seminal text on sulphide mineralogy, Mineral Chemistry of Metal Sulfides, still the major source for work in this field after 27 years. David has been president of the Mineralogical Society and the European Mineralogical Union and was an MSA Distinguished Lecturer.

The Max Hey Medal 2006 to Dominic Fortes

The Max Hey Medal for 2006 is awarded to Dominic Fortes for his outstanding research work in planetary science carried out over the past six years at University College London. His research at UCL has involved the use of experimental and computational mineral physics methods to study the properties of planet-forming ices. The technical challenges of working with ice should not be underestimated, and Dominic has developed techniques that open up great possibilities for planetary research. He is now poised to make a major impact on our understanding of the chemistry and behavioural evolution of icy moons. His data are now being used to predict the internal structure of bodies such as Saturn’s moon Titan, and these ideas in turn are being used to interpret the data returning from the Cassini mission. Dominic’s work has also been recognized by the British Crystallographic Association, which awarded him the PANanalytical Prize for outstanding research covered by his PhD thesis.

Dominic has an impressive list of first-author papers and is now extending his research through collaborations with the Institute of High Pressure Physics Troitsk (Russia) and the Jet Propulsion Laboratory at Pasadena in the USA.
Mineralogical Society of America

NOTES FROM CHANTILLY

• MSA members were contacted electronically by mid-October to renew their membership for 2007. Paper notices will be sent to those who do not renew online by the end of October. There is a $5 discount for renewing online before October 31, 2006. This is a change from the traditional discount and reflects the true cost savings for MSA.

MSA now has the capability to send each member their user ID (= e-mail address) and password (= MSA membership number) with the electronic renewal message. Not having this information at hand appeared to be a stumbling block for members renewing online. The number of members renewing online had remained at about one-third. We hope to build on the success of the 2006 renewal with a higher response and avoid a large hard-copy mailing by including all the information needed for renewal in the notice. In 2005, 916 MSA members attempted to renew online. In 2006, this increased to 1325.

• Members and Fellows who are in the senior, honorary, and life categories are sent renewal notices. They need not pay dues, but are sent notices because this is the best way to obtain an update of membership information, particularly mailing addresses.

Members qualify for Senior Member or Senior Fellow status if they have reached the age of 65, have retired from full-time professional employment, and have been a member of the Society for at least 30 years. Senior Members and Fellows retain all benefits of MSA membership (receiving Elements, voting, reduced rates on MSA products, etc.) but need not pay dues. They can subscribe to the paper or electronic version of American Mineralogist or other journals, purchase Society publications, and attend short courses all at member rates. If you are interested in senior status, select Senior Member or Fellow dues on your next renewal and write in the text box that you would like to become a Senior Member or Senior Fellow.

• Individuals can now apply for MSA membership online at www.minsocam.org/MSA/membership. They can also download application forms that can be printed out, completed, and mailed or faxed to MSA. If you know someone who ought to be a member of MSA, but is not, encourage him or her to join and direct them to the MSA website.

• MSA will have all of its usual social and technical functions at the GSA meeting in Philadelphia, Pennsylvania (October 22–25, 2006). This is also MSA’s annual meeting. There will be lectures by the Roebling Medalist and MSA Awardee on Tuesday, October 24, 2006, starting at 3 pm. W.G. Ernst, 2006 Roebling Medalist, will speak on the topic “Subduction Zone Metamorphism – An Evolving Mineralogical and Plate Tectonic Adventure.” Daniel Frost, 2006 MSA Awardee, will speak on the subject “Local Strain Heterogeneity in Mineral Solid Solutions: The Relationship between Line Broadening in IR Spectra and Excess Enthalpy.” Following these talks, at 4 pm, John Valley will give his MSA presidential address entitled “Minerals, Molecular Selection, and the Origin of Life.” The MSA business meeting will follow from 5:00 to 5:30 pm, and the MSA/GS joint reception will be held from 5:30 to 7:30 pm.

• The 2007 Dana Medal presentation will be made at the 2007 “Frontiers in Mineral Sciences” meeting, June 26–28, 2007, Cambridge, UK. This is a joint meeting of MSA, MAC, MS, and SFMC. More information about the conference is available on the MSA website.

J. Alex Speer
MSA Executive Director
j_a_speer@minsocam.org

New title
Reviews in Mineralogy and Geochemistry
Mineralogical Society of America
and The Geochemical Society

New Views of the Moon

This book assesses the current state of knowledge of lunar geoscience, given the data sets provided by missions of the 1990s and lists remaining key questions as well as new ones for future exploration to address. It documents how a planet or moon other than the world on which we live can be studied and understood in light of integrated suites of specific kinds of information. The Moon is the only body other than Earth for which we have material samples of known geologic context for study. This book seeks to show how the different kinds of information gained about the Moon relate to each other and also to learn from this experience, thus allowing more efficient planning for the exploration of other worlds. Volume 60, 2006, Bradley L. Jolliff, Mark A. Wieczorek, Charles K. Shearer, and Clive R. Neal, editors (eds) ISBN 093995072-3. US$45 (paperback) $55 (hardcover)

For more description and table of contents of this book, and online ordering visit www.minsocam.org or contact Mineralogical Society of America, 3635 Concordia Pkwy Ste 300, Chantilly VA 20151-7125 • USA, Tel.: +1 (703) 652-9850, Fax: +1 (703) 652-9831, e-mail: business@minsocam.org
AMERICAN MINERALOGIST UNDERGRADUATE AWARDS FOR OUTSTANDING STUDENTS

The Society welcomes the exceptional students listed below to the program’s honor roll and wishes to thank the sponsors for enabling the Mineralogical Society of America to join in recognizing them. MSA’s American Mineralogist Undergraduate Award (AMUA) is for students who have shown an outstanding interest and ability in mineralogy, petrology, crystallography, or geochemistry. Each student is presented a certificate at an awards ceremony at his or her university or college and receives an MSA student membership, a Reviews in Mineralogy or Monograph volume chosen by the sponsor, student, or both. Past AMUA recipients are listed on the MSA website, as are instructions on how and when MSA members can nominate their students for the award.

