

# Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology

August 2008  
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## Platinum-Group Elements

JAMES M. BRENAN and JAMES E. MUNGALL, Guest Editors

**“Admirably Adapted” for  
Science and Industry**

**Platinum-Group Elements  
in Cosmochemistry**

**Radioisotope Systems**

**Key Tracers for  
the Earth's Interior**

**Ore Deposits**

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# Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology



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Stacked array of high-purity platinum bars.  
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## The Platinum-Group Elements

James M. Brenan and James E. Mungall, Guest Editors



### The Platinum-Group Elements: "Admirably Adapted" for Science and Industry

James M. Brenan



### Platinum-Group Elements in Cosmochemistry

Herbert Palme



### Applications of PGE Radioisotope Systems in Geo- and Cosmochemistry

Richard W. Carlson, Steven B. Shirey, and Maria Schönbacher



### Platinum-Group Elements: A New Set of Key Tracers for the Earth's Interior

Jean-Pierre Lorand, Ambre Luquet, and Olivier Alard



### Ore Deposits of the Platinum-Group Elements

James E. Mungall and Anthony J. Naldrett



### Environmental Relevance of the Platinum-Group Elements

Sebastien Rauch and Gregory M. Morrison

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**The Mineralogical Society of America** is composed of individuals interested in mineralogy, crystallography, petrology, and geochemistry.

Founded in 1919, the Society promotes, through education and research, the understanding and application of mineralogy by industry, universities, government, and the public. Membership benefits include special subscription rates for *American Mineralogist* as well as other journals, 25% discount on Reviews in Mineralogy & Geochemistry series and Monographs, *Elements*, reduced registration fees for MSA meetings and short courses, and participation in a society that supports the many facets of mineralogy. For additional information, contact the MSA business office.

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

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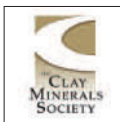
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**The Mineralogical Association of Canada** was incorporated in 1955 to promote and advance the knowledge of mineralogy and the related disciplines of crystallography, petrology, geochemistry, and economic geology. Any person engaged or interested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

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

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

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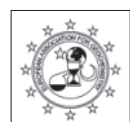
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**The Geochemical Society** is an international non-profit organization for scientists involved in the practice, study, and teaching of geochemistry. Membership includes a subscription to *Elements*, access to the online quarterly newsletter *Geochemical News*, as well as an optional subscription to *Geochimica et Cosmochimica Acta* (24 issues per year). Members receive discounts on publications (GS Special Publications, MSA, Elsevier and Wiley/Jossey-Bass) and on conference registrations, including the V.M. Goldschmidt Conference, the fall AGU meeting, and the annual GSA meeting.

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



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

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**The Société Française de Minéralogie et de Cristallographie**, the French mineralogy and crystallography society, was founded on March 21, 1878.

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The purpose of the Society is to promote mineralogy and crystallography. Membership

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

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**The Association of Applied Geochemists** is an international organization founded in 1970 that specializes in the field of applied geochemistry. Its aims are to advance the science of geochemistry as it relates to exploration and the environment, further the common interests of exploration geochemists, facilitate the acquisition and distribution of scientific knowledge, promote the exchange of information, and encourage research and development. AAG membership includes the AAG journal, *Geochemistry: Exploration, Environment, Analysis*; the AAG newsletter, *EXPLORE*; and *Elements*.

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**The Deutsche Mineralogische Gesellschaft** (German Mineralogical Society) was founded in 1908 to "promote mineralogy and all its disciplines in teaching and research as well as the personal relationships among all members." Its great tradition is reflected in the list of honorary fellows, which include M. v. Laue, G. v. Tschermak, P. Eskola, C.W. Correns, P. Ramdohr, and H. Strunz, to name a few. Today, the Society especially tries to support young researchers, e.g. to attend conferences and short courses. Membership benefits include the *European Journal of Mineralogy*, the DMG Forum, *GMI*, and now *Elements*.

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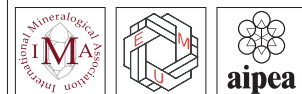


**The Società Italiana di Mineralogia e Petrologia** (Italian Society of Mineralogy and Petrology), established in 1940, is the national body representing all researchers dealing with mineralogy, petrology, and related disciplines. Membership benefits include receiving the *European Journal of Mineralogy*,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

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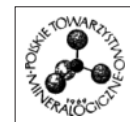
The International Mineralogical Association, the European Mineralogical Union, and the International Association for the Study of Clays are affiliated societies of *Elements*. The affiliated status is reserved for those organizations that serve as an "umbrella" for other groups in the fields of mineralogy,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



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

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**The Polish Towarzystwo Mineralogiczne** (Mineralogical Society of Poland), founded in 1969, draws together professionals and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The Society promotes links between mineralogical science and education and technology through annual conferences, field trips, invited lectures, and publishing. There are two active groups: the Clay Minerals Group, which is affiliated with the European Clay Groups Association, and the Petrology Group. Membership benefits include subscriptions to *Mineralogia Polonica* and *Elements*.

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**The Spanish Mineralogical Society** (Sociedad Española de Mineralogía, SEM) was founded in 1975 to promote research in mineralogy, petrology, and geochemistry. The Society organizes annual conferences and furthers the training of young researchers via seminars and special publications. The *SEM Bulletin* published scientific papers from 1978 to 2003, the year the Society joined the *European Journal of Mineralogy* and launched *Macla*, a new journal containing scientific news, abstracts, and reviews. Membership benefits include receiving the *European Journal of Mineralogy*, *Macla*, and *Elements*.

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## QUIET REVOLUTION IN THE GEOCHEMICAL SCIENCES



E. Bruce Watson

I am writing these words on my way home from the 2008 Goldschmidt Conference in Vancouver, so it's possible that I'm writing in a state of overstimulation: by any measure it was an extraordinary meeting that lived up to its promise to cover science "from SEA to SKY."

Much of the credit for the success of this year's Goldschmidt Conference should go to the organizers and sponsors of the meeting, and I hope all of you will join me in congratulating the program committee and chairs Rick Carlson, Barbara Sherwood Lollar, and Dominique Weis. Still, I think there is more going on in the field of geochemistry than a scenic venue and thoughtful planning: the conference took place within the context of far-reaching, fundamental developments in the geochemical sciences. These developments have been apparent at many recent meetings, and I think they will continue to be prominent for the foreseeable future. At the risk of being overly dramatic, I believe we are in the midst of a quiet revolution in the geochemical sciences.

At the root of this revolution is the unprecedented proliferation of technology that not only drives the science we're doing but also is driven by it. One side of the equation is the breathtaking advancement in our ability to measure the isotopic and elemental composition and structure of Earth materials—solid, fluids, vapors, and organic materials—at scales ranging vastly through time and space, down even to the nanometer and molecular level. Some of my colleagues in analytical geochemistry assure me that thirty years ago we were able to measure certain isotope ratios and trace-element abundances in many systems with precision and accuracy equalling today's capability. While this observation is certainly true, it misses the key point that today's analyst needn't be as experienced nor as committed to specific types of measurements in order to do them well. For better or for worse, we have entered a period

of exploration in analytical geochemistry in which discoveries are limited more by ideas than by analytical capabilities. The proliferation of technology has stimulated exploration of isotope ratios (e.g. non-traditional stable isotopes) that would never have been attempted even a decade ago: this, in turn, has engendered an adventuresome attitude among scientists that few laboratories could have justified previously. Some might argue that technology has put powerful tools in the hands of babes, but I think the evidence is that, on balance, this is a good thing.

Can we, as practicing scientists, be proud of this revolution, and can we really claim it as our own "grass roots" movement? Or, are we simply exploiting the technology made available to us by the innovative engineers employed by (for example) the gracious sponsors of our meetings and publications? Here, I think we are on a two-way street. I was told recently by a sales representative of a major instrument manufacturer that, of all the communities in which his instruments are marketed (physics, chemistry, materials science, biology), it is by far the geoscientists who are the most vocal in pushing for new capabilities. So maybe we are not simply the fortunate beneficiaries of corporate invention and entrepreneurship, but rather integral partners in the science/technology symbiosis. Our ambition and ideas drive the development of commercial instruments, and these in turn energize and diversify our science.

At the root of this revolution is the unprecedented proliferation of technology that not only drives the science we're doing but also is driven by it.

It is especially interesting to me that we seem to be at a juncture where our ability to measure chemical "signatures" has far outstripped our ability to interpret those signatures in a unique way. On fronts ranging from the origin of life to magmatic evolution, for example, intriguing inferences are being drawn from small apparent

anomalies in isotope ratios; however, in none of these areas have we comprehensively evaluated the mechanisms that could produce these anomalies. This makes the present time especially exciting and challenging for experimentalists like myself, whose "job" it is to characterize the behavior of elements and isotopes under controlled laboratory conditions and attempt to extrapolate findings to natural systems. In the distant future—if we are lucky and tireless—perhaps we will complete the interpretational framework for signatures, anomalies, and structures documented in natural systems. In the meantime, the profusion of new analytical results from natural samples provides experimentalists with ample motivation and inspiration, and in that respect makes us part of the revolution.

Cont'd on page 220

## THIS ISSUE

Guest editors James Brenan and James Mungall have brought together a cast of international authors to give you an up-to-date overview of the economic, scientific, and environmental significance of the platinum-group elements.

## PAST PRINCIPAL EDITOR HONORED

Michael F. Hochella Jr. was honored during the recent Goldschmidt Conference for his distinguished service to the Geochemical Society, as vice president, president, and past president (1998–2003), as co-organizer of the 2001 V.M. Goldschmidt Conference, and as “former Principal Editor of the extraordinarily successful *Elements* magazine.”



Citationist Scott Wood and Michael Hochella

As citationist Scott Wood pointed out, “Mike’s Presidential service in the Geochemical Society was distinguished by several extraordinary achievements. He was the major driving force in involving the Geochemical Society in the *Reviews in Mineralogy* series, culminating in the change of the name to *Reviews in Mineralogy and Geochemistry*. In 2001 Mike co-organized a highly successful Goldschmidt Conference held in Hot Springs, Virginia, with Bob Bodnar. Although Mike retired from active service on the GS Board of Directors after 2003, it was not long before he was to serve the society

again, this time as one of the founding Principal Editors of the magazine *Elements*. From the early days when Rod Ewing first pitched to the Geochemical Society his idea for a scientific magazine to be co-published by several mineralogical and geochemical societies, Mike was a strong supporter of the concept. According to Principal Editor Ian Parsons, Mike played a ‘pivotal role’ in making *Elements* the success it has become.”

Here are some excerpts from Mike’s response: “Whether science or service awards have come my way, I’m just doing what I love to do. I can’t imagine anything more important, in the long run, than understanding this third rock from the sun, what makes it work, where it came from and where it’s going, and how to best care for it. To be so privileged, and to be able to call all of you colleagues, is the greatest joy in my life next to my family. And if I can constructively and productively serve this constituency, as this award implies, then I am definitely on the right track, and I will continue to do that, whether I am testifying to a congressional subcommittee on Capital Hill, or telling a large introductory class that what we do is worth it. ...Earth science, in all its grand forms and permutations, is as important to the global society as ever. Insofar as our societies help us organize and project, anything we can do to serve our organizations is more important than we can possibly imagine.”

## ELEMENTS AT THE GOLDSCHMIDT CONFERENCE

The editors met for a full day on July 14, 2008. In attendance were principal editors Bruce Watson, Susan Stipp, and David Vaughan, incoming principal editor Hap McSween, past principal editors Ian Parsons and Rod Ewing (also chair of the Executive Committee), and managing editor Pierrette Tremblay. We reviewed the past year with its highlights and challenges and brainstormed about where we

want *Elements* to be five years from now. Among the highlights of the year, those deserving most mention are that *Elements* is now available on GeoScienceWorld and that an online version is available to members of participating societies.



*Elements* editors love a party, and Susan Stipp, Ian Parsons and Pierrette Tremblay were there to toast Tim Drever (MORE ON TIM DREVER’S PARTY ON PAGE 222).

Part of each principal editors meeting is devoted to reviewing proposals for future thematic issues. We had ten proposals on hand to review. We accepted and slated two to complete our 2009 lineup. We asked for revised proposals for three of them, and we plan to slate them in 2010 if the revisions are accepted. Some of the questions we ask ourselves when we review proposals are: Will this topic be of interest to a broad spectrum of members of our community? Will it be of interest to scientists outside our community? To industry? To policy makers? Is this a frontier area of research? Will this be particularly good for teaching? In any given year, we seek to ensure that mineralogists, geochemists, and petrologists will be particularly interested in some of the *Elements* issues, and that they will find it fun to learn about fields that are not their own from the other issues.

**Bruce Watson, Susan Stipp,**  
and **David Vaughan**, Principal Editors,  
and **Pierrette Tremblay**, Managing Editor

## EDITORIAL (cont’d from page 219)

New technologies have contributed to our science on other fronts besides chemical and isotopic analysis. New spectrometers allow us to look more closely at rocks and minerals for telltale indicators of geologic history (e.g. tiny grains of coesite indicating ultrahigh-pressure metamorphism; the hydrogen content of nominally anhydrous minerals as a barometer of mantle water fugacity). New microscopes provide images of minerals at the atomic scale. Beamlines at user facilities around the world (see *Elements* 2, number 1) let us explore structures and properties of phases that were previously inaccessible. The general availability of extraordinarily powerful computers enables us to deduce, through quantum-mechanical and molecular-dynamical models, the energetics and mobility of atoms in fluids and minerals and at the interfaces between them.

Is there really any difference between the present decade and past ones in the interval since V. M. Goldschmidt first elevated our science to the status of a unique discipline? I admit that it may be a matter simply of degree, but I do think the present time is unusual. Incredibly powerful tools are now accessible to a rapidly growing number of scientists applying chemistry and mineralogy to the study of the Earth. This has led to a proliferation not just of data but also of ideas—as well as an extraordinary blossoming of hypotheses that are realistically testable. From our

present vantage point of immersion in this scientific ferment, it is easy to overlook the remarkable growth of the geochemical sciences that drives and is driven by advances in analytical capabilities and other technologies. One day, I predict, we will look back upon this time period (say, 2000–2016, assuming Goldschmidt 2008 is the temporal midpoint!) as the defining interval during which our community recognized and quantified many of the chemical processes and phenomena that link the biosphere, atmosphere, oceans, and solid Earth. This is what our science is about, and right now is an exciting time—even if it’s not quite a revolution.

We should bear in mind that much of the knowledge we are accumulating can inform the increasingly urgent international discussion of energy and the environment. Perhaps we will also be able to look back on this time as one during which the geochemical sciences began to influence governmental decisions and policy.

**Bruce Watson\***  
Rensselaer Polytechnic Institute (watsoe@rpi.edu)

\* Bruce Watson was the principal editor in charge of this issue

# MUSEUMS ARE NOT ATTICS



Rodney C. Ewing

I am a museum addict. I get a rush when strange, unrelated objects are juxtaposed next to one another behind the glass of a poorly illuminated cabinet. The first symptoms of this affliction appeared early in life, when I proudly displayed rocks and plants from the yard in my garage and charged my parents a modest admission fee. Still, from the human impulse to collect and display comes some of the world's magnificent museums.

I recently had the opportunity to visit one of my favorites, the Harvard Museum of Natural History. It is in an old red brick building, and iron-

work stairs lead to the second-floor entrance. The main attraction is the collection of glass flowers, representing hundreds of species as scientifically accurate, life-size models. The collection is the work of Leopold and Rudolph Blaschka, father and son descendants of Bohemian glass-makers, who made these models over a fifty-year period ending in the 1930s (SEE PARTING SHOTS, PAGE 287). Next to the room of glass plants are the mineral-specimen displays. Giant crystals occupy floor-to-ceiling cabinets on opposite sides of the room and act as huge magnets for the small children pressing up against these cases. Smaller specimens are arranged by chemical group in old-style, glass-covered cabinets that rise to just below waist level. Most visitors pass through the grid of cases too quickly to appreciate what has been preserved for them, rushing to touch a few large meteorites in a small exhibit. Beyond is a narrow, crooked room with a series of exhibits on global climate change that features a constantly running film by Daniel Schrag (an *Elements* author) discussing the effects of climate change and challenging the audience to register their views by pressing buttons on a console in front of the screen. The kids treat answering his questions as if it is a video game where speed and force are more important than the right answer. With a quick turn, you pass into a room that (as I later realized) must be part of the Peabody Museum, but you are still not out of hearing of the pounded buttons of climate change. You pass large-scale reproductions of Mayan murals lining both sides of the room, until you finally emerge into a larger room of huge stone carvings and glass cases with a mixed assortment of Mesoamerican objects, such as brightly quilted vests, mannequins in natural dress, and a contemporary array of objects that celebrate the Dia de Los Muertos. If you go upstairs, you are in the South Pacific; downstairs, you may view a collection of early Japanese photographs with fine images of the indigenous Ainu. By retracing your steps back to the entrance, you can begin another journey in the opposite direction, where there is an exhibit of nests and eggs (with the world's largest egg), a display of the skeletons of dinosaurs and mammals in small dioramas, and at the very end of this journey a giant, 42-foot, short-necked plesiosaur, the Kronosaurus, from the Cretaceous of Queensland. After some hours on this Sunday afternoon, I reached saturation and walked into a fresh rain, happy that museums are very much a part of life.

Still, one has to worry about the fate of modern museums of natural science and particularly the large collections that support these displays. The Harvard Museum has a long history tied to the very foundations of our science and is an essential part of the scientific enterprise of exploration, collection, and classification. The greats, from Louis Agassiz to Stephen Jay Gould, were curators as well as professors—and these collections were integral to their research. The mineral collection now has over 60,000 catalogued specimens and 10,000 micromounts. Charles Palache and Clifford Frondel used and nurtured this collection.