- STEVEN R. BOYD, Towson University, sponsored by Dr. David Vanko
- JEREMIAH D. CHRISTMAN, Oklahoma State University, sponsored by Dr. Elizabeth Catlos
- KARA BETH DETRO, Texas A & M University, sponsored by Dr. Robert K. Popp
- EMILY A. FERTIG, Williams College, sponsored by Dr. Reinhard A. Wobus
- DANIEL HALLAU, University of Wisconsin–Madison, sponsored by Dr. Huifang Xu and Dr. Phil Brown
- JESSICA S. HARK, The College of Wooster, sponsored by Dr. Jade Star Lackey
- KASIA HARPER, Brigham Young University, sponsored by Dr. Dana Griffen
- SARA MCPHAIL, University of Victoria, sponsored by Dr. Dante L. Canil
- JASON STUART MONCRIEFF, University of Oklahoma, sponsored by Dr. David London
- BRIAN J. MUMAW, The College of Wooster, sponsored by Dr. Jade Star Lackey
- BRIAN ARTHUR SANFORD, Oklahoma State University, sponsored by Dr. Elizabeth Catlos
- MEGAN TRITES, University of New Brunswick, sponsored by Dr. Cliff Shaw
- SARAH VORHIES, Smith College, sponsored by Dr. John Brady

IN MEMORIAM

ALAN W. BERNHEIMER (Life Member – 1934)
FREDERICK HARVEY POUGH (Life Fellow – 1930)
HUGO STRUNZ (Honorary Fellow – 1948)
WERNER F. SCHREYER (Life Fellow – 1958)
ERNEST E. WAHLSTROM (Life Fellow – 1934)

Medical Mineralogy and Geochemistry

MSA/GS Short Course
December 8-10, 2006
Menlo Park, California


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The European Mineralogical Union (EMU) launched its series Schools and accompanying Notes (ISSN 1417 2917) in 1997:

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From Almaz Press
Perovskites; Modern and Ancient (2002) US$70

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For more description and table of contents of these books and online ordering visit www.minsocam.org or contact Mineralogical Society of America, 3633 Concordia Pkwy Ste 500, Chantilly VA 20151-1125 • USA, Tel: +1 (703) 652-9950, Fax: +1 (703) 652-9951, e-mail: business@minsocam.org

Mineralogical Society of America and Geochemical Society.
Short Course
December 7-8, 2006
Holiday Inn Bay Bridge, Emeryville, CA 94608
Hans-Rudolf Wink, University of California-Berkeley, and Nancy Rees, Virginia Polytechnic Institute, Conveons

More information and registration: http://www.minsocam.org/msa/sc

Society News
This year for the first time, the Clay Minerals Society held its annual meeting outside North America. The meeting was held jointly with the Groupe Français des Argiles (GFA) in early June in France. Following the format of recent years, the meeting was preceded by a one-day workshop, this year on the subject ‘Polymer–Clay Nanocomposites’, at the University of Poitiers and organized by Katie Carrado (Argonne National Laboratory) and Faïza Bergaya (CNRS, Orléans). The workshop was deemed a great success by the 81 participants, and a Workshop Lecture Series volume based on the presentations will be published soon. The main meeting was held on Oléron Island in the Bay of Biscay, north of the Gironde estuary. As this location is 200 km from Poitiers, workshop participants and some others made the connection between the two by coach. In the form of a field trip, the journey included visits to the delightful medieval villages of Montmorillon and Nontron (something of a pilgrimage for clay scientists) and the Cognac Museum.

The venue on Oléron Island was ‘Village Vacances Vielle Perrotine’, a CAES CNRS Centre, which is dedicated to CNRS family holidays but includes conference facilities. As there were 282 participants, considerably more than anticipated, the poster sessions and two of the four concurrent sessions were held in large tents, while the plenary sessions were conducted in the main conference room. The beautiful sunny weather and the holiday-type surroundings created a very relaxing atmosphere for the meeting. The truly international nature of the meeting was evident from the fact that delegates came from 37 countries: France as the host country had 101 delegates, 53 came from North America, 29 from countries outside North America and Europe, and the remainder from European countries other than France.

After the opening ceremony, at which local delegates, representatives of CNRS (one of the main sponsors) and the University of Poitiers, Faïza Bergaya (president of GFA) and Cliff Johnston (president of CMS) spoke, Theo Kloprogge (Queensland University of Technology), as the recipient of the Jackson Mid-Career Award, delivered the lecture ‘The Application of XPS to Clay Science’. Plenary sessions began the next two days. Fred Wicks (Royal Ontario Museum) gave the Bailey Distinguished Member Award lecture ‘Serpentine Minerals, the Mystery is Gone: You Too Can Identify Them’, and Jean-Maurice Cases (CNRS) gave the Pioneer in Clay Science lecture ‘Textural and Energetic Surface Properties of Clays Using Gas Adsorption Procedure’.

The technical programme, conducted in four parallel sessions, consisted of nine thematic sessions and two symposia covering a wide variety of topics, reflecting the great diversity of clay science. These included ‘Clays in Petroleum Systems’, ‘Polymer–Clay Nanocomposites’, ‘Iron Oxidation–Reduction in Clays’, ‘Clay–Water Interactions and Colloidal Behaviour of Clay Minerals’, ‘Equilibrium and Disequilibrium in Low-Temperature Processes’, ‘Environmental Mineralogy and Toxic Metals’, ‘Soils, Weathering and Alterations’, ‘Environmental Clay–Organic/Water Interactions’, ‘Clays and Clay Minerals in Extraterrestrial Environments’, ‘Advanced Techniques for Clay Minerals: Characterization’ and ‘Clays – From the Quarry to Industry’. Presentations were of consistently high quality, and many, both oral and poster, were made by young researchers, auguring well for the future. Awards were made to the winners of this year’s Reynolds Cup contest, and details are given in a separate article. Socializing during breaks and meals, which were included in the conference fee, was undoubtedly facilitated by the dispenser in the restaurant labelled blanc, rosé, et rouge.

The main social event was a dinner in the Aquarium at La Rochelle, and to get there, delegates embarked on a wonderful cruise in the Bay of Biscay in lovely sunny weather, past Fort Boyard and through the heavily fortified entrance to the beautiful harbour at La Rochelle.
This meeting was a great success in every way. It brought together clay researchers from all over the world in a venue that provided a relaxing ambience for enthusiastic discussions and presentations about the topic which binds us together — clay. This was all made possible by the prodigious efforts, organizational skills, attention to details and dedication of Sabine Petit and her team of willing helpers at HydrASA, University of Poitiers. To them all, and particularly to the indefatigable and unfailingly helpful Sabine, we are extremely grateful, and we can only say “Merci beaucoup”.

Next year, the annual meeting will return to North America and will be in Santa Fe, New Mexico. It will be on the theme ‘Enchanted Clays’ and will feature associated field trips. However, because of the success of the meeting in France and because about 40% of the members of The Clay Minerals Society reside outside of the North American continent, the society will be considering another meeting at a venue other than in the USA, as a joint venture with another national clay society.

**RESULTS OF THE 3rd BIENNIAL REYNOLDS CUP CONTEST**

Results of the CMS third biennial Reynolds Cup (RC) contest in quantitative mineral analysis were announced at the 2006 CMS/GFA annual meeting in Oléron, France. The winner of the contest was Douglas McCarty of Chevron, Texas, followed by Stephen Hillier of the Macaulay Institute, Aberdeen, Scotland and Reinhard Kleeberg of TU Bergakademie, Freiberg, Germany. Sixty sample sets were distributed and 37 individuals from 18 countries returned results, an increase of 5% over the last contest in 2004. The quality of the top seven entries was outstanding and provides an eye-opener to the patience and expertise required for accurate quantitative mineral analysis.

All participants received three samples made from ‘pure’ minerals commonly found in sedimentary rocks. Samples 1 and 2 comprised five clay minerals and twelve non-clay minerals each. The challenge in these samples was the accurate identification of different feldspars and the differentiation of 2:1 clay minerals (Al-clays in sample 1 and Fe-clays in sample 2). Only one participant correctly identified minor phases like zircon and tourmaline in sample 1. Mixed-layered illite-smectite in sample 1 and glauconite-smectite in sample 2 were seldom reported. Sample 3 was perhaps the most difficult despite having the smallest number of phases (10). The presence of poorly crystalline opal-CT and 2:1 trioctahedral clay mineral (saponite) made quantification of either phase difficult. The entries were ranked by the sums of the differences between the actual compositions and the compositions obtained by the participants (bias).

Most of the participants used X-ray diffraction for identification and quantification. The more successful entries, however, used a range of supplementary techniques, including elemental analysis, grain-size or magnetic separation, infrared spectroscopy, and thermogravimetric analysis. Participants using a synchrotron X-ray source were more successful at identifying minor, non-clay mineral phases. One participant used Mössbauer spectroscopy to correctly identify most of the Fe-bearing minerals.

The top three finishers used different quantitative X-ray diffraction methods. The winner used a variation of the single-line reference intensity ratio (mineral intensity factor) method based on pure mineral standards, with elemental composition optimization. Cation exchange capacity and thermogravimetric analysis were used as supplementary techniques. The runner-up also used a reference intensity ratio method with pure standards, but based on whole-profile fitting. The third-place finisher used the Rietveld method for quantification and identification of minor phases (using difference plots) and also used SEM/EDS to identify minor components and verify the composition of structures used in Rietveld analysis. Details of the top three quantitative methods will be published in a forthcoming issue of *Clays and Clay Minerals*.

The CMS presented commemorative plaques and cash prizes to the top three finishers and $1000 towards travel expenses for the contest champion, who also received a trophy. The next competition will be held in 2008, with registration commencing in January 2008. Details of the competition are available at [www.clays.org/reynoldscup.html](http://www.clays.org/reynoldscup.html)

**Dipo Omotoso**

Natural Resources Canada
This workshop provided a unique opportunity to measure the implication of the French science community in the field of biomineralization and to initiate fruitful exchanges between communities that are normally distant. As a consequence, the participants agreed that it would be most useful to hold similar meetings on a regular basis.


SFMC ANNUAL MEETING

The SFMC annual meeting was held in Paris on June 15. Two special events were associated with the meeting.

The Prix Haüy-Lacroix was awarded to Hélène Gailhanou (see Elements 2006, volume 2, number 3). Hélène gave an interesting talk on the subject of her PhD, “Experimental Determination of Thermodynamic Properties and Study of Nanostructures of Clay Minerals.” Since completion of her PhD, Hélène has been hired by the BRGM, and we wish her well in her new career.

Bruno Lanson, from the Environmental Geochemistry Group at LGIT, Grenoble, gave a presentation entitled “Crystal Chemistry of Nano-crystalline Manganese Oxides: Implications for the (Bio)geochemical Cycle of Trace Metal Elements in the Environment.”

The work of Bruno Lanson is devoted to the structure of finely divided minerals, i.e. the phyllosilicates and phyllosilicates (clays minerals, lamellar oxides), and their physical properties, particularly their surface reactivity. This field of research is now considered a key discipline in the studies of Earth’s surface, since it is applied in a wide range of environmental questions. Clays and related nanophases, among the most abundant minerals on Earth’s surface, are now considered to be remarkably effective materials for environmental protection and technologies.