Today's museums are moving beyond this sense of "collection" and are becoming interactive, "hands-on" affairs that have the laser focus of a google search. You can walk through lava tubes with badly simulated glowing lava below your feet or stand on a shaking platform that imitates an earthquake. Modern museums are becoming an entertainment for the senses, but often provide precious little for the mind. This shift from science to entertainment means that in some communities the museum becomes an economic "driver," pulling visitors to the community or locals to a renewed downtown. This change in purpose has an important impact on the fate of the precious collections so meticulously gathered by generations of natural scientists.

Once a collection becomes static—and the main issues become cost and space—then the banners of neglect, sell, and disperse are on the horizon. A recent major example of this fate was the mineral collection of the Philadelphia Academy of Natural Sciences (see [www.minvision.com/article-87.html](http://www.minvision.com/article-87.html)). The collection dates from the earliest years of the Republic, and the first contribution (1725 specimens) was from the first American formally trained in mineralogy, Adam Seybert (1773–1825), who studied under René Haüy. Through subsequent, major additions (the Franklin Institute donated its entire collection, as did William Vaux on his death in 1882), the collection grew to some 30,000 specimens by the early 20<sup>th</sup> century. The last curator was Samuel G. Gordon (1897–1952), who also founded the *American Mineralogist*, first published in 1916. After Gordon, there were no mineral curators (except for a period of five years) to look after the collection. Most of the collection was stored, with the loss of some material by neglect. In 2006, much of the collection (about 19,000 specimens) was sold to a consortium of mineral dealers in order to raise funds for other scientific activities of the Academy. Nearly half of the collection went to other museums, such as the Carnegie Museum in Pittsburgh and the Gemological Institute of America.

We need to create a structure and system of support that preserve the cultural and scientific heritage of our mineral collections.

This event and others has stimulated a proposed policy statement by the Mineralogical Society of America (<http://www.minoscam.org/MSA/policy.html>) designed to preserve mineral collections. Although I think that it is easy to sign on to the spirit of the proposal, I do not think that it recognizes the realities of small, but precious, collections held by universities and other private organizations. These collections are often created and sustained by just a few individuals without any substantial support from the organization. When these individuals are gone, there is no institutional memory of their origin or the obligation to have them continue. The financial support that might have gone to a curator competes against salaries for new professors, technical staff, and students. Often, little research relies on the collections, and despite their great cultural and monetary value, they are stored behind closed doors. If a major collection, such as that of the Philadelphia Academy of Natural Sciences, can fall prey to dismemberment, this must happen many times, without notice, to smaller institutional collections around the world.

What can be done? I think that the first step is to make clearer statements about the cultural and scientific value of such collections. There is a special connection to the past in handling material first studied by René Haüy. The scientific value lies in having material that has already been carefully analyzed or that has special properties or provenance. I have often relied on museums for a few rare minerals that preserve a record of radiation damage in specific, but unusual, structures. Professional mineralogists may appreciate the value of collections, but this is less clear to the public that sees only the exhibits at the museum. This is why it is so important to carry out scientific research on the collections, as well as emphasize public outreach, acquisition, and curating.

Finally, with proper financial support, certain national and regional museums should be designated as the proper recipients of collections that no longer have a home. It is not easy for an institution to divest itself of a collection. Most institutions want to preserve the cultural and scientific value of their collection, but this can be complicated by

Cont'd on page 222

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**JAMES GREGORY HIRTH**

For work on the rheology of quartz, olivine + melt + H<sub>2</sub>O, serpentine, and gabbro, and interdisciplinary insight, dedicated teaching, and service to AGU



**TETSUO IRIFUNE**

For contributions to the understanding of the mineralogical structure and dynamics of the Earth's interior through high-pressure experimental studies



**TERRY A. PLANK**

For contributions to the understanding of convergent margin processes and the formation of the continental crust



**BARRY VOIGHT**

For fundamental contributions to the understanding of volcano deformation, assessment of volcanic hazards, and forecasting



From left to right, present and past presidents of the Geochemical Society: Marty Goldhaber, Sue Brantley, and Tim Drever



The "Friend of Tim" button, destined to be a collector's item!

**TIM DREVER HONORED AT THE GOLDSCHMIDT CONFERENCE**

A special session was convened at the 2008 Goldschmidt Conference to pay tribute to James I. (Tim) Drever for his contributions to geochemistry and for his long career at the University of Wyoming. In addition to his best-selling book *The Geochemistry of Natural Waters* and countless research papers, Tim served as a long-time editor of *Chemical Geology* and as the president of the Geochemical Society and was a founding advisor to *Elements* magazine. The session "Rates of Geochemical

Processes and Their Application to Natural Systems" included a keynote address by Art White (U.S. Geological Survey) entitled "Approaches to Estimating Chemical Weathering Rates"; invited talks by David Clow (U.S. Geological Survey)—"Sensitivity of Mineral Weathering Rates to Annual Variations in Climate," and by Chris Gammons (Montana Tech University)—"Biogeochemical Processes in Flooded Underground Mine Workings of Butte, Montana, USA"; and an additional 28 volunteered presentations on mineral weathering and secondary precipitation, global climate cycles, environmental geochemistry of mining, geochemistry of natural waters, and redox reactions at mineral surfaces. A highlight of the festivities was a reception for Tim and his wife, Irene, held at the botanical gardens of the University of British Columbia. Many old and new friends, all wearing a "Friend of Tim" badge, toasted Tim as the "first critical zone geochemist" and a "true gentleman scientist."



Tim and Irene Drever with Hiroshi and Koya Ohmoto. Tim and Hiroshi were grad students together at Princeton in the 1960s.

**Lisa L. Stillings**  
USGS

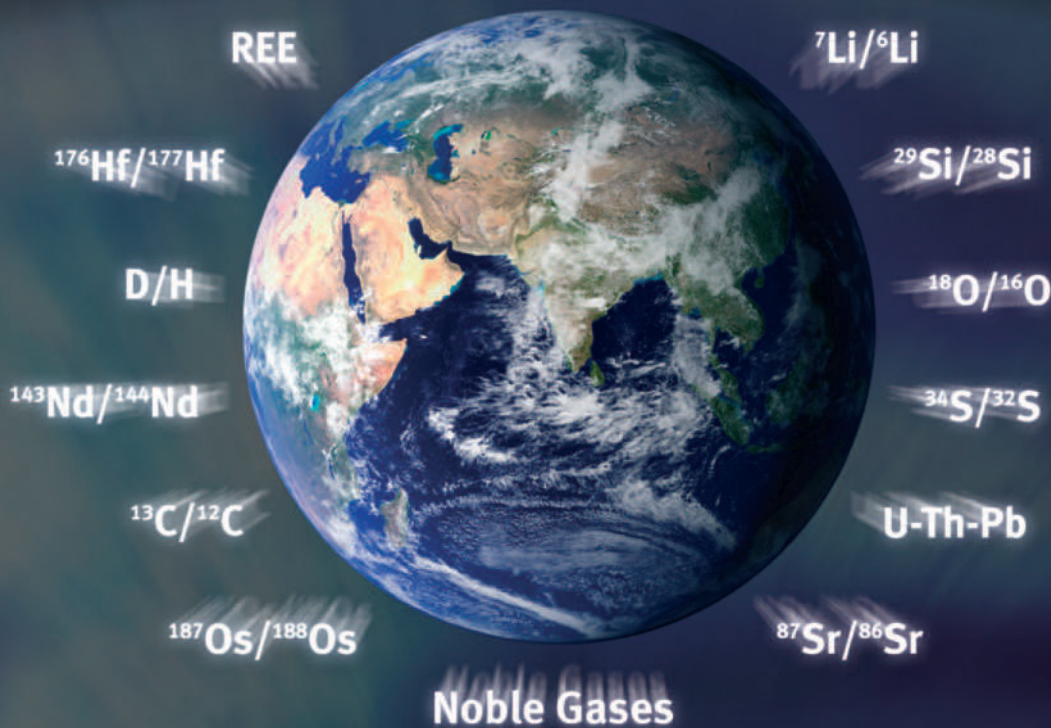
**TRIPLE POINT** (cont'd from page 221)

covenants on donated specimens or the cost of properly appraising the value of the collection. The situation at the Philadelphia Academy is regrettable, but understandable. Collections in storage are not different from our attics filled with old, but valued memorabilia. If we want to prevent these events in the future, we have to clean out our attics

and put these collections to scientific use or on display. We need to create a structure and system of support that preserve the cultural and scientific heritage of our mineral collections.

**Rodney C. Ewing**  
University of Michigan (rodewing@umich.edu)



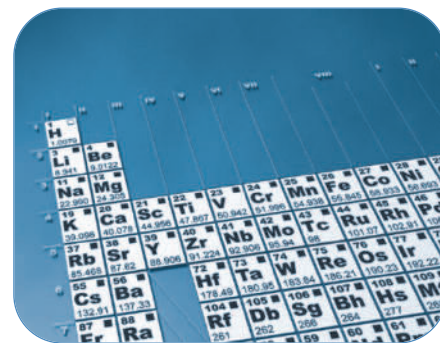


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# Meet the Authors



**Olivier Alard** is a CNRS researcher in the core-mantle group at Geosciences Montpellier (France). Since his PhD (GEMOC, Macquarie University, Australia), he has been interested in the formation and differentiation

of Earth-like planets and in the long-term evolution of the Earth's mantle. His approach uses *in situ* techniques to determine the micron-scale elemental and isotopic distribution of the siderophile and chalcophile elements within their main sulfide and metal-alloy host phases.



**James M. Brenan** is an associate professor in the Department of Geology at the University of Toronto. He obtained a PhD at Rensselaer Polytechnic Institute in 1990 and then did postdoctoral work at the

Geophysical Laboratory and Lawrence Livermore National Laboratory. He simulates rock-forming conditions in the laboratory to establish inter-phase partitioning of minor and trace elements, to assess the role of diffusion in controlling the rates at which natural systems approach equilibrium, and to determine the extent to which geological fluids influence mass transfer. His recent work has focused on understanding the role of sulfide, oxide, and metal phases in controlling the behavior of highly siderophile elements in magmatic systems.



**Richard W. Carlson** is a staff scientist in the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. He pursues various applications of isotope and trace element geochemistry in

the fields of cosmochemistry and solid-Earth science. His recent work has focused on isotopic anomalies in solar system materials, early planetary differentiation using the  $^{146}\text{Sm}$  and  $^{107}\text{Pd}$  chronometers, the causes of continental intraplate volcanism, and the processes that form continental crust and its underlying sections of mantle lithosphere, the latter done mostly with the Re-Os system.



**Jean-Pierre Lorand** is a research director at the Centre National de la Recherche Scientifique (CNRS). He works at the Museum National d'Histoire Naturelle (Paris) as head of the Laboratory of Mineral-

ogy. After pioneering work on mantle-derived sulfide minerals in the 1980s, his research topics focused on the abundance of sulfur in

the mantle. More recently, his major topic of research was platinum-group elements (PGE), their distribution among mantle minerals, and their fractionation in response to igneous processes involving the mantle. Now, he centers his attention on the origin of PGE-rich micronuggets in mantle sulfides. He was involved in the organization of the first three International Workshops on Highly Siderophile Elements.



**Ambre Luguët** is an assistant professor at the Steinmann Institut of Bonn University. She completed her PhD at the Paris Natural History Museum in 2000, which was followed by postdoctoral work at the

Carnegie Institution of Washington (DTM) and at Durham University. She was involved in the organization of the 3<sup>rd</sup> International Workshop on Highly Siderophile Elements held in Durham and in the resulting special issue of *Chemical Geology* (volume 248). Her research interests focus on the isotopic compositions of the highly siderophile elements (HSE) and osmium in mantle-derived peridotites and lavas with a particular emphasis on the role of HSE host minerals in controlling these geochemical signatures.



**Gregory M. Morrison** is a professor in the Department of Civil and Environmental Engineering at Chalmers University of Technology, Sweden. His research interests include water-quality analysis,

water-systems assessment, and water engineering. He started research on the platinum-group elements during a postdoctoral visit in Australia in 1988 and has maintained his interest in the subject since then.



**James E. Mungall** is an associate professor in the Department of Geology at the University of Toronto. His research is largely oriented toward understanding the genesis of magmatic ore deposits,

using inputs from igneous and hydrothermal geochemistry, extensive field work, and experimental petrology. A major focus of his work in recent years has been the use of platinum-group elements as tracers to illuminate the genetic processes that form magmatic ores, spanning the range from melting and magma transport to phase separation and collection.



**Anthony J. Naldrett** is a University Professor emeritus at the University of Toronto. Although he retired from the university 10 years ago, he has continued both his research into the origin of magmatic

sulfide deposits and advising mining companies in their exploration for them. Currently he spends five months each year at the University of the Witwatersrand, where he holds an honorary professorship and is studying the concentration of PGE in the Merensky Reef, UG-2, and Platreef.



**Herbert Palme** is professor of geochemistry and mineralogy in the Department of Geology and Mineralogy at the University of Cologne. Earlier he had spent more than 20 years in the

Cosmochemistry Department of the Max-Planck Institute for Chemistry in Mainz. His main interest is in the formation and early evolution of the solar system, including the Earth. He has published papers on PGE in terrestrial crater samples, in meteorites and their components, and in lunar rocks. Together with Alexander Borisov, he has experimentally determined one-bar solubilities of PGE in silicate melts. These data lead to extremely high metal-silicate partition coefficients for the PGE.



**Sebastien Rauch** is an associate professor in the Department of Civil and Environmental Engineering at Chalmers University of Technology, Sweden. His research deals primarily with emerging metallic contaminants and the biogeochemical processes

controlling the fate of these contaminants. Platinum-group elements have been a major component of this research, resulting in over 30 peer-reviewed articles on platinum-group element analysis, emissions, environmental levels and physicochemical forms, dispersion mechanisms, bioaccumulation, and toxic effects.



**Maria Schönbacher** is a lecturer at the University of Manchester, UK, since October 2007. She received her PhD in cosmochemistry from ETH Zürich, Switzerland, which was followed by postdoctoral studies in

the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and in the Imperial College London. She is partic-

ularly interested in extinct radionuclides, mainly  $^{107}\text{Pd}$  and  $^{92}\text{Nb}$ , in order to understand processes in the early solar system, such as the depletion of volatile elements, the differentiation and evolution of planetary bodies. Further research subjects include stable-isotope fractionation of non-traditional volatile elements, isotopic anomalies in solar system materials, and the development of new techniques for the analysis of isotopes in geologic materials.



**Steven B. Shirey**

is a staff scientist in the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. He is a trace-element and isotope geochemist interested in problems of

continent formation, Archean mantle evolution, and the geodynamics of the modern oceanic mantle. Recent work has centered on the onset of subduction on Earth, the petrogenesis of diamonds, and novel applications of the Re-Os isotopic system to geological processes in the mantle keels beneath continents.



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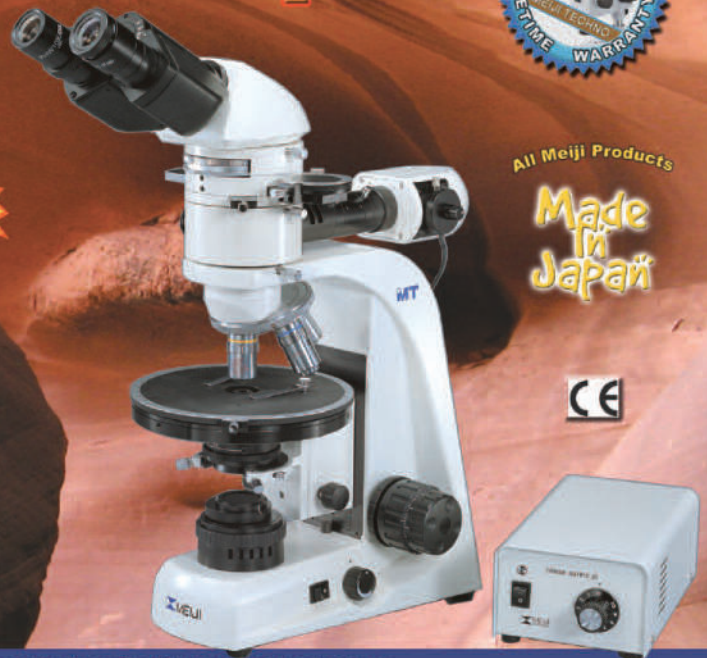


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# A. G. TINDLE Minerals of Britain and Ireland



*Minerals of Britain and Ireland* is a completely comprehensive treatment of the minerals found in Britain, Ireland and the surrounding islands. Beautifully illustrated throughout with over 550 colour and black and white images, the book provides exhaustive coverage of the remarkably wide range of minerals found in this part of the world. *Minerals of Britain and Ireland* is replete with bibliographical references and it describes many additional discoveries never previously published. Coverage includes all relevant articles from national mineralogical organizations such as the Mineralogical Society of Great Britain and Ireland (from 1876) and the Russell Society (from 1982). The last time a book of this type was attempted was 150 years ago, long before modern analytical instrumentation had been developed. Over 900 additional species new to Britain or Ireland have been described since that time. In total, over 2200 minerals are listed, including over a thousand confirmed species. This monumental work will be warmly welcomed by mineral collectors, curators, dealers, students and research scientists.

Andrew Tindle is Senior Project Officer in the Department of Earth Sciences, the Open University, Milton Keynes, UK. He has published over 90 scientific papers and is co-author of two books.