Lanson’s talk focused on birnessite, a lamellar manganese oxyhydroxide (phyllomanganate) whose layers are composed of MnO₆ octahedra. Their non-stoichiometry arises from the coexistence of heterovalent Mn cations (Mn³⁺, Mn⁴⁺) and/or from vacant sites, and is compensated for by the presence of interlayer cations. Despite the low natural concentration of Mn, birnessite is ubiquitous in the environment and plays a pivotal role in geochemical reactions and especially in the fate of pollutants such as organics and heavy metals. Its high reactivity arises from its high surface area and its high cationic exchange capacity, combined with its adsorption and redox properties.

The rest of the afternoon was devoted to the SFMC general assembly. Among other things, members unanimously approved participation in Elements. They praised the quality of the magazine, which they started receiving in 2006.
EMU NOTES IN MINERALOGY, VOLUME 7

Mineral Behaviour at Extreme Conditions
Edited by Ronald Miletich

Amongst its various activities, the European Mineralogical Union organizes short courses (‘Schools’) in front-rank fields of the mineralogical sciences. Each of these schools is accompanied by the publication of a review volume in the series EMU Notes in Mineralogy. We reported on the first six volumes in the series in the last issue of Elements. In 2005, EMU held a school entitled Mineral Behaviour at Extreme Conditions. The school was organized by Ronald Miletich and held in Heidelberg (Germany) from June 19 to 25, 2005. Recently, the seventh volume of the EMU Notes in Mineralogy was published; it contains the contributions presented during this school.

This most recent volume of the EMU Notes in Mineralogy provides up-to-date reviews of our understanding of the behaviour of minerals and geo-materials under external conditions that are sufficiently extreme to induce significant changes. The volume’s eighteen chapters reflect the diversity of this theme. They also demonstrate how highly interdisciplinary this domain of modern mineralogy has become, bringing together physicists, chemists and geologists, experimentalists and computer scientists. The chapters are well balanced with respect to providing basic introductory material, information on the experimental facilities to be found in modern laboratories, and the evaluation and interpretation of experimental data at the limits of conditions achievable in modern laboratories. In addition, discussions of theoretical approaches help the reader to understand experimental results and to gain insights where the necessary experimental conditions are still far from feasible.

All authors are internationally known specialists, each focusing on theoretical, practical or experimental aspects. The EMU Notes series was introduced to provide university teachers with up-to-date reviews in important, rapidly evolving areas of mineralogical science and to introduce both senior scientists and students to new topics.

The volume consists of the following chapters:

- **Introduction to minerals under extreme conditions**
  (H. Keppler, Bayreuth, Germany and D.J. Forst, Bayreuth, Germany)

- **Mineral structures, defects and their evolution with pressure and temperature**
  (R. Miletich, Heidelberg, Germany and T. Malcherek, Hamburg, Germany)

- **Displacive phase transitions**
  (T. Malcherek, Hamburg, Germany)

- **Diamagnetic and ferromagnetic properties of minerals**
  (S.L. Webb, Göttingen, Germany)

- **Elastic and piezoelectric properties of minerals I. Principles and experimental approaches**
  (J. Schreuer, Frankfurt, Germany and S. Haussühl, Cologne, Germany)

- **Elastic and piezoelectric properties of minerals II. Structure-property relationships**
  (J. Schreuer, Frankfurt, Germany and S. Haussühl, Cologne, Germany)

- **Basics of first-principles simulation of matter under extreme conditions**
  (D.Y. Jung, Zurich, Switzerland and A.R. Oganov, Zurich, Switzerland)

- **Dynamics of atomic structure at high pressure**
  (R. Boehler, Mainz, Germany)

- **Laser heating at megabar pressures: Melting temperatures of iron and other transition metals**
  (R. Boehler, Mainz, Germany)

- **Diffraction techniques: Shedding light on structural changes at extreme conditions**
  (R. Miletich, Heidelberg, Germany, C. Hejny, Heidelberg, Germany, G. Kraus, Zurich, Switzerland and A. Ulrich, Heidelberg, Germany)

- **Plastic deformation of minerals at high pressure: Experimental techniques**
  (P. Cordier, Lille, France, H. Couvy, Lille, France, S. Merkel, Berkeley, USA and D. Weidner, Stony Brook, USA)

- **Shock experiments on minerals: Basic physics and techniques**
  (F. Langenhorst, Jena, Germany and U. Hornemann, Efringen-Kirchen, Germany)

- **Plastic deformation of minerals at high pressure: Multiscale numerical modelling**
  (P. Cordier, Lille, France, F. Barbe, Rouen, France, J. Durinck, Lille, France, A. Tommasi, Montpellier, France, and A.M. Walker, Canberra, Australia)

- **Viscoelasticity of the Earth’s mantle**
  (S.L. Webb, Göttingen, Germany)

- **Theory of minerals at extreme conditions: Predictability of structures and properties**
  (D.J. Adams, Zurich, Switzerland and A.R. Oganov, Zurich, Switzerland)

All chapters include an extended list of references. Some figures are in colour. At the end of the book there are author and subject indexes.

**How to place an order**

Please send an e-mail to: herta.silvia.effenberger@univie.ac.at asking for:

Vol. 7 (2005): “Mineral Behaviour at Extreme Conditions”
Price: 24 € (excl. postage)

Order forms are available from EMU’s home page
http://www.univie.ac.at/Mineralogie/EMU/school.htm#Notes.

The eighth EMU School was held in Budapest, Hungary, from August 28 to September 1, 2006. The topic was Technical Mineralogy: Silicate-Based Materials. The accompanying volume is expected to be published by the end of the year. The editor is Bernard Grobéty, University of Fribourg, Switzerland.

**Peter Ulmer**, President
**David Vaughan**, Past President
**Herta Effenberger**, Secretary
The excellent 19th general meeting of IMA in Kobe is described by the organizers elsewhere in this issue of Elements. Everyone I spoke to agreed it was a thoroughly enjoyable event. The scientific standard of the talks was particularly high, reflecting the emphasis placed by universities and government on mineralogy and materials science in Japan. Heartfelt thanks are due to Takamitsu Yamanaka and his team for an extremely smoothly run meeting and some memorable (sometimes deafening!) social events.

Slightly smaller and more mineralogical than competing conferences, it is the emphasis on ‘international’ that gives IMA meetings their distinctive flavour.

IMA has an important role in fostering international collaboration, particularly for the smaller mineralogical societies, and it is always a pleasure to renew old acquaintances. It is, however, disappointing that many members of the larger mineralogical societies do not automatically make IMA meetings their first choice of ‘big’ meeting. They should. I contend that the international character of science – the set of common rules and practices that all scientists share – is of enormous potential benefit to mankind, well worth the effort of some extra travel or the need to concentrate a little harder on slightly less-than-perfect English.

IMA meetings are complex for the officials of IMA. As president, I had to chair two meetings of the IMA Council and two business meetings (at which supporting organizations are represented, in proportion to their size, by between one and five national representatives), before handing the reins over to Takamitsu Yamanaka, my successor as president, for a final council meeting. All this activity has to be orchestrated, and papers provided, by our very hard-working Secretary, Maryse Ohnenstetter. Thanks from all of us, Maryse. In addition, the various commissions and working groups of IMA each hold at least one meeting – thanks too to their chairs and secretaries.

Practical Matters

From this behind-the-scenes activity emerged both formal changes and exciting initiatives for IMA. The Council for 2006–2010, was approved, with some new members (see photo page 318). Missing from the picture is a new communications officer, yet to be appointed, who, together with the president, secretary and treasurer, will be a member of the Executive Committee. New officials were appointed to commissions and working groups. Dogan Paktunc, Katsu Tsukamoto and Sergey Smirnov become chairmen of the Commission on Applied Mineralogy, the Commission on Mineral Growth and Interface Processes and the Working Group on Inclusions in Minerals, respectively. A full list of officials can be found at www.ima-mineralogy.org.

The Commission on New Minerals and Mineral Names (CNMMN) has been merged with the Commission on the Classification of Minerals (CCM) to form the new Commission on New Minerals, Nomenclature and Classification (CNMNC). These commissions represent the most widely known activities of IMA. The merger will solve problems encountered in the past at the boundaries of the fields of activity of the former commissions. The CNMNC will operate under the leadership of the hard-working Ernst Burke, who described the activities of CNMMN in Elements 1 (3).

Although far in the future, IMA needs to find a venue for the 2014 general meeting. In view of the locations of recent meetings and the 2010 meeting in Budapest, it would be appropriate to meet in North America, and we hope that proposals will come forward. Business meetings take place every two years, and it was decided to hold business and council meetings at the time of the 2008 Goldschmidt Conference in Vancouver, Canada. Council will meet during the combined societies ‘Frontiers in Mineralogy’ meeting in Cambridge, England, in 2007.

We hope that the problems of collecting membership dues [Elements 2 (1)] have been solved. The formula for calculating subscriptions leads to per capita payments that are smallest for the largest societies. Rather than increasing contributions paid by the larger societies, the subscriptions of our fifteen smallest societies, each with less than 25 members, will be reduced from 60 to 30 US$. The decrease in income will be compensated by an improvement in our annual investment income. The problem of the costs of international bank transfers has been solved by Bob Downs’ discovery of a bank that will not charge for accepting cheques in foreign currencies. We can further help societies by accepting payment up to four years in advance at business meetings.

Strategic Initiatives

Several initiatives will be developed in the months to come:

• An annual IMA Medal for Excellence has been founded. A Medals Committee will be formed, chaired by Joel Grice. Candidates can be nominated by national societies and by individuals.

• IMA will become the home of the comprehensive Internet mineral database, being built by the RRUFF project, which is led by Bob Downs and George Rossman, with support from Michael Scott, the first president of Apple Computers, who himself is a keen mineral collector. The database will contain X-ray diffraction data, Raman and infrared spectra and microprobe data and analyses. It has spectacular opportunities to be linked to new, miniaturized spectrometers for mineral identification in the field.

• Many councillors feel that some of the commissions and working groups are not fulfilling their role adequately. Suggestions include forming a nucleus of experts in each field to lead developments, making more use of the Internet, and ensuring that chairmen serve no more than four years.

• The presidency of IMA will, in the future, be decoupled from chairmanship of the general meeting, a connection that has developed through custom rather than statute. A democratic system and a shorter term of office for the president would ensure that an increasing number of leaders in the field of mineralogy would become aware of the workings of IMA and contribute fresh ideas.

I will end by wishing my successor, Takamitsu Yamanaka, every success in the next four years.

Ian Parsons
President of IMA, 2002–2006
IMA 2006, KOBE, JAPAN

The 19th general meeting of the International Mineralogical Association took place on July 23–28, 2006. The National Committee for Mineralogy of the Science Council of Japan (SCJ) has supported IMA since it was established in 1958. At a business meeting during IMA 2002 in Edinburgh, a proposal from the National Committee of SCJ for a meeting in Kobe was accepted. The meeting was run jointly by the Science Council of Japan, the Mineralogical Society of Japan, the Association of Mineralogists, Petrologists and Economic Geologists, and the Society of Resource Geology. The organizing committee would like to express hearty thanks to all participants for their cooperation and contribution to this conference. A total of 975 participants registered (including accompanying persons), from 50 countries. A total of 874 papers (488 oral presentations, 386 poster presentations) were contributed during the six days. Six hundred delegates attended the receptions and banquet, maintaining old friendships and making new ones, and discussing recent and future progress in science.