## CONTENTS

Preface; Acknowledgements; Abbreviations Introduction

THE MINERALS [listing a small fraction of the 2200 minerals in the book]

abhurite, abichit, abriachanite, acadialite, acanthite, . . . babel-quartz, babingtonite, baddeleyite, baltimorite, balvraidite, . . . cacholong, cacoxenite, cairngorm, calamine, calaverite, . . . dahllite, damourite, danalite, danburite, daphnite, . . . earthy cobalt, eastonite, eandrewsite, ecdemite, edenite, . . . fahlerz, fairfieldite, fäerolite, famatinite, fargite, . . . gadolinite-(Y), gahnite, galactite, galena, galenite . . . haarkies, haema-ovoid-agate, haematite, haidingerite, halite, . . . ice, iceland spar, idaite, iddingsite, idocrase, . . . jacobsite, jade tenace, jahnite, jalpaite, jamborite, . . . kaersutite, kahlerite, kainosite-(Y), kakochlor, kaloglimmer, . . . labradorite, lady's slipper, laitakarite, lanarkite, langbeinite, . . . macaulayite, mackinawite, macphersonite, maghemite, magnesio-anthophyllite, . . . nacrite, nadorite, nagyagite, nailhead spar, nakauriite, . . . oakstone, ochre, octahedrite, offretite, okenite, . . . palagonite, palladium, palladoarsenide, palladsseite, palygorskite, . . . qitianlingite, quandilite, quartz, quartzine, queitite, . . . radiolite, rammelsbergite, ramsbeckite, ramsdellite, rancieite, . . . sadanagaite, safflorite, sagenite, sahlite, sal-ammoniac, . . . tacharanite, tachyhydrite, talc, talcite, tallingite, . . . ugrandite, uigite, ullmannite, ulvöspinel, umangite, . . . vaesite, valentinite, valleriite, vanadinite, vandenbrandeite, . . . wad, wairakite, wakefieldite-(Ce), walkerite, walpurgite, . . . xanthosite, xanthochroite, xanthoconite, xantholite, xanthophyllite, . . . yarrowite, yellow arsenic, yellow copper or yellow ore, yellow ochre, . . . zálesite, zaratite, zavaritskite, zeunerite, zeuxite, . . .

Tables; Museums; Glossary; Bibliography

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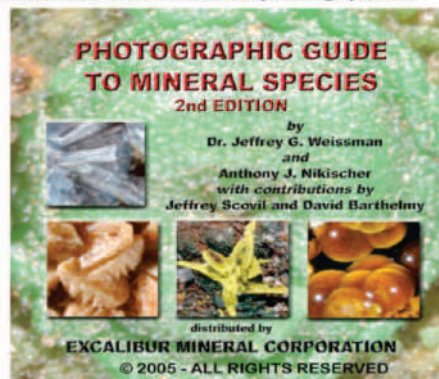
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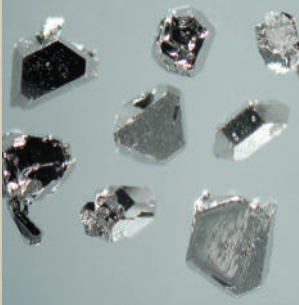
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# The Platinum-Group Elements: "Admirably Adapted" for Science and Industry

James M. Brenan\*

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KEYWORDS: platinum-group elements, siderophile, chalcophile, alloy, sulfide, catalysis

## INTRODUCTION

On 23 January 1817, Sir Humphry Davy delivered a lecture to the Royal Society of London describing the results of his recent experiments on the combustion of gas mixtures. Davy reported "the discovery of a new and curious series of phenomena," in which mixtures of highly explosive coal gas and air were found to cause a heated wire of platinum to "become ignited nearly to whiteness." Once the glowing of the wire was extinguished, it was found that the gas mixture was no longer inflammable. Davy reported that "I tried to produce these phenomena with various metals; but I have succeeded only with platinum and palladium; with copper, silver, iron, gold and zinc, the effect is not produced." What Davy had discovered was heterogeneous catalytic oxidation. Davy immediately recognized the practical application of his discovery and modified the safe-lamp he had designed for coal miners to include a Pt wire around the lamp flame (Fig. 1), thus limiting the amount of combustible gas available to the flame and reducing the chance of explosion.

Fast forward to the year 2007, and the impact of Davy's original discovery becomes apparent: ~9 million ounces of Pt and Pd (worth ~US\$7 billion) were produced for the heterogeneous catalytic oxidation of automobile exhaust gas. This is in addition to the amounts produced for jewelry and other industrial processes (mostly catalysis related) involving one or more of the platinum-group metals (PGE: Os, Ir, Ru, Rh, Pt, Pd), totaling some 7 million ounces, worth ~US\$10 billion<sup>1</sup>. How does an issue of *Elements* devoted to the PGE fit into

"Platinum is a most valuable metal; as it is not oxidisable, nor fusible under common circumstances, and only with difficulty combinable with sulphur, and not acted upon by common acids, it is admirably adapted for the uses of the philosophical chemist." *Elements of Chemical Philosophy*,  
BY HUMPHRY DAVY

this picture? Most significantly, many of the chemical properties of the PGE that are of industrial interest also result in distinct geochemical behavior, affording a unique view of early solar system evolution and planet formation and differentiation. The PGE, along with rhenium and gold, are grouped together as the highly siderophile elements, which are defined by their extreme partitioning into the metallic, relative to the oxide, phase. The PGE are highly refractory, as gauged by their high melting and condensation temperatures (Fig. 2), and were therefore relatively concentrated in the feedstock for the terrestrial planets (Palme 2008 this issue). However, because of an aversion to bonding with oxygen, the PGE are now scarce in the crusts of differentiated planets and, instead, are concentrated in the core-forming Fe-Ni alloy. As discussed in the articles by Palme (2008) and Lorand et al. (2008 this issue), this tendency to exist in the metallic state (termed siderophile) or bond with sulfur and other Group Va and VIa ligands (termed chalcophile) has thus provided geochemists with a sensitive tracer of differentiation processes that involved metal or sulfide phases. As an invaluable bonus, three radioisotope decay systems include the PGE as parent (<sup>107</sup>Pd-<sup>107</sup>Ag), daughter (<sup>187</sup>Re-<sup>187</sup>Os), or both (<sup>190</sup>Pt-<sup>186</sup>Os). These systems have not only provided chronological information, but differences in parent-daughter fractionation have produced distinct isotopic tracers of a variety of geochemical processes (Carlson et al. 2008 this issue).

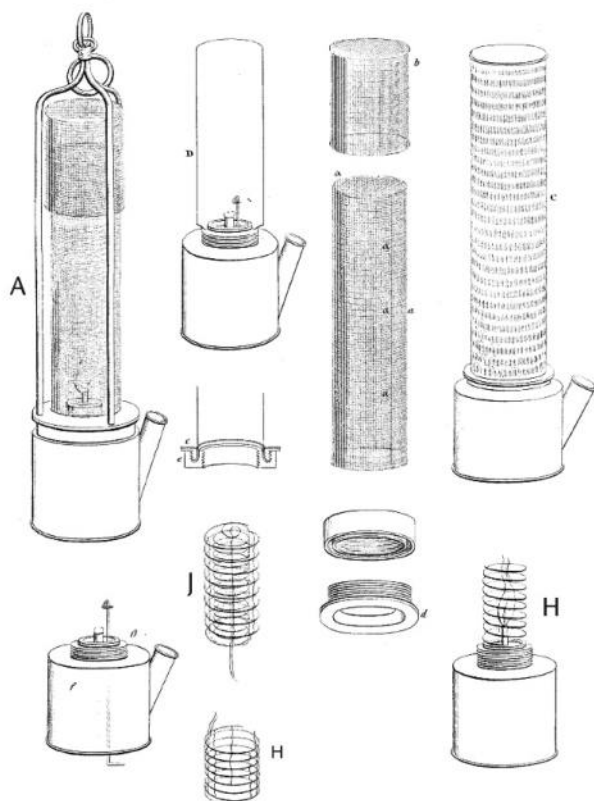
Owing to their scarcity, but enormous industrial demand, there is significant interest in understanding the rare occurrence of mineable PGE concentrations in the highly depleted crust. In this context, Mungall and Naldrett (2008 this issue) emphasize the chalcophile behavior of the PGE and the massive extraction capacity of magmatic sulfide liquids.

As a resident of London in the 1800s, Humphry Davy would have most certainly been subject to the poor air quality that typified this time. Today, it's not the burning of coal, but

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<sup>1</sup> 2007 PGE production statistics obtained from Johnson Matthey market data tables ([www.platinum.matthey.com/publications/](http://www.platinum.matthey.com/publications/)). Total PGE values are calculated from metal prices averaged for the 12-month period.

automobile exhaust that degrades the air quality of many urban centers. Autocatalysts have significantly reduced this problem (see below), but the PGE they contain (and those from other industrial sources) are released to the environment, and some of these PGE are bioavailable. As Rauch and Morrison (2008 this issue) describe, this is a matter of some concern, as the risks of PGE emissions to human health and the environment have not been accurately assessed. There is a clear call for more intense research in this area.



**FIGURE 1** Detail of the Davy Safe-Lamp (A) employed in British coal mines, with the Pt wire modification (J and H) used to catalyze methane oxidation (after Davy 1817). REPRINTED WITH PERMISSION OF THE ROYAL SOCIETY OF LONDON

Platinum-Group Elements (PGE)				
44 <b>Ru</b> hcp mp 2607 K	45 <b>Rh</b> fcc mp 2237 K	46 <b>Pd</b> fcc mp 1828 K		
75 <b>Re</b> hcp mp 3459 K	76 <b>Os</b> hcp mp 3306 K	77 <b>Ir</b> fcc mp 2739 K	78 <b>Pt</b> fcc mp 2041 K	79 <b>Au</b> fcc mp 1337 K

**FIGURE 2** A portion of the periodic table containing the highly siderophile elements, which includes the platinum-group elements, rhenium, and gold. Elements are depicted with their atomic number, crystal structure, and melting point. COURTESY OF H. PALME

## DISCOVERY AND PURIFICATION OF THE PGE

In 1741, the metallurgist Charles Wood returned to England with samples of platinum acquired in Jamaica but which likely came from the placer deposits of the Choco district of Colombia<sup>2</sup>. This material was given to Dr. William Brownrigg, whose description was read to the Royal Society of London by William Watson (Watson and Brownrigg 1750). In this description, the samples are referred to as “platina,” which is derived from the Spanish for “little silver” and alludes to their appearance (FIG. 3). William Lewis performed an exhaustive battery of tests on this newly found material and concluded that “it follows, that platina is not, as some believe, gold naturally debased by the admixture of some other metallic body, but a metal of the peculiar kind, essentially different from all others” (Lewis 1757).

One important discovery made by Lewis is that platina is soluble in aqua regia, “excepting a little blackish matter” (Lewis 1754), which suggested the presence of impurities in the raw sample. Subsequent work on this residue led to the discoveries of iridium and osmium by Smithson Tennant, reported to the Royal Society of London on 21 June 1804. In the case of iridium, Tennant writes, “I should incline to call this metal *Iridium* [from *iris*, Greek for rainbow], from the striking variety of colours which it gives, while dissolving in marine acid [HCl]” (Tennant 1804). Tennant notes that during one of the osmium purification steps, “a pungent and peculiar smell is immediately perceived.” He discovered that this smell “arises from the extrication of a very volatile metallic oxide,” providing the basis for the name *Osmium*, which is derived from *osme*, Greek for smell. That smell, of course, originates from the highly toxic osmium tetroxide.

Three days later, Tennant’s colleague William Wollaston reported the discovery of rhodium (Rh), which was purified from the solution remaining after precipitating platinum by treatment with sal ammoniac (NH<sub>4</sub>Cl). He indicated that this new element should be “distinguished by the name *Rhodium* [from *rhodon*, Greek for rose], from the rose-colour of a dilute solution of the salts containing it” (Wollaston 1804). The following year, Wollaston (1805) reported the discovery of palladium, which was purified from the aqua regia solution used to dissolve raw platina. In his report to the Royal Society of London, Wollaston proposed the name palladium, “from the planet that had been discovered nearly at the same time by Dr. Olbers,” referring to the discovery of the Pallas asteroid (originally considered to be a planet) by the German astronomer Heinrich Olbers on March 28, 1802. Records from his monetary accounts (Chaldecott 1979) reveal that Wollaston garnered significant income from a method he developed for platinum purification from raw platina, which he only made public in the Bakerian Lecture to the Royal Society (Wollaston 1829) shortly before his death in 1828. This income helped to furnish the endowment for the Wollaston Medal awarded by the Geological Society of London (FIG. 4). The medal was originally cast in gold, but from 1846 to 1860 it was cast in palladium extracted from Brazilian gold donated by noted assayer and metallurgist P. N. Johnson.

Ruthenium (Ru) was the last of the PGE to be discovered, and was isolated from the insoluble residue after aqua regia digestion of platinum ore from the Urals. The initial claim of discovery was by the German chemist Gottfried Osann in

<sup>2</sup> The pre-Hispanic natives of this region had used material from the Choco deposits to produce exquisite jewelry and objects of practical use (fishing hooks, sewing needles, awls, tweezers). These people had remarkable metallurgical ability, making use of liquid-phase sintering of Au–Pt mixtures to produce malleable alloys which were fabricated into intricate objects (Scott and Bray 1980).

1827, although the definitive purification is attributed to the Russian chemist Karl Klaus, reported in 1844. Ruthenium is derived from *ruthenia*, Latin for Russia, named for Klaus's homeland, and in honor of Osann's original work (Griffith 1967).

## INDUSTRIAL DEMAND FOR THE PGE

The most significant industrial demand for the PGE (see Figure 1 of Rauch and Morrison 2008) arises from their important role in the operation of modern automobiles, which is to catalyze key reactions involved in fuel production and engine emission control. The special role of the PGE in this context arises from two key properties. First, as a consequence of the very high oxygen potential defined by their metal-oxidation reactions, the platinum-group metals are stable in air even at relatively high temperature (see Figure 1 of Palme 2008). Second, the PGE have the remarkable ability to chemisorb simple gaseous molecules, like  $O_2$  and  $CO$ , so as to result in significant coverage of the metal surface, but adherence is not so strong that surface reaction rates are retarded (Bond 1991). Consequently, the rates of certain chemical reactions are vastly accelerated by the presence of the PGE metal surface, although the metal itself is not a reactant or product, and reactions can be allowed to take place at higher temperatures without degradation of the metal surface. Optimal engine performance requires fuel that can be highly compressed before controlled ignition by the spark plug, and the measure of fuel performance in this regard is the octane rating. At petroleum refineries, the octane rating of fuel is improved by using Pt-Ir or Pt-Re catalysts in the reforming process to convert aliphatic hydrocarbons to aromatic hydrocarbons, such as in the dehydrogenation of n-heptane (octane rating = 0) to toluene (octane rating = 114). Octane ratings can also be enhanced using platinum catalysts for the isomerisation of  $C_4$ - $C_6$  alkanes (Parkins 1991). Combustion of fuel in car engines produces  $CO_2$  and  $H_2O$ , as well as lesser amounts of  $CO$ , volatile organic compounds, and nitrogen oxides ( $NO$  and  $NO_2$ , together known as  $NO_x$ ). The latter three are considered harmful and can be reduced at the tailpipe using two important emission-control devices that incorporate the PGE as essential components. Just downstream from the fuel combustion chamber is an oxygen sensor, which consists of a ceramic solid electrolyte (usually impurity-doped  $ZrO_2$ ) plated with platinum electrodes. This device monitors the oxygen content of the combustion gas and is part of a feedback loop to adjust the fuel/air ratio in the combustion chamber for peak performance and to optimize the conversion of unburnt fuel,  $CO$ , and  $NO_x$  in the catalytic converter. The catalytic converter is located downstream from the oxygen sensor and consists of a honeycomb-structured ceramic core, coated with a porous "washcoat" of alumina, then the catalyst, which consists of some combination of Pt, Pd, and Rh (Bond 1991). The converter catalyzes three reactions that result in the production of harmless products:

- (1)  $2NO_x = 1/2 N_2 + xO_2$  ( $NO_x$  reduction)
- (2)  $2CO + O_2 = 2CO_2$  ( $CO$  oxidation)
- (3)  $2C_xH_y + (2x+y/2)O_2 \rightarrow 2xCO_2 + yH_2O$  (oxidation of unburned fuel)

A combination of physical and chemical degradation of the catalyst is thought to be responsible for the release of PGE aerosols to the roadside environment and beyond (see Figure 2 of Rauch and Morrison 2008).



**FIGURE 3** Samples of "platina" recovered from the placer deposits in the Choco district of Colombia. Similar material was described by William Lewis to the Royal Society of London in 1754 and served as the feedstock for the first purification of Pt, Pd, Ir, and Os by Smithson Tennant and William Wollaston. The field of view is 5 cm wide (each nugget is about 3–5 mm in length). Sample is from the mineralogy collection of the Museum National d'Histoire Naturelle (#4.283; Picture D. Brabant, MNHN). PHOTO COURTESY OF JEAN-PIERRE LORAND

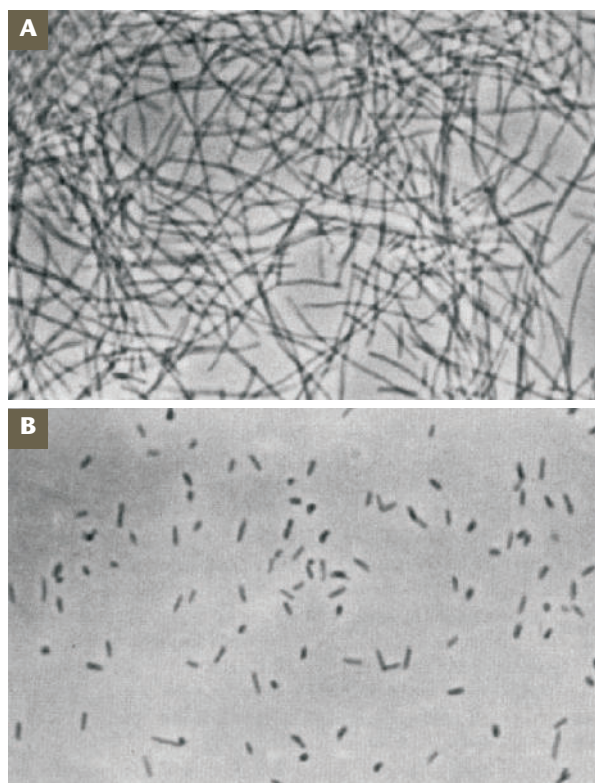


**FIGURE 4** Front and back faces of the Wollaston Medal presented to Sir William Logan (first director of the Geological Survey of Canada) in 1856. The front of the medal depicts William Wollaston, the benefactor of the award. The medal is cast in palladium, which Wollaston discovered in 1805. The Wollaston Medal is the highest award bestowed by the Geological Society of London. NATURAL RESOURCES CANADA IMAGE NRCAN-4374, USED WITH PERMISSION OF NATURAL RESOURCES CANADA. HER MAJESTY THE QUEEN IN RIGHT OF CANADA

## HEALTH AND WELL-BEING FROM THE PGE

From improving our smiles to curing life-threatening diseases, PGE are used in a number of therapies to enhance our health and well-being. For example, prosthetic teeth (bridges and crowns) are typically made of gold alloyed with Pt and/or Pd, which are added to improve strength and stiffness so as to endure the rigors of biting and chewing. Owing to their biocompatibility, high electrical conductance, and resistance to corrosion, Pt and Pt-Os alloy are essential components of implant devices used to treat irregular heart-beat and in the replacement of defective heart valves. Surgeons also make use of Pt as X-ray-opaque guidewires when performing angioplasty. Although osmium tetroxide is highly toxic to living tissue, biomedical researchers have long employed solutions of this compound to fix and stain fatty tissue for electron microscopy. Perhaps one of the most important PGE-based therapeutic materials is the anticancer drug cis-diamminedichloroplatinum(II) or cis-[Pt(NH<sub>3</sub>)<sub>2</sub>Cl<sub>2</sub>],

also known as cisplatin. Although the cisplatin molecule had been known for some time, the discovery of its cancer-fighting properties was by chance. Barnett Rosenberg, a biophysicist at Michigan State University, had set out to examine the effects of electric fields on bacterial growth. Cultures of *E. coli* were immersed in a buffer solution containing ammonium chloride, and Pt was used as the electrode due to its perceived chemical inertness. The specific choice of AC electric field frequency and current were to eliminate electrolysis effects. As described in their original letter to the journal *Nature* (Rosenberg et al. 1965), it was subsequently realized that “both are mistaken ideas which led, via serendipity, to the effects described in this communication.” Rosenberg and coworkers observed that the bacteria in cultures subject to the electric field exhibit filamentous growth (FIG. 5A), in contrast to their typical “sausage” shape (FIG. 5B). The effect was not due to growth, but rather to inhibition of cell division, and after further investigation, it was determined that the causative agent was not the electric field, but hydrolysis products of the platinum electrode. Subsequent work showed that several Pt(II) and Pt(IV) compounds exhibit antitumor activity, effectively inhibiting a type of sarcoma and leukemia in mice (Rosenberg et al. 1969). In 1971, cisplatin underwent clinical trials and was determined to be effective against tumors in human subjects, and in 1978, it was approved for treatment of ovarian and testicular cancers. A number of cisplatin analogs have since been developed that show less toxicity and equal or greater antitumor activity.

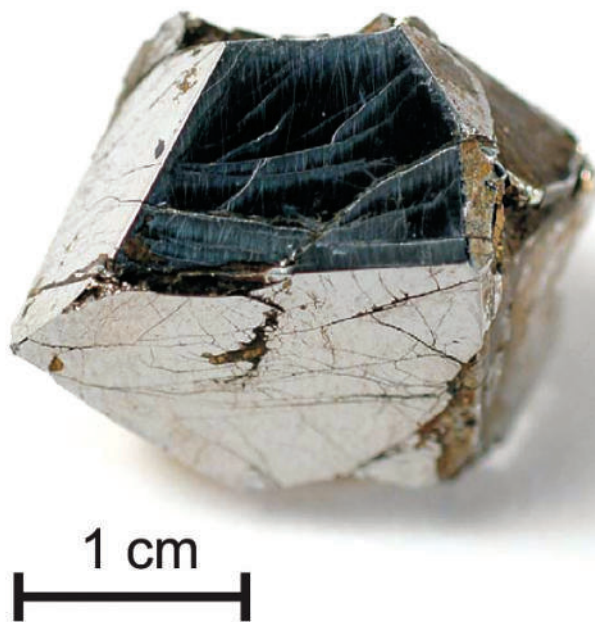


**FIGURE 5** Phase contrast photomicrographs of *E. coli* cultured in growth medium containing (A) 8 ppm of platinum as the neutral species  $[\text{PtCl}_4\text{-(NH}_3)_2]^0$  and (B) less than 6 ppm of platinum as the doubly negative species  $[\text{PtCl}_6]^{2-}$ . Magnified 600x. The image in (A) shows the development of filamentous forms, in contrast to the normal sausage shape shown in (B), indicating the inhibiting effect of  $[\text{PtCl}_4\text{-(NH}_3)_2]^0$  on cell division, but not on growth. From Rosenberg et al. (1967). COPYRIGHT 1967 BY THE AMERICAN SOCIETY FOR BIOCHEMISTRY AND MOLECULAR BIOLOGY. USED WITH PERMISSION OF AMERICAN SOCIETY FOR BIOCHEMISTRY AND MOLECULAR BIOLOGY IN THE FORMAT MAGAZINE VIA COPYRIGHT CLEARANCE CENTER

## THE IMPORTANCE OF PGE ACCESSORY MINERALS

One of the most fundamental, but perhaps least understood, aspects of PGE geochemistry is their distribution in rocks. Knowledge of this has an important bearing on the behavior of these elements during melting and solidification, in turn affecting PGE isotopic systems, as well as mineral beneficiation and ore recovery. Both experiments and studies of natural samples suggest that although trace quantities of Ir, Ru, and Rh can reside in the structures of silicate and oxide minerals (i.e. olivine and chromite), by far the dominant hosts for all the PGE are base-metal sulfides (pyrrhotite, chalcopyrite, and pentlandite) and PGE-bearing “accessory” minerals (PGM; Lorand et al. 2008). Although present in very low modal abundances, the PGM can dominate the whole-rock budget of the PGE they concentrate, especially in the case of refractory mantle samples. This is directly analogous to the role of zircon, apatite, monazite, etc., in controlling the behavior of trace lithophile elements in felsic igneous rocks. There are more than 100 distinct PGM species: some are comprised of PGE only, some occur in combination with Fe, Cu, or Ni, and some are bonded to Group Va and VIa ligands, such as S, As, Sb, and Te (Cabri 2002). Knowledge of intensive variables during PGM formation can be obtained with the appropriate phase-equilibrium and partitioning information, for which there is a growing literature (Makovicky 2002; Andrews and Brennan 2002; Bockrath et al. 2004). In sulfide-saturated igneous rocks, the PGM are likely to form either by exsolution from primary base-metal sulfides as a consequence of cooling, or by enrichment of PGM-forming components during the final stages of differentiation of magmatic sulfide liquid (e.g. Barnes et al. 2006). Although rare, spectacular, relatively large (centimeter-sized), euhedral crystals can be found in some differentiated massive-sulfide bodies (FIG. 6).

A common but somewhat enigmatic petrographic association for the PGM in sulfur-poor ultramafic igneous rocks is their occurrence as inclusions within chromite. Although a wide range of compositions have been documented for chromite-hosted inclusions (Legendre and Augé 1986), typical PGM



**FIGURE 6** Single crystal of the mineral sperrylite ( $\text{PtAs}_2$ ) from Noril'sk (Russia). The sample is from the mineralogy collection of the Museum National d'Histoire Naturelle (#193.27; picture D. Brabant; MNHN). PHOTO COURTESY OF JEAN-PIERRE LORAND

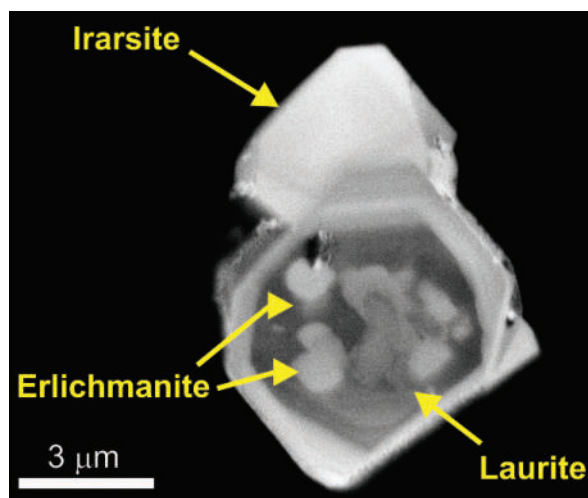


are isoferroplatinum (Pt<sub>3</sub>Fe), osmiridium (*hcp* Os–Ir alloy), and laurite–erlichmanite (RuS<sub>2</sub>–OsS<sub>2</sub> solid solution; FIG. 7). Inclusions are generally submillimeter in size but may also occur at the nanometer scale, as inferred using in situ analysis by laser ablation ICP–MS (e.g. Ballhaus and Sylvester 2000). Although the process of PGM formation is not well understood, the presence of primary magmatic minerals included with some PGM suggests both phases formed at high temperature and were entrapped at the time of chromite crystallization. Alternatively, some chromite-hosted PGM could be the product of deposition from a PGE-laden hydromagmatic fluid or the result of desulfidation of pre-existing base-metal sulfides.

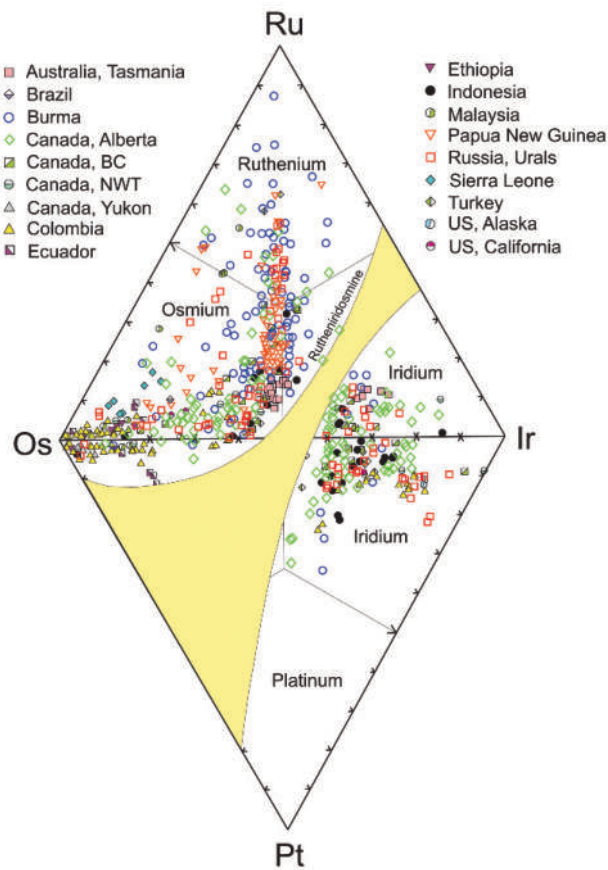
Weathering and erosion of PGM-bearing rocks produces PGM placers, which are dominated by alloys. Placer alloys are typically either Pt–Fe or Ru–Ir–Os–Pt; the latter exhibit a compositional gap consistent with the limits of miscibility known from phase-equilibrium experiments (FIG. 8; Cabri et al. 1996). Placer PGM have compositions similar to those found as inclusions in chromite, consistent with studies that have located placer sources in sulfur-poor ultramafic rocks (Hattori and Cabri 1992; Cabri et al. 1996). Of historical significance is that samples of platinum alloy from which the other PGE were originally purified were from placer deposits located in the Chocos district of Colombia and the Ural Mountains of Russia.

## FUTURE PROSPECTS

Improved chemical separation and analytical techniques have provided the means to measure the elemental and isotopic composition of the PGE in laboratory and natural samples with unprecedented precision. The wealth of data acquired by these methods has expanded our knowledge of these elements and posed new questions regarding their behavior. As noted by Lorand et al. (2008), estimates of the primitive-mantle concentrations of the PGE are not in complete accord with levels in primitive meteorites, and our understanding of this discrepancy will require fuller knowledge of PGE fractionation processes during mantle differentiation. The distribution and stability of scarce platinum-group minerals may be critical to this assessment. In the context of core formation, Palme (2008) has emphasized that metal–silicate partitioning does not adequately account for the upper-mantle abundances of PGE, supporting a heterogeneous accretion model for Earth evolution. Complete assessment of this model awaits more experiments on the effect of high temperature on metal solubility, and agreement as to the interpretation of metal heterogeneity in experimental run-products. Although PGE ore deposits such as those in the Bushveld Complex in South Africa have been exploited for many years, the debate continues regarding the primary metal-concentration mechanisms. Whereas immiscible sulfide liquids have been shown to be important, both experiments and detailed field observations provide support for the role of hydrothermal solutions in dissolving and transporting the PGE (Mungall and Naldrett 2008). The PGE isotope systems have provided a wealth of insights regarding a range of geochemical processes. Uncertainties still exist, however, concerning the origin of Os isotope anomalies in oceanic basalts (Carlson et al. 2008), in terms of core input or the production of isotopically distinct reservoirs by low-pressure processes. As mentioned previously, the extraction and industrial use of the PGE have accelerated their dispersal in the natural environment. Rauch and Morrison (2008) emphasize that the ecological impact of the PGE is not well known, and there is clear need for further research in this area.



**FIGURE 7** Backscattered-electron image depicting an aggregate of platinum-group minerals included in a chromite grain from the Mayarí-Baracoa ophiolite belt of eastern Cuba. The inclusion consists of distinct grains of irrasite (IrAsS) and laurite (RuS<sub>2</sub>). The laurite contains a core of Ru-rich erlichmanite (OsS<sub>2</sub>) surrounded by a layer of Os-poor laurite grading to Os-rich laurite at the rim. USED WITH PERMISSION FROM SPRINGER SCIENCE+BUSINESS MEDIA: GERVILLA ET AL. (2005; FIG. 4G)



**FIGURE 8** The quaternary system Ru–Os–Ir–Pt depicting the composition of platinum-group element alloys from world-wide placer deposits (after Cabri et al. 1996). The minerals in this system are either hexagonal (osmium, ruthenium, rutheniridosmine) or cubic (platinum, iridium). The majority of platinum-group minerals found in placer deposits are Ru–Ir–Os–Pt and Pt–Fe alloys. Rhodium and palladium are typically minor constituents of these phases. The yellow shaded region corresponds to the miscibility gap in the quaternary system, as defined empirically by the alloy compositions, and is consistent with experimental data in the Ru–Ir, Os–Ir and Os–Pt binary systems. Figure from *Exploration and Mining Geology*, volume 5, no. 2; REPRODUCED WITH PERMISSION OF THE CANADIAN INSTITUTE OF MINING, METALLURGY AND PETROLEUM

## FOR MORE INFORMATION

The articles in this issue of *Elements* have been written with a specific focus on topics relevant to Earth scientists, but the scope of research related to the PGE is significantly broader. Useful texts that provide synopses of the chemical properties of the PGE are by Cotton (1997) and a compendium of papers edited by Hartley (1991). The reader is referred to *Platinum Metals Review*, published by Johnson Matthey Ltd., for a range of technical and historical information on the PGE. A detailed account of the history of the PGE, including important discoveries and scientific work, can be found in the book *History of Platinum and Its Allied Metals* by Donald McDonald and Leslie B. Hunt (1982). Enjoy!

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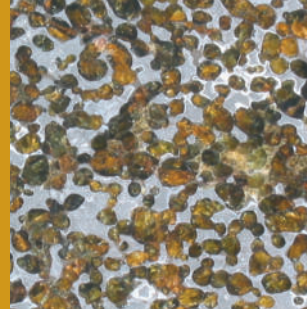
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# Platinum-Group Elements in Cosmochemistry



Pallasitic meteorite: mixture of olivine and metal resembling the core–mantle region of an asteroid; width ca. 3 cm. PHOTO A. PACK

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**In a cooling solar nebula, five of the six platinum-group elements (PGE) condense as refractory-metal alloys at temperatures above the condensation of Fe–Ni metal. Non-refractory Pd condenses in solid solution with Fe–Ni. Such refractory alloys are preserved in some meteorites, although they are often highly altered. The high resistance of PGE to oxidation leads to efficient extraction with metallic Fe–Ni during metal segregation and core formation. Experimentally determined PGE metal–silicate partition coefficients predict lower contents of PGE in planetary silicates than are found, supporting a late addition of PGE components. PGE are particularly useful as tracers of impacting extraplanetary materials in the strongly PGE-depleted crusts of the Earth and other planets.**

KEYWORDS: refractory metal, meteoritic component, noble-metal solubility, Ir enrichment

## INTRODUCTION

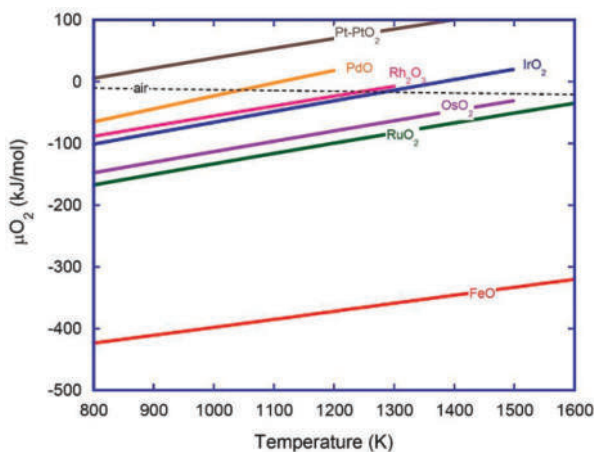
The platinum-group elements (PGE) comprise a group of six rare metals – Os, Ir, Ru, Rh, Pt, Pd – with similar physical and chemical properties (see Brenan 2008 this issue). All six PGE have melting points significantly above the melting point of Fe (1665 K), ranging from 1828 K for Pd to 3306 K for Os (Fig. 2 in Brenan 2008). Metal vapour pressures vary in parallel, with Os having the lowest vapour pressure and the highest melting point of the six PGE. Only two metals, W and Re, have lower vapour pressures than Os.