Mineral science has expanded widely, not only in geosciences but also in planetary science, bioscience, and materials sciences. Mineral scientists contribute strongly in interdisciplinary fields. Consequently we decided that the catch phrase of the conference would be “Expansion to Nano, Bio and Planetary Worlds.” After considering many significant suggestions and comments from our international program committee and from IMA commissions and working groups, the local program committee prepared a timetable of 37 sessions. We express our gratitude to the Science Council of Japan for their cooperation and large financial contribution. We also extend our appreciation to Kobe City and to many companies for their financial donations or support. Many thanks are due to Dr. K. Korokawa, president of SCJ, and to Mr. T. Yada, mayor of Kobe, for their welcoming speeches during the opening ceremony. We greatly appreciated the message from Mr. S. Koizumi, prime minister of Japan.

Kobe City is one of the most beautiful port cities in Japan. Unfortunately, eleven years ago, an enormous tragedy struck Kobe. More than 6000 lives were lost during a big earthquake. But the city was completely rebuilt. I personally believe many of the participants enjoyed the night view of Kobe, and I hope they took pleasure in the Japanese culture during the meeting. Finally, we hope the Kobe conference will be fondly remembered by all participants.

Takamitsu Yamanaka
President of IMA 2006–2010

Impressions from the outgoing President

From the standpoint of a participant, without the considerable responsibilities of actually running the meeting, Kobe 2006 was thoroughly enjoyable. Takamitsu and his team did a magnificent job, and the organization was relaxed and faultless. The scientific programme was intense, based on 37 sessions with up to 7 oral sessions running simultaneously. The organizers had assembled a galaxy of international plenary lecturers (Catherine McCammon, Bayreuth; Christoph Heinrich, ETH Zurich; Eiji Ito, Okayama; Jillian Banfield, Berkeley; Lindsay Keller, NASA Houston; Lukas Baumgartner, Lausanne; Yoshiyuki Tatsumi, JAMSTEC Yokosuka; Michael Carpenter, Cambridge; Sumio Iijima, Meijo) whose excellent early afternoon talks were very well attended. The overall scientific standard of the oral presentations was extremely high, reflecting, I think, the quality of the science done in Japan and the resources that its government puts into our field of science.

Session topics covered all of mineralogy, with experimental and theoretical work at the very high pressures of the deep Earth well represented, as one would expect in Japan. Crystal and glass structure and properties, of both natural and synthetic materials, and modern applications of spectroscopy, synchrotron radiation and neutron science figured strongly, together with crystal growth and texture formation; the big word ‘nano’ appeared in two contexts. Petrological sessions had a distinctly active margin emphasis: sea-floor hydrothermal systems; metal deposits in magmatic arcs; extreme P–T metamorphism; subduction factory; ocean crust and mantle. Fluid– and bio–mineral interactions, environmental mineralogy, clays and zeolites were all covered, as was the role of minerals in the emergence of life. Solar system evolution, lunar and martian rocks and several up-to-the minute accounts of interplanetary dust returned by the Stardust mission from the comet Wild-2 contributed to strong sessions on matter extraterrestrial. The very distinctively mineralogical topics of new minerals and mineral classification, and of museums, were well supported. IMA Kobe more than lived up to the reputation of these meetings as the flagship international conference of the mineralogical world.

Kobe is a dramatic place, and the one-hour drive through the extraordinary close-packed industrial landscape from Osaka airport, with steep, densely forested hills rising immediately behind the coastal lowlands, leaves an indelible impression. As little driver-less trains shuttle faultlessly about, it is hard to believe that such a complex, high-tech urban area could have been devastated by a great earthquake so recently. Only a strangely deformed block pavement, preserved near the conference centre, provided a reminder of the displacements and mighty forces involved.

Japanese society is renowned not just for its energy and efficiency but also for its calm and devotion to good manners. All these were very visible at the meeting. But when they let go, our Japanese friends clearly like brilliant noise. We were treated to dragon dancers, lion dancers and ear-splitting drumming as well as more restrained, and very beautiful, Japanese traditional music. Kobe more than fulfilled the ‘international’ in IMA and it was good to see mineralogists from 50 countries so obviously enjoying themselves. I’m already looking forward to Budapest in 2010.

Ian Parsons
I have developed a new procedure allowing unambiguous fingerprinting of the source of carbon tapped in the formation of carbonate minerals. Using radiogenic and stable isotope techniques, it is possible to determine whether the carbon in carbonate efflorescences has been derived from the atmosphere. Using isotope data and Rietveld results, I have quantified the amount of atmospheric CO\textsubscript{2} bound in carbonate minerals.

Studying mineral carbonation in active mines at Mount Keith, Western Australia, and Diavik, NWT will contribute towards the design of new mining processes that will accelerate CO\textsubscript{2} uptake to create the world’s first generation of zero-emissions mining operations. I have observed and quantified the precipitation of hydromagnesite in tailings at Mount Keith and have documented the precipitation of nesquehonite in the kimberlite tailings at Diavik. Further field work and bench-top precipitation experiments will determine whether mineral carbonation is a valid means of CO\textsubscript{2}-sequestration under the desert conditions at Mount Keith and in the tundra at Diavik.

Global implementation of carbon sequestration in ultramafic mine tailings has the potential to draw CO\textsubscript{2} directly from the atmosphere at a rate of 10\textsuperscript{15} tonnes of carbon per year. In situ sequestration in mine tailings bypasses the need to transport large quantities of tailings to industrial point sources and can be accomplished without high-pressure, high-temperature reactors. Mine tailings may, therefore, represent the optimal environment in which to pursue carbon sequestration in minerals.