The term “noble metal” is often used in connection with PGE. There are several definitions of noble metal, such as “any metal that is resistant to corrosion and oxidation” or “a metal whose potential is positive relative to the hydrogen electrode.” The second definition includes the six PGE, Cu, Ag, Au and Hg. The resistance of PGE to oxidation is important for understanding their geochemistry. In FIGURE 1, the reduction potentials of the PGE oxides are compared to the reduction potential of FeO. The high values for the PGE reflect the instability of the oxides and the stability of the metals, with Pt oxide being the least stable oxide. All PGE have a strong tendency to partition into metal phases. A quantitative measure is the metal–silicate partition coefficient,  $D^{\text{met/sil}}_{\text{PGE}}$ . This is the ratio of the concentration of a PGE in liquid or solid metal to that in silicate melt at given pressure, temperature and oxygen fugacity, and assuming equilibrium between metal and silicate. Elements with partition coefficients above about 10,000 are called *highly siderophile elements* (HSE) and include the PGE, Re and Au. All HSE have very low concentrations in the silicate Earth,

reflecting their extraction from the mantle of the Earth with core-forming metal and sulphide (see Lorand et al. 2008 this issue). Of the six PGE, five are classified as *refractory metals*, i.e. their condensation temperatures are above the condensation temperature of Fe–Ni alloys (see FIG. 2). Only Pd is a non-refractory metal, i.e. it has a condensation temperature similar to Fe–Ni (see FIG. 2). Besides the five PGE, the group of refractory metals includes W, Mo and Re.

For a long time, analysis of the PGE was carried out mostly by neutron activation. This method has been particularly effective for Ir, which

can be analysed by instrumental neutron activation analysis (INAA) without dissolving the sample and applying radiochemical separation procedures. The other PGE are more than a factor of 10 less sensitive with NAA. Their analysis requires lengthy radiochemical procedures. With the increasingly popular use of inductively coupled plasma–mass spectrometry (ICP–MS), NAA has lost ground and is routinely done in only a few laboratories around the world. Judging from the small number of published analyses, the element Rh may be considered a neglected element compared with the other PGE. Rhodium has no suitable long-lived radioactive isotope for  $\gamma$  counting and it has only one isotope.



**FIGURE 1** Reduction potentials ( $\mu\text{O}_2$ ) of PGE oxides and FeO as a function of temperature. Data are for equilibrium between pure oxide and pure metal. The reduction potential indicates the thermodynamic stability of oxides compared to metals. The most noble metal is Pt. Its oxide is the least stable of all PGE oxides. FIGURE ADAPTED FROM O'NEILL ET AL. (1995), UPDATED BY J. BRENNAN (PERSONAL COMMUNICATION)

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## ABUNDANCES IN CI-CHONDRITES AND IN THE SUN

Type 1 carbonaceous chondrites (CI-chondrites) have, within analytical uncertainty, the same chemical composition as the Sun, excluding hydrogen, lithium, carbon, nitrogen, oxygen and highly volatile elements such as the rare gases. Thus they are appropriate reference materials for the average concentrations of PGE in the solar system. The abundances of PGE in CI-chondrite meteorites are around 3 µg/g, corresponding to six PGE atoms for one million Si atoms (TABLE 1). The uncertainties in the meteoritic abundances are around 10% for all PGE (Palme and Jones 2003). For comparison, the abundances of the PGE in the Sun are listed in TABLE 1 (Grevesse et al. 2005). Their errors range from 10 to 30%. The differences between CI-chondrites and the Sun are within the combined uncertainties. As the errors associated with solar abundances are larger than those of CI-chondrites, abundances in the latter should be used for estimating bulk solar system abundances.

The comparatively large differences in the PGE abundances between the Horan et al. (2003) Orgueil meteorite and those in the compilation by Palme and Jones (2003) (TABLE 1) primarily reflect variable absolute contents of refractory PGE in the Orgueil meteorite, which are dependent on the content of inhomogeneously distributed water. Ratios of PGE are less variable.

**TABLE 1** PGE ABUNDANCES IN CI-CHONDRITES AND THE SUN

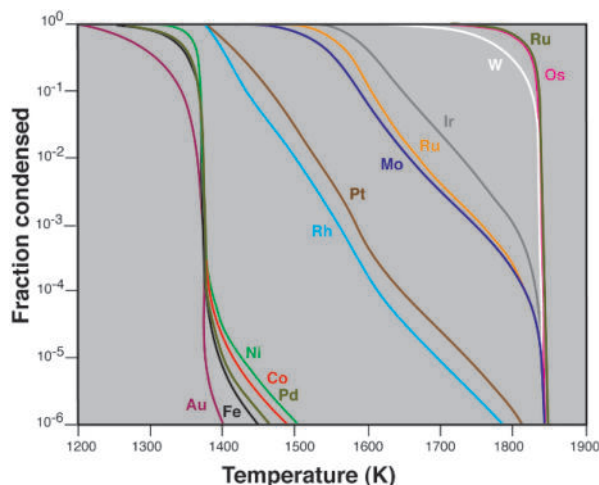
	CI-chondrites		Sun	
	concentration (by weight) ng/g		element/10 <sup>6</sup> atoms Si	
	(a)	(b)	(b)	(c)
<b>Ru</b>	649	683	1.78	2.0
<b>Rh</b>		140	0.358	0.38
<b>Pd</b>	574	556	1.37	1.4
<b>Os</b>	458	506	0.699	0.81
<b>Ir</b>	444	480	0.657	0.69
<b>Pt</b>	867	982	1.32	

Data: (a) Horan et al. (2003); (b) Palme and Jones (2003); (c) Grevesse et al. (2005). Uncertainties: meteorites, around 10%; Sun, from 10 to 30%

## BEHAVIOUR OF PGE DURING CONDENSATION IN THE SOLAR NEBULA

The abundances of elements in chondritic meteorites are, to a large extent, determined by their volatility. A quantitative measure of volatility is the 50% condensation temperature. This is the temperature of a cooling gas of solar composition at which 50% of an element is in the solid phase and 50% is in the gas phase, assuming equilibrium between gas and solid. The low vapour pressure of PGE leads to high condensation temperatures. Because of their low abundances and their similar physical and chemical properties, PGE very likely condense as alloys and not as pure elements. In FIGURE 2, the fractions of metals condensing in a common alloy at a given temperature are shown (Palme and Wlotzka 1976; Campbell et al. 2001). The compositions of the condensed alloys can be calculated from the condensation curves and the abundances of the PGE in CI-chondrites.

Five of the six PGE are refractory metals, condensing at higher temperatures than Fe–Ni alloy as refractory metal (RM) nuggets, whereas Pd is a non-refractory metal with a condensation behaviour similar to that of Fe (FIG. 2). This leads to a very different behaviour for Pd compared to the refractory PGE in chondrites and iron meteorites. Unlike



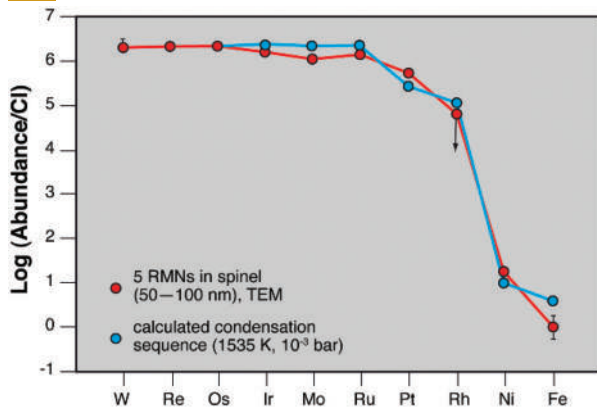
**FIGURE 2** Results of condensation calculations. Fractions of PGE condensed at a given temperature are shown (at 10<sup>-4</sup> atm). Five PGE condense in alloy with W, Mo and Re, but Pd condenses with Fe–Ni alloy. ADAPTED FROM CAMPBELL ET AL. 2001

the other PGE, palladium is not enriched in refractory components of chondritic meteorites. Also, Pd does not show the large compositional variations that are characteristic of Ir and other refractory metals in many iron meteorites. The similar volatilities of Pd and Fe lead to approximately constant Pd contents in iron and stony meteorites. Radioactive <sup>107</sup>Pd, with a half-life of 6.5 million years, decays to <sup>107</sup>Ag. Variations in the <sup>107</sup>Ag/<sup>109</sup>Ag ratios of iron meteorites and carbonaceous chondrites are largely due to variable depletions of the much more volatile Ag. The Pd–Ag chronometer thus essentially dates the time of fractionation of volatile elements in the early solar system, with younger ages in iron meteorites resulting from slow cooling and low closure temperatures for Ag isotopes (Carlson et al. 2008 this issue).

FIGURE 3 shows the CI-chondrite-normalized pattern of nanometre-sized metal alloys enclosed in refractory meteoritic spinel grains analysed with transmission electron microscopy (TEM) (Eisenhour and Buseck 1992). The agreement with calculated values is striking. The presence of W and Mo in PGE alloys is evidence that such grains formed by condensation in a cooling gas of solar composition. If these RM nuggets were residues of extensive heating and vaporisation, W and Mo would be lost as volatile oxides.

On cooling, initial alloys of refractory metals are modified by exsolution, oxidation and sulfuration, forming complex opaque assemblages. Such an opaque assemblage with silicates, metal and spinel in a Ca,Al-rich inclusion from the Allende meteorite is shown in FIGURE 4, with secondary phases such as Mo-sulphides (molybdenite), W- and Mo-oxides (scheelite and powellite), Pt,Rh-rich Fe–Ni metal and Os–Ru alloys, the latter two with various amounts of Ir. The bulk grain has a composition perfectly in agreement with condensation calculations, including W and Mo (Bischoff and Palme 1987).

Some of these opaque assemblages look so unusual that El Goresy et al. (1978) initially postulated an origin from outside the solar system and termed them *Fremdlinge*, meaning foreigners in German. Further research has shown, however, that *Fremdlinge* are born in our solar system, primarily because they are isotopically normal (Hutcheon et al. 1987), but the term *Fremdlinge* is still used to describe unusual opaque assemblages in Ca,Al-rich inclusions.



**FIGURE 3** CI-chondrite-normalized pattern of nanometre-sized alloys of refractory metals, compared with single-phase condensation calculations. Terrestrial PGE nuggets never contain Mo and W. RMN, refractory metal nugget. FIGURE ADAPTED FROM EISENHOUR AND BUSECK (1992)

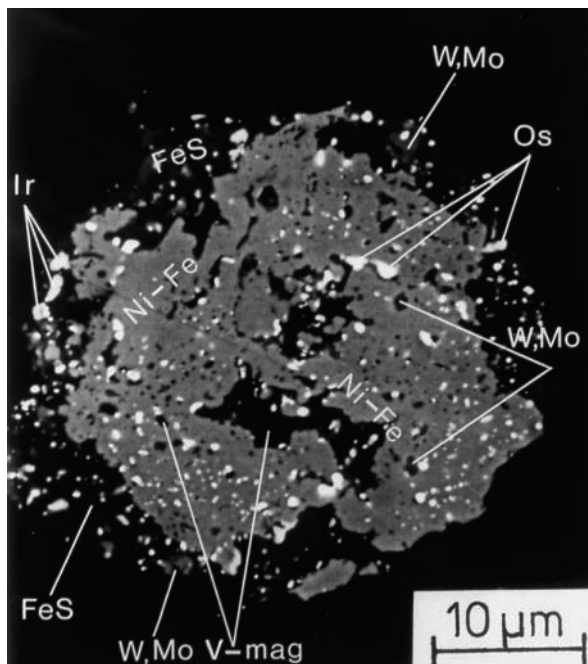
### PGE IN CHONDRITIC METEORITES

Chondritic meteorites contain variable fractions of a refractory (high-temperature) component with high concentrations of refractory lithophile elements, such as Al, Ca and REE, and also refractory metals. The abundances of all refractory elements are correlated. A good example is a correlation of Al with Ir in various types of undifferentiated meteorites (O'Neill and Palme 1998). The Al–Ir correlation is used when estimating the bulk-planet inventory of refractory PGE (i.e. PGE without Pd). The Ir content of bulk Earth, for example, is derived from the CI-chondrite Al/Ir ratio of  $1.77 \times 10^4$ , which corresponds to an Ir content for the bulk Earth of 0.91 ppm (O'Neill and Palme 1998). Thus only about 0.2% of the total Ir inventory of the Earth is in the mantle; the rest is in the core (see Lorand et al. 2008).

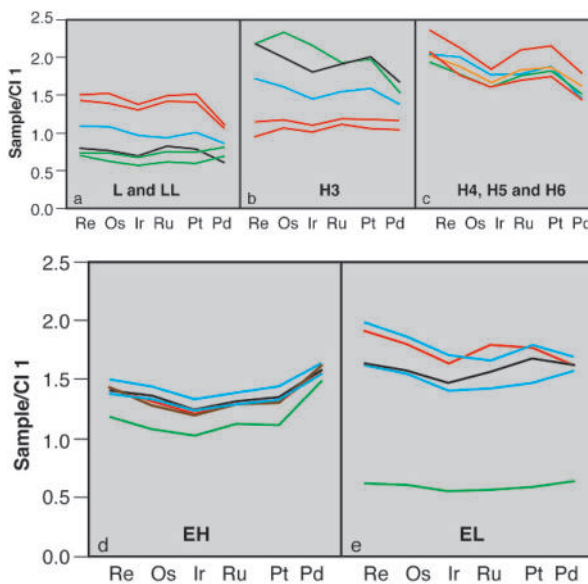
Recent analyses have confirmed that abundance variations of PGE in chondritic meteorites exceed analytical uncertainties (Fig. 5). Variable ratios of the moderately volatile Pd to the refractory PGE are expected. However, the variability in absolute and relative abundances of the five refractory PGE is comparatively large and cannot be understood in terms of volatility. Some chondrites have high Os/Ir and low Ru/Pt ratios contradicting a simple volatility trend (Fig. 5). Even different meteorites from a single group show variable patterns. Variations in absolute PGE contents in a single meteorite (indicated by the same colour in Fig. 5) reflect inhomogeneous distribution of PGE host phases.

### PGE IN PLANETARY MANTLES AND BASALTS

Because of their strong siderophile nature, very low contents of PGE are expected in silicates of differentiated planets. Core-forming metal effectively extracted PGE from the silicate mantles. The comparatively high contents of PGE in the Earth's mantle are often considered to reflect the presence of a late veneer with chondritic PGE patterns. Alternatively, unusually low metal–silicate partition coefficients at very high pressures and temperatures have been invoked (see Lorand et al. 2008). The patterns of PGE in basalts derived from the Earth's mantle are fractionated, with very low Os and Ir and increasing abundances from Ru and Rh to Pd and Pt. This sequence resembles the sequence of increasing crust/mantle abundance ratios (see Fig. 2 of Lorand et al. 2008). The mechanism of fractionation is not known in detail, but likely involves the selective uptake of Os, Ir and Ru, relative to Pt and Pd, in residual olivine, spinel and crystalline monosulphide solid solution.



**FIGURE 4** Opaque assemblage in an Allende Ca,Al-rich inclusion. Bright spots are Os–Ru alloys with up to 80% Os. On the left side are Ir-rich alloys. Grey phase is Fe–Ni metal with some Pt; the dark phases are powellite, scheelite and V-magnetite. FROM BISCHOFF AND PALME (1987)



**FIGURE 5** The absolute and relative abundances of PGE in chondritic meteorites are variable, certainly beyond analytical uncertainties, which are only a few percent. Each colour designates a different meteorite. Elements are arranged in order of increasing volatility (decreasing condensation temperatures) from left to right, with Pd, the most volatile PGE, at the extreme right. FIGURES ADAPTED FROM HORAN ET AL. (2003)

The PGE pattern in Martian basalts is very similar to that in terrestrial basalts, suggesting similar mantle patterns for both planets (Jones et al. 2003). It is not possible to test this hypothesis as there are no Martian mantle samples available for analysis. If the mantles of Earth and Mars have indeed the same endowment of PGE, Mars may have accreted a late veneer component much like what is assumed for the Earth.

Basalts from the dry (water-free) Moon and the similarly dry asteroid Vesta (the eucrite parent body) have significantly lower PGE contents than basalts from Earth and Mars (Morgan et al. 1978; Righter et al. 2000). The pattern of PGE in the primitive Apollo 12 and 15 basalts is relatively unfractionated compared to that of the more evolved basalts from Apollo 11 and 17, which have more fractionated patterns resembling terrestrial MORB patterns but with one twentieth the absolute PGE contents (Day et al. 2007). The higher than expected PGE contents obtained from partition coefficients (see below), the largely chondritic PGE mantle patterns, and the primitive Os isotope composition suggest that a late chondritic component has been added to Earth, Moon, Mars, and probably also Vesta.