**NEW IMA COUNCIL**

The current Council of IMA. Left to right, back row: Anhui Lu (China), Joel Grice (Canada), Okkehart Tillmanns (Austria, Chairman of the 2010 General Meeting), Nicolai Yushkin (Russia), Maryse Ohnenstetter (Secretary, France), Herta Effenberger (attending on behalf of EMU). Front row: Walter Maresch (Germany), Ian Parsons (Great Britain and Ireland), Takamitsu Yamanaka (President, Japan), Robert Downs (Treasurer, USA), Marcello Mellini (Italy), Kari Kojonen (Finland).

**MAC FOUNDATION SCHOLARSHIP TO SASHA WILSON**

Every year since 1998, the Mineralogical Association of Canada awards a $10,000 scholarship to a deserving student in one of the fields of mineralogy, crystallography, petrology, or geochemistry. This year’s winner is Siobhan A. (Sasha) Wilson, from the University of British Columbia. Born in Oshawa, Ontario, in 1980, Sasha graduated from McMaster University in 2003 with an Honours Bachelor of Science in physics with a minor in Earth sciences. She began her studies at the University of British Columbia as a master’s student in the fall of 2003 working under the supervision of Gregory M. Dipple and Mati Raudsepp. She completed her MSc in the fall of 2005 and began work toward her PhD immediately thereafter.

Sasha’s MSc and PhD thesis research concern the disposal of atmospheric carbon dioxide in mine tailings. Mineral carbonation is a safe and permanent method of carbon disposal in which silicate minerals react with atmospheric or industrial CO\textsubscript{2} to produce geologically stable, environmentally benign carbonate minerals. Naturally occurring mineral carbonation phenomena have recently been observed at the surface of chrysotile mine tailings at Clinton Creek, Yukon; Cassiar, British Columbia; and Thetford Mines, Québec; as well as at the Mount Keith nickel mine, Western Australia; and the Diavik diamond mine, NWT. The primary focus of her master’s research was to characterize and quantify natural mineral carbonation at the abandoned Clinton Creek and Cassiar chrysotile mines. Her PhD research involves documentation and acceleration of mineral carbonation phenomena in the active mine sites at Mount Keith and Diavik. Sasha describes her research as follows:

The principal techniques employed in my study have been mapping and sampling, X-ray powder diffraction (XRPD), scanning electron microscopy (SEM), Raman spectroscopy, radiogenic carbon dating, stable isotope analysis, and bulk chemical analysis.

As part of my master’s research, I presented the first detailed field characterization of natural mineral sequestration in ultramafic mine tailings at Clinton Creek, YT, and Cassiar, BC. I detailed the modes in which the hydrated magnesium carbonate minerals hydromagnesite, diopsite, nesquehonite, and lansfordite occur in tailings environments and defined the mechanisms by which they form.

I have successfully applied the Rietveld method for quantitative phase analysis to X-ray powder diffraction profiles for natural and synthetic serpentinite mine residues. This is the first instance in which the Rietveld method has been used successfully to compensate for structural disorder in the kaolinite-serpentinite group minerals. I have confirmed crystallographic binding of carbon and have quantified CO\textsubscript{2} uptake in tailings samples.

**CSIRO GEOScientist AwarDeD RESEARCH MEDAL**

CSIRO scientist Dr Ravi Anand has been awarded the Butt Smith Medal for his outstanding contribution to geoscientific research. The award acknowledges Dr Anand’s long-term dedication and excellence in the development of geochemical mineral exploration techniques for Australia’s deeply weathered landscapes. Awarded by the Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME) and CSIRO’s Exploration and Mining Division, the Butt Smith Medal recognises sustained excellence in Australian geochemistry research. The award takes its name from two eminent geoscientists, Dr Charles Butt and Dr Ray Smith, who through long association with CRC LEME and CSIRO, have made significant research contributions to the Australian minerals exploration industry.

CRC LEME Chief Executive Officer Dr Steve Rogers said it was fitting that Dr Anand becomes the second recipient of the Butt Smith Medal. “For more than three decades Dr Anand has followed in the footsteps of Dr Butt and Dr Smith to emerge as a leader in regolith research,” Dr Rogers said. “His work into understanding how geochemical anomalies form in deeply weathered terrains has contributed to the mineral industry’s appreciation that regolith is an essential consideration when designing exploration strategies and interpreting geochemical data.”

CSIRO Exploration and Mining Chief Dr Peter Lilly added that recently Dr Anand had discovered an association in plant biogeochemistry and mineralisation. “Some of Dr Anand’s newer research has shown that deep-rooted mulga trees in transported regolith over some Australian mineral provinces act as hydraulic pumps for dissolved metals.” Dr Lilly said. “His work has raised the awareness of a biological process that can create geochemical anomalies in the plant’s biomass near the surface, which could become a valuable indicator for mineral explorers.” The Butt Smith Medal complements Dr Anand’s other research accolades including the Sir Ian McLennan Achievement for Industry, CSIRO Research and Stillwell Awards.
THE LYCURGUS CUP: A UNIQUE GLASS ARTIFACT

The Lycurgus Cup dates from the fourth century AD and was probably made in Rome. This extraordinary cup, 16.5 cm high, is the only complete example of dichroic glass, which changes colour when held up to the light. The opaque green cup turns to a glowing translucent red when light is shine through it. This unusual optical property is due to tiny amounts of colloidal gold and silver in the glass, according to the curators of the British Museum, where the cup resides.

Only a handful of ancient glasses showing this effect are known, all of them Roman. The gilded bronze base and rim were added in more recent times. The cup is surrounded by a frieze showing the myth of King Lycurgus, a king of the Thracians (around 800 BC). He is seen being dragged into the underworld by Ambrosia, who has been turned into a vine. In this ‘cage-cup,’ the frieze stands out from the body of the vessel, connected to it only by small shanks or bridges. Adapted from the British Museum website.