## SOLUBILITIES OF PGE IN SILICATE MELTS

The reason for the low concentrations of PGE in silicates from differentiated planets and planetesimals is the strong partitioning of the PGE into metal and sulphides and the subsequent segregation of these phases to form planetary cores. How efficiently can metal extract PGE from silicates? Does the present abundance level in various planetary silicates represent equilibrium between core-forming metal and residual silicates? The answers to these questions require the knowledge of metal-silicate partition coefficients for the PGE. The experimental determination of metal-silicate partition coefficients of PGE relevant to core formation is very difficult. The partition coefficients are very high, and the PGE are only trace elements in Fe-Ni metal equilibrating with silicates during core formation. The task is much easier if equilibrium between pure PGE metals and coexisting silicates is considered. This is essentially the determination of PGE solubilities in silicate melts. Metal-silicate partition coefficients can then be calculated from PGE solubilities. An example is given in FIGURE 6. Powdered silicates compacted and glued together are suspended in a millimetre-sized Pd-wire loop and heated in a furnace at various oxygen fugacities. The strong decrease in solubility with decreasing oxygen fugacity (FIG. 6) indicates the presence of Pd ions in the silicate melt. The content of Pd in silicate melt increases with increasing oxygen partial pressure. The concave curve can be deconvoluted into a series of straight lines with decreasing slopes, each corresponding to a certain valence of Pd. From these data, a metal-silicate partition coefficient for Pd of  $1.5 \times 10^7$  is calculated at 1350°C and an oxygen fugacity appropriate for core-mantle equilibrium (Borisov et al. 1994). The effects of pressure and temperature need to be considered when applying these data to core formation in the Earth (see Lorand et al. 2008).

Other PGE show a similar behaviour. All resulting metal-silicate partition coefficients are extremely high and variable; some are orders of magnitudes greater than those of Pd (Borisov and Palme 1997). Instead, the measured or estimated PGE contents of planetary mantles are much higher than predicted by these partition coefficients, and the patterns predicted would be much more variable if they depended on metal-silicate partitioning.

Either there are other, perhaps kinetically controlled, mechanisms that led to the observed PGE abundance levels in silicates of Earth, Mars, Moon and Vesta, or all of these bodies received a late veneer component with more or less chondritic relative abundances, after silicates had been completely stripped of their PGE during an earlier period of core formation.

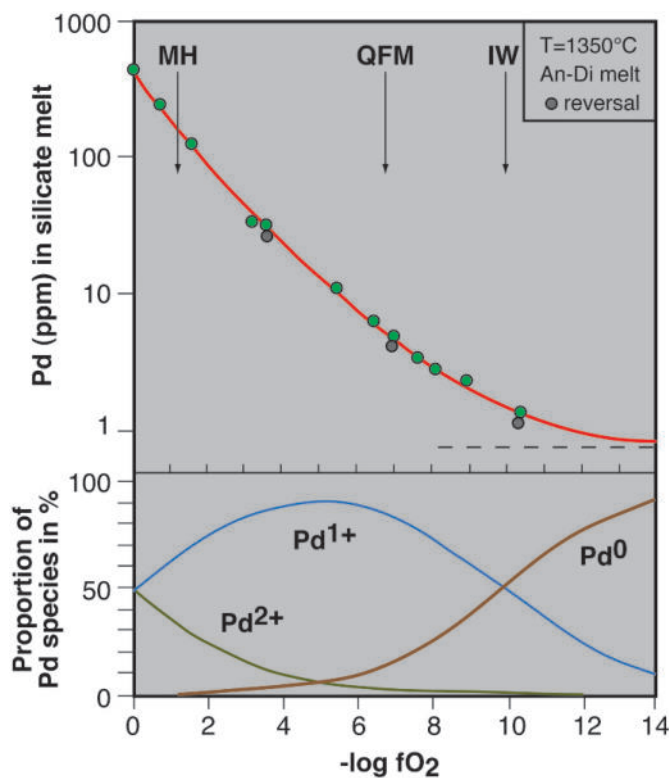
One problem with the solubility measurements is that often they do not appear to produce reasonable results under reducing conditions, where the solubilities of Pt and other PGE have been shown to be dominated by the presence of inhomogeneously distributed micronuggets (Borisov and

Palme 1997; Ertel et al. 1999). The role of these nuggets in experiments for determining partition coefficients is not clear (e.g. Cottrell and Walker 2006), indicating that the solubilities of PGE in silicate melts are not yet fully understood, despite much experimental effort.

Sulphides are also capable of extracting PGE from silicates. The partition coefficients between liquid sulphide and liquid silicate are expected to be very high (O'Neill et al. 1995). Experimentally determined partition coefficients show a very large range and depend strongly on the composition of sulphides (Fleet et al. 1999; Pruseth and Palme 2004). In addition, the role of sulphur in extracting PGE from planetary mantles is probably minor. After initial separation of S-rich metals, Fe-Ni metal will dominate, as all four solar system bodies we have samples from (Earth, Moon, Mars, Vesta) are depleted in volatile elements, including sulphur. Dreibus and Palme (1996) estimated a maximum S content for the Earth of 0.56%, assuming that Zn and S have similar volatilities. Mars has somewhat more S, but the final stage of PGE extraction will only include Fe-Ni-metal extraction. Moon and Vesta have less S than the Earth.

## PGE AS INDICATORS OF METEORITIC CONTAMINATION

The level of PGE in the Earth's mantle is less than one percent of the CI-chondritic abundances (see Lorand et al. 2008). The Ir and Os contents of the crust are a factor of one hundred below those of the mantle. Thus for Ir and Os, there is a difference of four orders of magnitude between their meteoritic and crustal abundances. This makes these



**FIGURE 6** Experimental determination of Pd solubility in silicate melts. A strong decrease in solubility with decreasing oxygen fugacity is observed. In the lower diagram, the contributions of various Pd species to the total number of dissolved Pd ions are indicated. Reversals with high Pd in the initial silicates are indicated. Oxygen fugacity buffers: MH, magnetite-hematite; QFM, quartz-fayalite-magnetite; IW, iron-wüstite. An-Di, anorthite-diopside. FIGURE MODIFIED FROM BORISOV ET AL. (1994)

elements ideal for studying even minute amounts of extraterrestrial material in impact melts associated with terrestrial craters, as long as the impacting projectile is a chondrite.

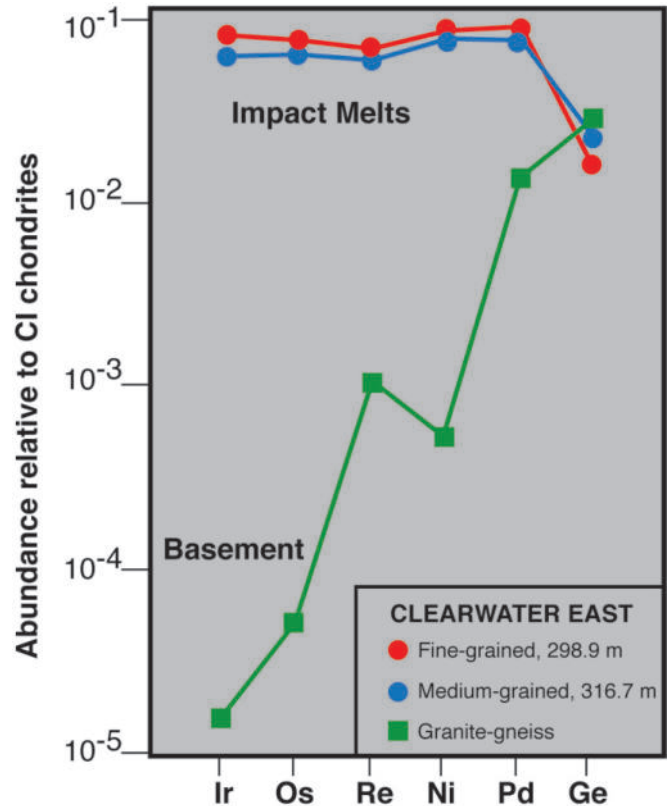
A good example is the impact melt sheet at the 20 km diameter Clearwater East crater in Canada (Fig. 7). Based on Ir and Os excesses, more than 5% of a chondritic component was found to be dissolved in the melt rocks at a depth of 320 m below the water level of the lake (Palme et al. 1978). Clearwater East melt rocks have the highest fraction of extraterrestrial component of any terrestrial impact structure. Evidence for PGE enrichment is lacking in many of the 150 impact craters (see review by Koeberl 1998). Low or absent PGE signals indicate that either the projectiles had low PGE contents or the velocity of the impacting object was very high, leading to almost complete vaporisation of the impactor and/or producing such a large amount of melt that the concentrations of dissolved PGE are below the detection limit. Recently, variations in Os isotopes have been used to identify extraterrestrial material. As the  $^{187}\text{Os}/^{188}\text{Os}$  ratio of Earth's crust is much higher than the ratio in primitive meteorites, a small fraction of meteoritic contamination can produce a measurable effect on the  $^{187}\text{Os}/^{188}\text{Os}$  ratio of crustal rocks (Carlson et al. 2008).

A strong meteoritic signature is also present in samples from the K/T boundary layer. Alvarez et al. (1980) first noticed Ir anomalies at the K/T boundary in Gubbio, Italy. Further research showed that (1) the Ir anomaly is present in many marine and terrestrial K/T sections (but not in all) and (2) Ir is accompanied by other PGE metals. The predominance of Ir data in the literature reflects the preference for analysing K/T samples by neutron activation. An example of a terrestrial K/T section is given in FIGURE 8. The strong decrease in angiosperm pollen coincides exactly with the Ir anomaly. The spore spike reflects a short but severe crisis for land plants, which could arise from lack of sunlight, a prolonged frost period, or acid rain. There is now overwhelming evidence that the Ir and the other PGE at the K/T boundary are of extraterrestrial origin, but it is still unclear if the PGE were transported from the Chixulub crater as meteoritic nuggets, or if the PGE represent condensates from the impact vapour cloud.

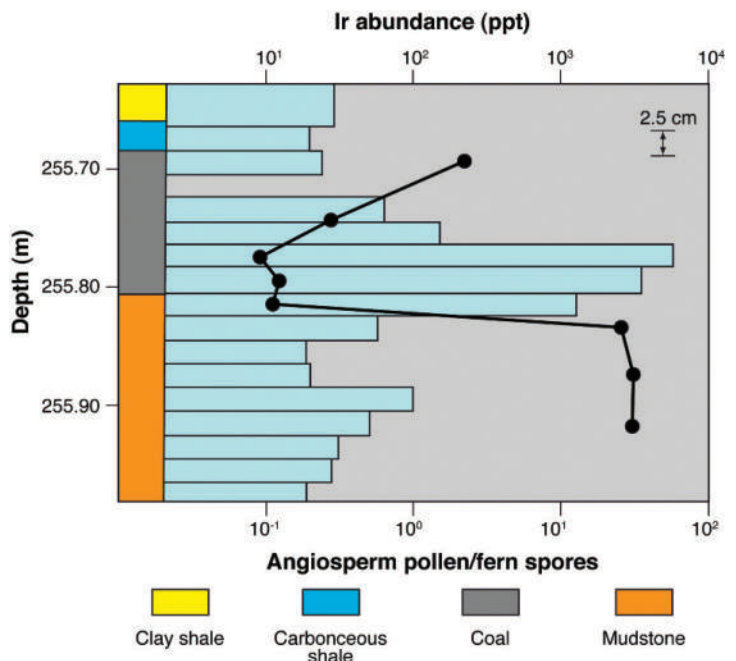
## CONCLUSIONS

Two properties of the PGE are of particular interest in cosmochemistry. All six PGE (Os, Ir, Ru, Rh, Pt, Pd) have lower vapour pressures than Fe metal, and all six require a higher oxygen fugacity for oxidation than Fe metal. Because of their low vapour pressures, the PGE (except Pd) condense at temperatures above the condensation temperature of Fe-Ni as a common refractory-metal alloy. They condense along with three other refractory metals, W, Mo, Re, and a small fraction of Fe and Ni, but without the more volatile Pd and Au. High-temperature components in meteorites may still contain such alloys, although they may often be sulphurised and/or oxidised. In bulk meteorites, the concentrations of the refractory PGE correlate with those of refractory lithophile elements such as Al and Ca. New data clearly show that ratios of PGE in chondrites are more variable than expected from analytical uncertainties.

During planetary core formation, PGE strongly partition into Fe-Ni metal and are largely removed from the mantle. Experimentally determined solubilities of PGE in silicate allow calculation of metal-silicate partition coefficients. These PGE solubilities are very low and depend on oxygen fugacity, indicating that PGE are dissolved as ions in silicate melts. Calculated partition coefficients between metal and silicate melt are very high, above  $10^5$  in most cases. The contents of PGE in planetary mantles are higher than



**FIGURE 7** Impact melts from bore holes drilled in winter through a thick ice cover on the 320 m deep Clearwater East Lake, marking a 20 km diameter impact crater in Quebec (Canada). The difference in Ir and Os abundances between meteorites and the Canadian Shield basement is four orders of magnitude. FIGURE ADAPTED FROM PALME ET AL. (1978)



**FIGURE 8** Ir anomaly at a terrestrial K/T section in the Raton basin (Colorado, USA). The strong decrease in angiosperm pollen (solid black circles) coincides exactly with the Ir anomaly (light blue histogram), reflecting severe changes in the environment exactly at the time of Ir delivery. MODIFIED FROM ORTH ET AL. (1981)

calculated from partition coefficients, suggesting that PGE were added to the mantles of Earth, Mars, Moon and Vesta in the form of a late chondritic component (late veneer) after core formation. Because of the low PGE content of the Earth's crust, PGE are ideal as indicators of extraterrestrial materials in rocks from terrestrial craters formed by impacting cosmic projectiles. The Ir anomaly at the K/T boundary is an excellent example.

## ACKNOWLEDGMENTS

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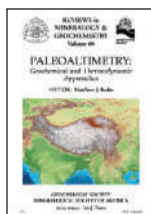
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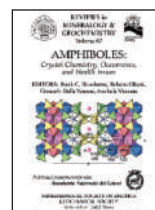
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# Applications of PGE Radioisotope Systems in Geo- and Cosmochemistry



Photomicrograph of diamond with Fe-sulfide inclusion

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**The platinum-group elements contain three radioisotope systems that have been used in many and varied ways in geo- and cosmochemistry. Unique chronological applications include dating the formation of such diverse materials as sulfides, gold, organic-rich sediments, iron meteorites, and sulfide inclusions in diamonds. These systems also serve as isotope tracers for processes such as continental erosion, the deposition of extraterrestrial materials on Earth's surface, crust–mantle differentiation, recycling of subducted crust into the mantle, core–mantle exchange, and volatile-element depletion of planets and planetesimals. Although these systems have been in use for only a short time, the discoveries they have provided bode well for their incorporation as staples in the geochemical toolbox.**

KEYWORDS: isotopes, PGE, Re–Os, Pd–Ag, chronology, crust–mantle differentiation

## INTRODUCTION

The utility of the platinum-group elements (PGE) as geochemical tools is enhanced by the three radioisotope decay systems that they contain. Osmium is the daughter element in two decay systems, the very long-lived  $^{190}\text{Pt}$  to  $^{186}\text{Os}$  alpha-decay (half-life =  $4.5 \times 10^{11}$  y) and the more widely used beta-decay of  $^{187}\text{Re}$  to  $^{187}\text{Os}$  (half-life =  $4.16 \times 10^{10}$  y). In addition, the now-extinct isotope  $^{107}\text{Pd}$  decays to  $^{107}\text{Ag}$  (half-life =  $6.5 \times 10^6$  y) (TABLE 1). A key feature of these systems is that they track the unique chemical behavior of the PGE in the natural environment and thus provide information on natural processes to which the more commonly applied, lithophile-element-based radioisotope systems are not sensitive. All the elements involved show strong preference for metal and/or sulfide compared to silicate (Palme 2008 this issue; Lorand et al. 2008 this issue). Unlike any other element in a radioisotope system, osmium is a compatible element during melting in the mantle (stays in the residue). As a result, most magmas, and the crust formed from such magmas, have high Re/Os ratios compared to mantle rocks. With time, this results in distinctively radiogenic Os in the crust that serves both as a sensitive tracer of crust–mantle differentiation and the eventual transport of crustal materials into the marine environment through weathering and erosion.

Of these systems, Re–Os has seen the most use by far (Shirey and Walker 1998; Carlson 2005). Applications of Pt–Os decay are limited, but this system has been used to date Pt-rich ores and to address the fundamental question of

whether there is chemical exchange between Earth's mantle and core. The Pd–Ag system is being used to define the chronology of iron meteorite formation and to investigate the mechanism and timing of the volatile-element depletion that distinguishes Earth, and many meteorites, from the solar composition. The key to the explosion in applications of the PGE-based radioisotope systems is the improvement of chemical separation and mass spectrometric techniques (Reisberg and Meisel 2002). These techniques now provide sufficient sensitivity to analyze elements present at the  $10^{-9}$  to  $10^{-12}$  g/g range in many rock

types, and they are precise enough to resolve very small differences in  $^{186}\text{Os}$  and  $^{107}\text{Ag}$  created by Pt and Pd decay, respectively.

## PGE-BASED CHRONOMETRY

The most obvious use of radioisotope decay schemes is to tell geologic time. For this purpose, the remarkable success of PGE-based systems is based on their application to materials that cannot be dated using other systems.

### Ore Genesis

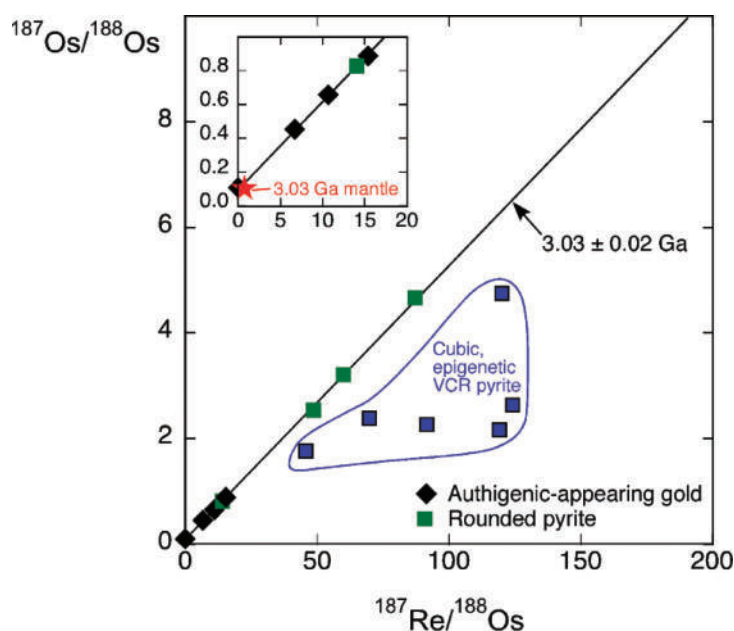
Unlike lithophile-element-based radioisotope systems (e.g. Rb–Sr, Sm–Nd), the PGE-based systems can be applied directly to study the origin of ore minerals rather than associated silicate phases. An early use of the Re–Os system was in dating molybdenite ( $\text{MoS}_2$ ) formation. Molybdenite is so Re rich and Os poor that Os in old molybdenite crystals consists almost exclusively of  $^{187}\text{Os}$ . Extensive recent development of this technique now allows excellent age precisions limited only by the rarity and paragenesis of molybdenite (Stein et al. 2001). At the other end of the range of Re/Os ratios, chromite has proven to be a particularly important mineral for Re–Os studies where its very low Re/Os ratio essentially “freezes in” the Os isotope composition of the magma from which it crystallizes, providing both a model age and petrogenetic information. This utility is enhanced by its resistance to alteration, high closure temperature, and generally high (many ppb) Os content.

Another ore-mineral group that has found extensive use in Re–Os dating is  $\text{Fe}(\pm\text{Ni}\pm\text{Cu})$  sulfide. Sulfides have a high affinity for both Re and Os and can have high Re/Os ratios. Sulfides form the basis for numerous studies regarding the timing and petrogenesis of nickel, copper, gold, and lead ores in a variety of environments (e.g. magmatic, hydrothermal, and sedimentary; Walker et al. 1991; Morelli et al. 2004; Bierlein et al. 2006). One interesting application has

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been to reveal the source of gold in the world's largest gold deposit, the Witwatersrand basin of South Africa (Fig. 1). Models that suggest a detrital origin, precipitation from hydrothermal solution, or some combination of both have been debated for decades. Re–Os dating applied directly to gold from the Vaal Reef gold horizon produced an isochron age of  $3033 \pm 21$  Ma with an initial  $^{187}\text{Os}/^{188}\text{Os}$  ratio essentially identical to the mantle value at that time (Kirk et al. 2002). These results leave little doubt that the Os in these gold ores originated from the weathering of mantle-derived, mafic to ultramafic rocks in surrounding Mesoproterozoic terranes. The unusually high Os concentrations in the Vaal Reef gold, however, have been variably interpreted as supporting its derivation from high-degree melts of the mantle, such as komatiites, or indicating that hydrothermal gold grew around detrital PGE-rich alloy grains, weathered from the komatiites, that served only as nucleation centers for gold deposition. The definitive study to resolve these options has not yet been done.



**FIGURE 1** Re–Os isochron diagram for gold and pyrite from the 2.8–2.9 Ga Witwatersrand Supergroup, South Africa, redrawn from the data and information in the study by Kirk et al. (2002). Vaal Reef gold and rounded pyrite interpreted to be detrital produce an excellent  $3.03 \pm 0.02$  Ga isochron with an initial  $^{187}\text{Os}/^{188}\text{Os}$  ratio identical to the mantle value at this time (inset). Because both age constraints are older than the  $<2.9$  Ga age of the conglomerates, they confirm the detrital nature of the gold and suggest that the provenance of the conglomerate included magmatic rocks in a nearby 3 Ga greenstone belt. Epigenetic, cubic-morphology pyrite in the hydrothermally altered Ventersdorp Contact Reef (VCR) shows open-system behavior of the Re–Os system.

## Organic-Rich Sediments

A peculiar aspect of the PGE is their affinity for organic compounds in sediments such as black shales, coal, oil host rocks, and tar sands. Recent work has focused on leaching techniques that allow the isolation of the detrital versus hydrogenous components of Os found in the sediments. When the shales remain closed systems after deposition, such studies yield excellent Re–Os isochrons that provide both the age of sediment deposition and the Os isotope composition of the water mass from which they were deposited (e.g. Turgeon et al. 2007). This technique has been particularly useful for obtaining an absolute timescale for sediment stratigraphy, global glaciation events, and the rise of oxygen in the atmosphere (Bekker et al. 2004).

## Diamond Dating and Petrogenesis

The treasured gem properties of diamond stem from its crystal structure, but this structure effectively excludes radioactive isotopes suitable for direct dating of diamond formation. Diamonds, however, sometimes contain inclusions that provide both age and petrogenetic information. The high (ppm to ppb) Os concentrations in typical sulfide inclusions in diamond allow the Re–Os system to be applied to dating individual grains (e.g. Pearson et al. 1998; Fig. 2). The current “champion” among the oldest diamonds provided a  $3.52 \pm 0.17$  Ga isochron defined by 11 sulfides separated from 5 diamonds from the Panda kimberlite of the Slave Province, Canada (Fig. 2; Westerlund et al. 2006). The initial  $^{187}\text{Os}/^{188}\text{Os}$  ratio defined by this isochron is about 6% greater than expected for the mantle at that time. This likely implies diamond formation from fluids rising from an ancient subducting crustal plate into an overlying section of mantle. But not all diamonds are Archean in age. Indeed, there is good evidence from southern African diamond localities that the age and chemical properties of diamond correlate with the general physical features, for example, seismic velocities (Shirey et al. 2002) of the subcontinental mantle inherited during their Proterozoic crystallization. Re–Os examination of sulfide inclusions, particularly when combined with carbon and nitrogen isotope studies of the host diamond, offers a promising avenue to study the history of carbon-rich fluid migration at depths in excess of 150 km in the mantle.

## TRACERS OF EARTH EVOLUTION

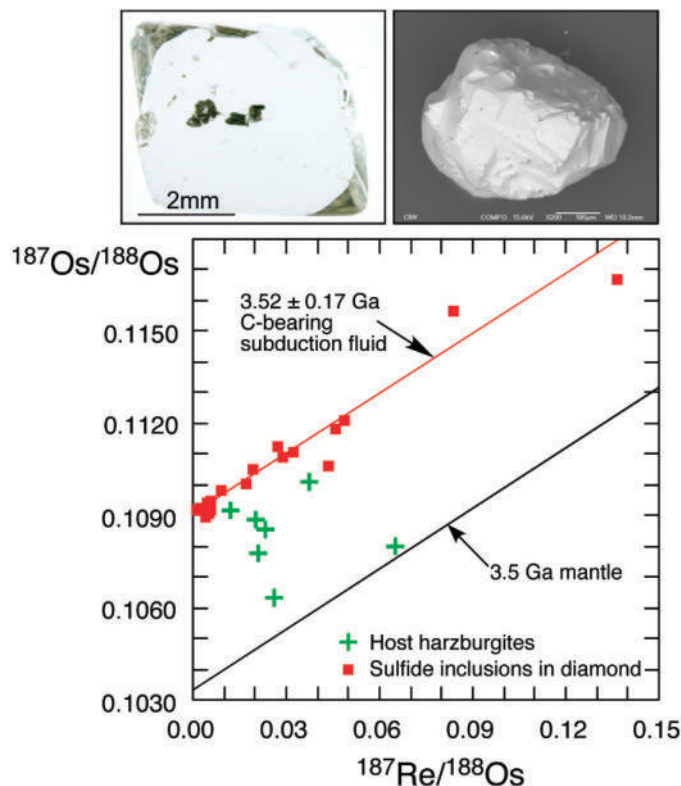
### The Marine Os Record

The Re–Os system has been used extensively to track the evolution of Earth's surface through the marine record of Os isotope variation (Pegram et al. 1992). Weathering of crustal rocks contributes Os with a very high  $^{187}\text{Os}/^{188}\text{Os}$  ratio to the oceans. Whereas most mantle-derived and extra-terrestrial rocks have  $^{187}\text{Os}/^{188}\text{Os}$  ratios near 0.13, modern ocean water has a  $^{187}\text{Os}/^{188}\text{Os}$  ratio closer to 1.0 (Levasseur et al. 1998). An important aspect of the marine record of Os

**TABLE 1** ISOTOPIC COMPOSITION OF PGE-BASED RADIOISOTOPE SYSTEMS

Isotope	Atomic %	Isotope	Atomic %	Isotope	Atomic %	Isotope	Atomic %	Isotope	Atomic %
$^{102}\text{Pd}$	1.02			$^{184}\text{Os}$	0.02				
$^{104}\text{Pd}$	11.1					$^{185}\text{Re}$	37.4		
$^{105}\text{Pd}$	22.3			$^{186}\text{Os}$	1.59			$^{190}\text{Pt}$	0.01
$^{106}\text{Pd}$	27.3			$^{187}\text{Os}$	1.51	$^{187}\text{Re}$	62.6	$^{192}\text{Pt}$	0.79
		$^{107}\text{Ag}$	51.8	$^{188}\text{Os}$	13.3			$^{194}\text{Pt}$	32.9
$^{108}\text{Pd}$	26.5			$^{189}\text{Os}$	16.2			$^{195}\text{Pt}$	33.8
		$^{109}\text{Ag}$	48.2	$^{190}\text{Os}$	26.4			$^{196}\text{Pt}$	25.3
$^{110}\text{Pd}$	11.7			$^{192}\text{Os}$	41.0			$^{198}\text{Pt}$	7.2

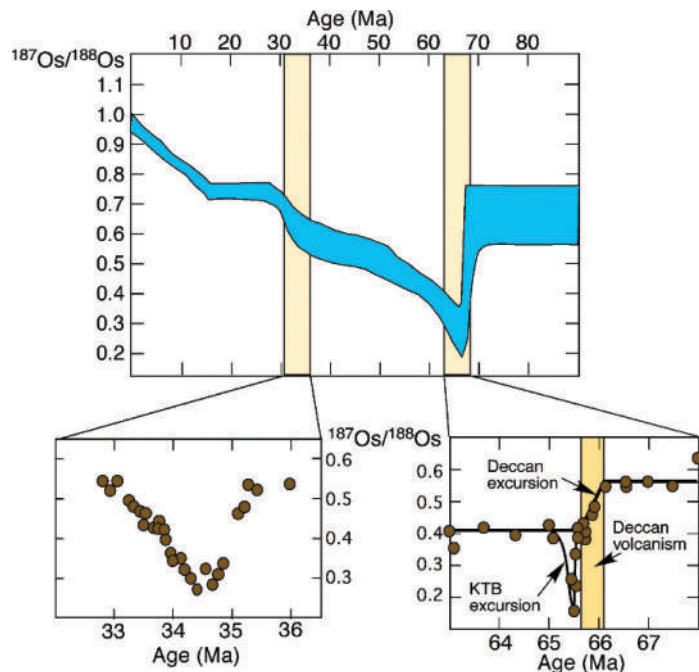
Data from Emsley (1992) except for Os from Shirey and Walker (1998)



**FIGURE 2** Re–Os isochron diagram for sulfide inclusions in diamonds and putative host harzburgites from the Panda kimberlite pipe, Slave craton, NWT, Canada (after Westerlund et al. 2006). The sulfide inclusions (red squares) regress to an age of  $3.52 \pm 0.17$  Ga (with 4 additional inclusions off scale) and have an elevated initial  $^{187}\text{Os}/^{188}\text{Os}$  isotope composition compared to a 3.5 Ga mantle (black line). With one exception, harzburgites that host the diamonds (green crosses) have  $^{187}\text{Os}/^{188}\text{Os}$  ratios above primitive mantle values, but less so than the diamonds. The upper left panel shows a polished Panda diamond plate with 4 inclusions in their “rosette” fracture system. Shown in the upper right is a typical scanning electron micrograph of a released inclusion prior to dissolution, chemical separation of the Re and Os, and mass spectrometry.

isotope variation is that the residence time of Os in seawater is short (35,000 years; Livasseur et al. 1999); hence one can obtain high chronological resolution in the marine Os record contained in sediments to the point of being able to track glacial–interglacial variations in continental input to the oceans (Fig. 3; Oxburgh et al. 2007). Between about 15 Ma and the present and again from 40 to 25 Ma, the  $^{187}\text{Os}/^{188}\text{Os}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of seawater increased. These correlated variations presumably reflect periods of high weathering of the continental crust (Peucker-Ehrenbrink et al. 1995). The Sr and Os isotope compositions of seawater, however, do not always covary. Between 65 and 40 Ma, seawater Os became more radiogenic while the Sr isotope composition changed little. This likely reflects the fact that specific rock types involved in continental weathering can differentially influence the Os and Sr isotope compositions of continental runoff. For example, weathering of old organic-rich sediments can provide large quantities of highly radiogenic Os, but minimal Sr, to the oceans. In these situations, Os isotope variation in marine sediments could serve as an independent monitor of carbon recycling from the continents to the oceans (Pegram et al. 1992).

The Os isotope composition of the ocean shows a strong downward excursion at the Cretaceous–Tertiary boundary that is not accompanied by much variation in the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio. This strong swing is attributed to a combination of



**FIGURE 3** Os isotope data tracking the composition of seawater Os over the last 90 My. The upper figure shows the general increase in the  $^{187}\text{Os}/^{188}\text{Os}$  ratio following the steep decline near the Cretaceous–Tertiary boundary (Peucker-Ehrenbrink et al. 1995). The lower figures show high-resolution data for smaller time slices illustrating the ability of Os to record fine-scale variations in inputs into the ocean. Near the K–T boundary (KTB), this includes contributions of mantle Os attributed to eruption of the Deccan flood basalts and extraterrestrial Os added by the K–T impactor (Ravizza and Peucker-Ehrenbrink 2003). In the Oligocene (lower-left figure), the rapid rise in the  $^{187}\text{Os}/^{188}\text{Os}$  ratio is attributed to an increase in continental weathering after removal of glacial cover exposed fine-grained glacial sediments (Dalai et al. 2006).

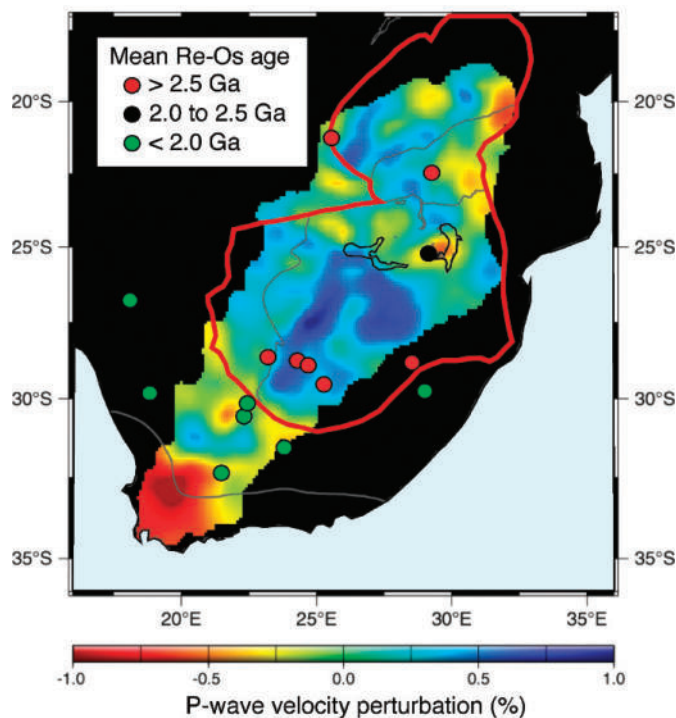
input of mantle Os from eruption of the Deccan flood basalts and input of extraterrestrial Os from the K–T impactor (Fig. 3). The big  $^{187}\text{Os}/^{188}\text{Os}$  excursion precisely at the K–T boundary reflects a nearly unique sensitivity of the PGE that allows detection of extraterrestrial contributions to the Earth. Most meteorites have PGE concentrations  $\sim 10^3$  times greater than those of mantle rocks and  $\sim 10^5$  times greater than those of most crustal rocks, but have PGE ratios and Os isotope compositions similar to those of Earth’s mantle (Palme 2008). Consequently, even small additions of extraterrestrial material will significantly reduce the  $^{187}\text{Os}/^{188}\text{Os}$  ratio and introduce concentration spikes in Ir in slowly accumulating sediments. This feature has been used to obtain constraints on the mass influx of extraterrestrial material to Earth and the variation in time of this influx (Dalai et al. 2006). It also been used to detect the contribution, and even the type (Koeberl and Shirey 1997) and size (Paquay et al. 2008), of meteorites involved in various terrestrial impacts.