August 12–17 9th EMU School ‘Nanoscopic Approaches in Earth and Planetary Sciences’, Munich, Germany. Organizers: Frank E. Brenker (Frankfurt, Germany), Guntram Jordan (Munich); e-mail: info9th-emu-school.de; website: www.9th-EMU-School.de

August 13–17 2007 Meteoritical Society Annual Meeting, Tucson, Arizona, USA. Details: Dr. Tim Jull, e-mail: jull@u.arizona.edu; website: http://metos2007.org

August 13–18 Twelfth International Symposium on Water–Rock Interaction (WR-I2), Kunming, China. Details: Secretary General, Yanxin Wang, School of Environmental Studies, China University of Geosciences, 430074 Wuhan, P.R. China. Tel.: +86-027-67885040; fax: +86-027-67841365; e-mail: wr12@cug.edu.cn; website: www.wr12.org

August 19–23 American Chemical Society 234th National Meeting, Boston, Massachusetts, USA. Details: ACS Meetings, 1155-16th St., N.W., Washington, DC 20036-4899. Tel.: (202) 872-4396; fax (202) 872-6128; e-mail: natlmtgs@acs.org; web page: www.chemistry.org/portal/acis/1/acdispaly.html#TDC=meetings%5cfuture.html

August 19–24 Goldschmidt 2007, Cologne, Germany. Details: Dr. Herbert Palme, e-mail: herbert.palme@uni-koeln.de; website: www.the-conference.com/ gold2007/index.php

August 20–24 9th Biennial SGA Meeting, Trinity College, Dublin, Ireland. Details: Gerry Stanley, Geological Survey of Ireland; e-mail: gerry.stanley@gsi.ie; website: www.cprregistrations.com/sga2007

August 22–27 24th European Crystallographic Meeting (ECM24), Marrakech, Morocco. E-mail: thalal@menara.ma; website: www.ecm24.org

September 1–15 Modular Course in Structure, Tectonics, and Mineral Exploration (Field-Based), Sudbury, Ontario, Canada. Information: Bruno Lafrance, Mineral Exploration Research Centre, Department of Earth Sciences, Laurentian University, Willet Green Miller Centre, 933 Ramsey Lake Road, Sudbury, Ontario, Canada, P3E 6B5. Tel.: 705-675-1151, ext. 2264; fax: 705-675-4898; e-mail: blafra@laurentian.ca; website: http://earthsciences.laurentian.ca.

September 6–7 AGREE II – Arctic Geology, Resources and Environment Conference, Tromsø, Norway. Details: Geological Society of Norway (NGF). Web page: http://www.geologi.no/cgi-bin/geologi/imaker?id=8529


September 10–14 23rd International Organic Geochemistry Meeting (IMOG07), Torquay, Devon, UK. Details: Sally Conford, IGI Ltd, Hallanserney, Bideford, Devon EX39 5HE, UK. Tel.: +44 (0) 1237 471749; fax: +44 (0) 1237 421700; e-mail: sallygift@igl.com; web page: www.eaog.org/meetings/meetings.html

September 13–17 Hutton, Horne and Barrow Classic Field Localities Visit Edinburgh and in the Eastern Scottish Highlands, Geological Society of London: Details: Alys Johnson, Burlington House, Piccadilly, London, W1 0BG. Tel.: 020 7434 9944; fax: 020 7439 8975; e-mail: alys.johnson@geoloc.org.uk; web page: www.geoloc.org.uk/template.cfm?name=Bicentenary_Field_Excursion_Hutton_Horne_and_Barrow

September 14–19 Geological Society of London Mineral Deposits of South-West England, Venue TBA. Details: Alys Johnson, Burlington House, Piccadilly, London, W1 0BG. Tel.: 020 7434 9944; fax: 020 7439 8975; e-mail: alys.johnson@geoloc.org.uk; web page: www.geoloc.org.uk/template.cfm?name=Bicentenary_Field_Excursion_Mineral_deposits


September 23–28 SEG International Exposition & 77th Annual Meeting, San Antonio, Texas, USA. E-mail: meetings@seg.org

September 25–29 WIRMS 2007: International Workshop on Infrared Microscopy and Spectroscopy with Accelerator Based Sources, Awarai Island, Japan. Details: Takao Nanba, Hiroaki Kimura, or Shin-ichi Kimura, Kobe University, SPring-8, UVSOR Facility. E-mail: nanba@phys.sci.kobe-u.ac.jp, or kimura@spring8.or.jp or kimura@ms.ac.jp; web page: www.uvsor.kek.jp/WIRMS2007


October 28–November 1 Geological Society of America Annual Meeting, Denver, Colorado, USA. Details: GSA Meetings Dept., P.O. Box 9140, Boulder, CO 80301-9140, USA; tel.: 303-447-2020; fax: 303-447-1133; e-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings/index.htm

November 19–23 Cities on Volcanoes 5, Shimabara, Japan. Details: Secretariat, Cities on Volcanoes 5, Gamadas Dome, Shimabara City 855-0879, Japan. Tel.: +81-957-65-5542; e-mail: convention@citiesonvolcanoes5.com; website: www.citiesonvolcanoes5.com

November 26–30 Materials Research Society Fall Meeting, Boston, MA USA. Details: Duane Dimos, e-mail: dbdimos@sandia.gov; web page: www.mrs.org/s/mrs/sec.asp?CID=47498&Did=164574

December 10–14 AGU Fall Meeting, San Francisco, California, USA. Details: AGU Meetings Department, 200 Florida Avenue NW, Washington, DC 20009, USA. Tel.: 202-777-7335; fax: 202-328-0566; e-mail: meetinginfo@agu.org; web page: www.agu.org/meetings

2008

April 6–10 American Chemical Society 235th National Meeting, New Orleans, LA, USA. Details: ACS Meetings, 1155-16th St., N.W., Washington, DC 20036-4899, USA. Tel.: 202-872-4396; fax: 202-872-6128; e-mail: natlmtgs@acs.org; web page: www.chemistry.org/portal/acis/1/acdispaly.html#TDC=meetings%5cfuture.html

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

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