### Dating the Age of Mantle Differentiation

Radiogenic isotope studies of mantle differentiation traditionally involve elements (Sr, Nd, Hf, Pb) that strongly prefer melt over residual solid. Therefore, mantle residues after melt extraction are difficult to study because they have very low concentrations of these elements. Furthermore, due to their low concentrations, these systems are extremely sensitive to overprinting should new melts migrate through older melt-depleted sections of the mantle. Although the Re–Os system is not completely insensitive to this type of metasomatic overprinting (e.g. Griffin et al. 2004), it has

proven uniquely suited to examining the history of melt extraction from the mantle (Walker et al. 1989). This is important because melt extraction changes the physical properties of mantle peridotite, lowering the residue's density by increasing its Mg to Fe ratio and reducing its Al concentration, and hence abundance of the dense aluminous phase garnet. Melt extraction also removes water and radioactive elements like U, Th, and K in the melt, leaving a residue that is of higher viscosity and that will grow colder than fertile mantle. Thus the ability to date the time of melt extraction from various portions of the mantle provides temporal information on a process that fundamentally alters the physical characteristics of Earth's mantle.

Perhaps the most definitive result from dating mantle differentiation with the Re–Os system has been to show that many sections of continental crust are underlain by mantle that suffered melt extraction at times approaching the age of the oldest overlying crust (Fig. 4). This result shows not only that continental crust formation is closely coupled to melt depletion of the underlying mantle, but also that the long-term survival of continental crust at Earth's surface may be due to the presence of this underlying thick layer of cold, rigid, buoyant mantle. Dating mantle samples using the Re–Os system has now been applied throughout the world to provide, in essence, a 3D map of continental ter-



**FIGURE 4** Overlay of P-wave seismic velocity variations at a depth of 150 km and average Re–Os model ages for mantle samples from kimberlites distributed across southern Africa. The points show kimberlites containing mantle samples from depths of up to 200 km. The points are color coded according to the average Re–Os age for all the mantle samples studied from each individual kimberlite. The red line outlines areas of Archean crust. Within the Archean crustal section, most mantle samples give Archean ages and most diamond-bearing kimberlites are confined to the blue areas of fastest seismic velocities. The fields outlined in black show the surface outcrop of the 2.05 Ga Bushveld and Molopo Farms igneous intrusions. The one kimberlite erupted near this area (Premier kimberlite, black dot) contains mantle samples that predominantly give Re–Os ages near 2 Ga. The correlation of younger mantle ages at Premier with slower seismic velocities suggests that the Bushveld event substantially modified the mantle under this part of the ancient southern African crust. Off the Archean craton, mantle samples give only Proterozoic ages, consistent with the age of the overlying crust. The light grey lines show boundaries between crustal terranes of different ages. Tomography is from Fouch et al. (2004), and Re–Os data are summarized in Carlson et al. (2005).

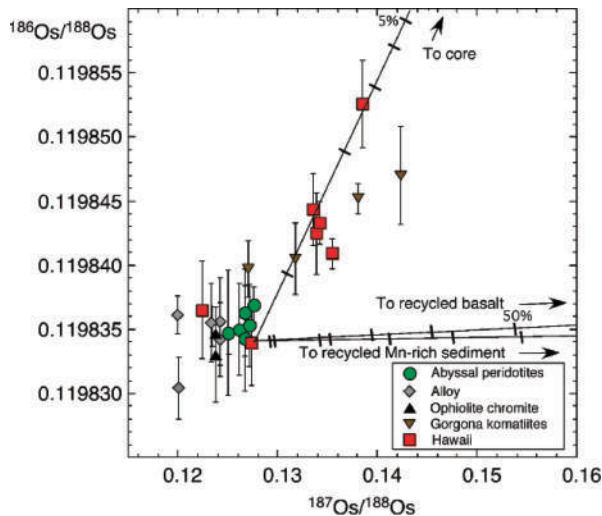
ranes showing where crust and mantle have similar ages, where young crust has been thrust over older mantle, and where old sections of mantle have detached from old crust, most likely as a result of major tectonic events (Carlson et al. 2005). The unique signatures of unradiogenic Os and Nd coupled with radiogenic Sr also have been used to show that old sections of melt-depleted subcontinental mantle are a particularly important source of the magmas that host igneous chromium and PGE deposits (e.g. Marques et al. 2003; Mungall and Naldrett 2008 this issue).

Widely dispersed, often intragranular, micron- to submicron-sized grains of PGE-rich minerals such as Fe–Ni sulfides, Ru–Os ± Ir sulfides, and Pt–Ir ± Os alloys contain the majority of the PGE in the mantle (Lorand et al. 2008). Although diffusion coefficients of the PGE through base-metal sulfides are quite high (Brenan et al. 2000), measurements of discrete PGE-rich phases in mantle rocks often show wide ranges in Os isotope composition (Meibom et al. 2002). While some of this isotopic variation may be due to precipitation from recent infiltrating melts, some of it must be long-lived. How can such isotopic heterogeneity survive for billions of years in the mantle when PGE diffusion is so fast? The likely answer is that the PGE are concentrated into discrete grains that are sufficiently separated from one another that diffusion over geologic timescales is ineffective in erasing the distinct differentiation history recorded by the discrete grains. As a result, sections of the mantle that were only recently removed from the actively convecting mantle can retain old melt-depletion ages (Parkinson et al. 1998). This result reflects an active Earth where any given portion of the convecting mantle may have passed through sites of differentiation (e.g. ocean ridges, intraplate hot spots, or the mantle wedge in convergent margins) several times over the history of the Earth. Indeed, recent Os isotope results for PGE-alloy grains from ophiolites of various ages suggest that the Os isotope composition of the mantle records “pulses” of mantle depletion attributable to discrete continental crust extraction events (Pearson et al. 2007).

### Crust–Mantle or Core–Mantle Exchange

Should some portion of Earth's crust be reintroduced into the mantle, for example by subduction, its presence will increase the  $^{187}\text{Os}/^{188}\text{Os}$  ratio of the mixture because of the crust's very high Re/Os and  $^{187}\text{Os}/^{188}\text{Os}$  ratios. Indeed, many intraplate ocean island basalts have more radiogenic Os than expected for mantle-derived melts, consistent with the contribution of recycled crustal components in the mantle sources of the lavas (e.g. Reisberg et al. 1993). Because of the long half-life and low natural abundance of  $^{190}\text{Pt}$ , the  $^{186}\text{Os}/^{188}\text{Os}$  ratio of this subducted crust will be only slightly higher than that of the mantle and hence will cause minimal change to the  $^{186}\text{Os}/^{188}\text{Os}$  ratio of the mantle (Fig. 5). Some hot-spot-related magmas, however, show a steep correlation between  $^{186}\text{Os}/^{188}\text{Os}$  and  $^{187}\text{Os}/^{188}\text{Os}$  (e.g. Brandon and Walker 2005). A suggested explanation for this correlation is that these magmas were derived from a section of mantle that had undergone chemical exchange with the core.

The PGE will be present in the iron metal of Earth's core at concentrations some thousand times higher than their abundance in the silicate Earth (Palme 2008). Models for core differentiation, based on iron meteorite analogs, suggest that the liquid of the outer core will evolve to high Re/Os and Pt/Os ratios. Although these ratios will be nowhere near as high as in crustal rocks, the high Os concentration in core metal will impose both the  $^{186}\text{Os}$  and  $^{187}\text{Os}$  characteristics of the core on a core–mantle mixture, even at very low percentages of core in the mixture (Fig. 5). A core–mantle interaction explanation for the  $^{186}\text{Os}$ – $^{187}\text{Os}$  correlation,



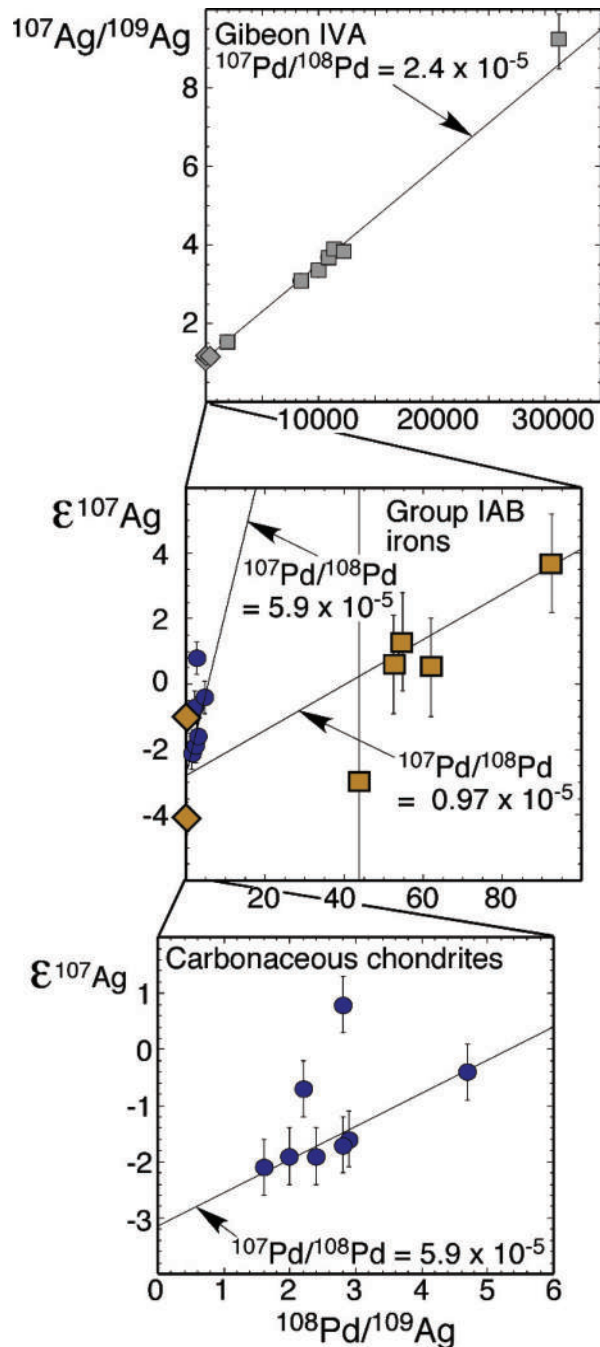
**FIGURE 5** Coupled  $^{186}\text{Os}$ – $^{187}\text{Os}$  isotope variation in direct samples of the mantle (abyssal peridotites and PGE-alloys and chromites from ophiolites) and volcanic rocks believed to originate by melting of plumes rising from the core–mantle boundary. Although crustal rocks (e.g. basalt) and various types of sediment have high Re/Os and Pt/Os ratios, their low Os concentrations coupled with only small ingrowth of  $^{186}\text{Os}$  due to  $^{190}\text{Pt}$  decay lead to nearly horizontal mixing lines with mantle peridotite on this diagram. In contrast, due to the very high concentrations of Os in the core, even a small addition of core material to the mantle will shift the Os isotope composition of the mixture towards the core component. The lines on the diagram show mixing trajectories expected for fertile mantle peridotite mixed with two types of crustal rocks (tick marks give 10% by mass increments of crustal rock in the mixture) and outer core (tick marks show 1% increments in core addition). The mixing lines were constructed using the end member parameters given in Carlson (2005), with data sources summarized in Carlson (2005) and Brandon and Walker (2005).

however, is not universally accepted. Alternatives include (1) the recycling of unusual, low-abundance sediment types that have enough Os to affect a sediment–mantle mixture (Scherstén et al. 2004); (2) the formation of discrete PGE-rich phases in the mantle that can effectively separate Pt and Re from Os; and (3) the recycling of eclogite with a sufficiently high Pt/Os ratio (Luguet et al. 2008) to produce the necessary isotopic differences. The controversy over the correct interpretation of the  $^{186}\text{Os}$ – $^{187}\text{Os}$  correlation is likely to remain for some time, but its resolution will help address the fundamental issue of whether there is chemical exchange between Earth’s core and mantle.

## METAL–SILICATE FRACTIONATION AND THE TIMING OF CORE FORMATION

### Core Formation and the Thermal History of Planetesimals

Due to the strongly siderophile nature of the PGE and Re, their radioisotope decay schemes provide one of the few avenues available for determining the timescale of formation of the various iron-metal-rich meteorites. Several excellent Re–Os isochrons suggest age differences in the range of tens of millions of years between the various groups of iron meteorites (Smoliar et al. 1996). Although the age range defined by Re–Os isochrons is robust, the absolute ages are dependent on the value used for the  $^{187}\text{Re}$  decay constant because the currently used decay constant was calculated from an extremely well-defined Re–Os isochron for the group IIIA iron meteorites, by assuming that this meteorite formed just shortly after the solar system, even though no other precise radiometric age for these meteorites exists (Smoliar et al. 1996).



**FIGURE 6** Pd–Ag isochrons from various classes of meteorites. For extinct radioisotope systems, isochrons give not the age of the sample, but the abundance ratio of the extinct isotope at the time the isochron relationship was established (e.g. the  $^{107}\text{Pd}/^{108}\text{Pd}$  ratio). The higher this ratio is, the older the sample, with the ratio decreasing by a factor of 2 every 6.5 My, the half-life of  $^{107}\text{Pd}$ . The top panel shows the results for the volatile-depleted Group IVA iron meteorite Gibeon (Chen and Wasserburg 1990). Here the very high Pd/Ag ratios (x-axis) have created a wide range in  $^{107}\text{Ag}/^{109}\text{Ag}$  ratios between metal (squares) and sulfides (diamonds). At much lower Pd/Ag ratios, and consequently much smaller variation in Ag isotope composition (now expressed as  $\epsilon^{107}\text{Ag}$ , i.e. the parts in 10,000 difference between  $^{107}\text{Ag}/^{109}\text{Ag}$  in the sample compared to that in a terrestrial Ag standard), the middle panel shows that the Group IAB iron meteorites Toluca and Canyon Diablo have correlated Pd/Ag ratios and Ag isotope compositions in metal (squares), but not in sulfides (diamonds). The middle panel also shows that MC–ICP–MS analyses are much more precise than the one thermal ionization analysis shown (Chen and Wasserburg 1990), whose error bars extend off the diagram. The lower panel shows that 6 out of 8 carbonaceous chondrites (also shown in the middle panel) lie on a Pd/Ag versus Ag isotope regression line with a slope of  $5.9 \times 10^{-5}$ , the highest value yet seen for any solar system material. Data sources include Chen and Wasserburg (1990) and Schönbachler et al. (2008) and references therein.

The Pd–Ag system also can be used to date iron meteorites, but its ability to do so is in part determined by the fact that Ag is a moderately volatile element while Pd, though among the more volatile of the PGE (Palme 2008), is more refractory than Ag. As a result, some groups of volatile-depleted iron meteorites have Pd/Ag ratios over 100,000, compared to a solar Pd/Ag ratio of about 3, leading to  $^{107}\text{Ag}/^{109}\text{Ag}$  ratios above 9, compared to a solar value of 1.079 (Chen and Wasserburg 1996). This huge range in Ag isotope compositions was critical in the discovery that  $^{107}\text{Pd}$  existed in the early solar system (e.g. Kelly and Wasserburg 1978) because the technique used for Ag isotope measurements (thermal ionization mass spectrometry) was limited in precision to a few per mil. Multicollector ICP analysis improves Ag isotope precision by a factor of ~20 (Fig. 6), which now allows this system to be applied even to meteorites with low Pd/Ag ratios. Even the most volatile-rich meteorites, the carbonaceous chondrites, provide enough variation in Pd/Ag and  $^{107}\text{Ag}/^{109}\text{Ag}$  ratios to define a correlation corresponding to an initial  $^{107}\text{Pd}/^{108}\text{Pd}$  value of  $5.9 \pm 2.2 \times 10^{-5}$  (Fig. 6; Schönbächler et al. 2008).

Given the initial abundance of  $^{107}\text{Pd}$  determined by the Pd–Ag isochron for carbonaceous chondrites, a variety of iron meteorites define Pd–Ag ages that range from 8.5 to 19.5 My after solar system formation (Schönbächler et al. 2008). These ages are much greater than the ca. 1 My metal–silicate separation ages inferred from Hf–W systematics of iron meteorites (Markowski et al. 2006), but they

date different events: Hf–W dates the time of metal–silicate separation on the parent planetesimal and Pd–Ag the time of crystallization of the planetesimal core.

## CONCLUSION

Over the last 20 years, the Re–Os system has made the transition from a novel technique undergoing development in only a few laboratories to an established tool of isotope geochemistry. Simplification of chemical separation and mass spectrometric procedures over this time period has opened the system to general use and to a much wider, and still expanding, range of applications. Pt–Os and Pd–Ag still require elaborate measurement procedures, but even the applications of these systems are expanding dramatically. These three radioisotope systems take advantage of the unique chemical characteristics of the PGE to open many new avenues of research that are not accessible in conventional isotopic studies. Given the youth of the application of these systems, the expectation is high for continued and expanded novel contributions to our understanding of a wide variety of fundamental problems in the Earth and planetary sciences.

## ACKNOWLEDGMENTS

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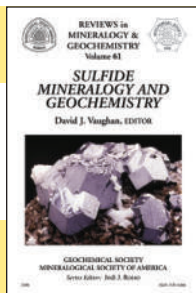
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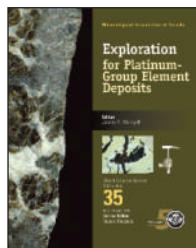


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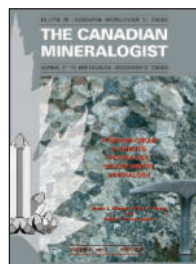
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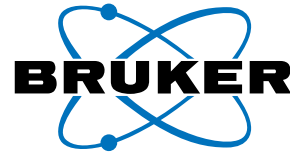
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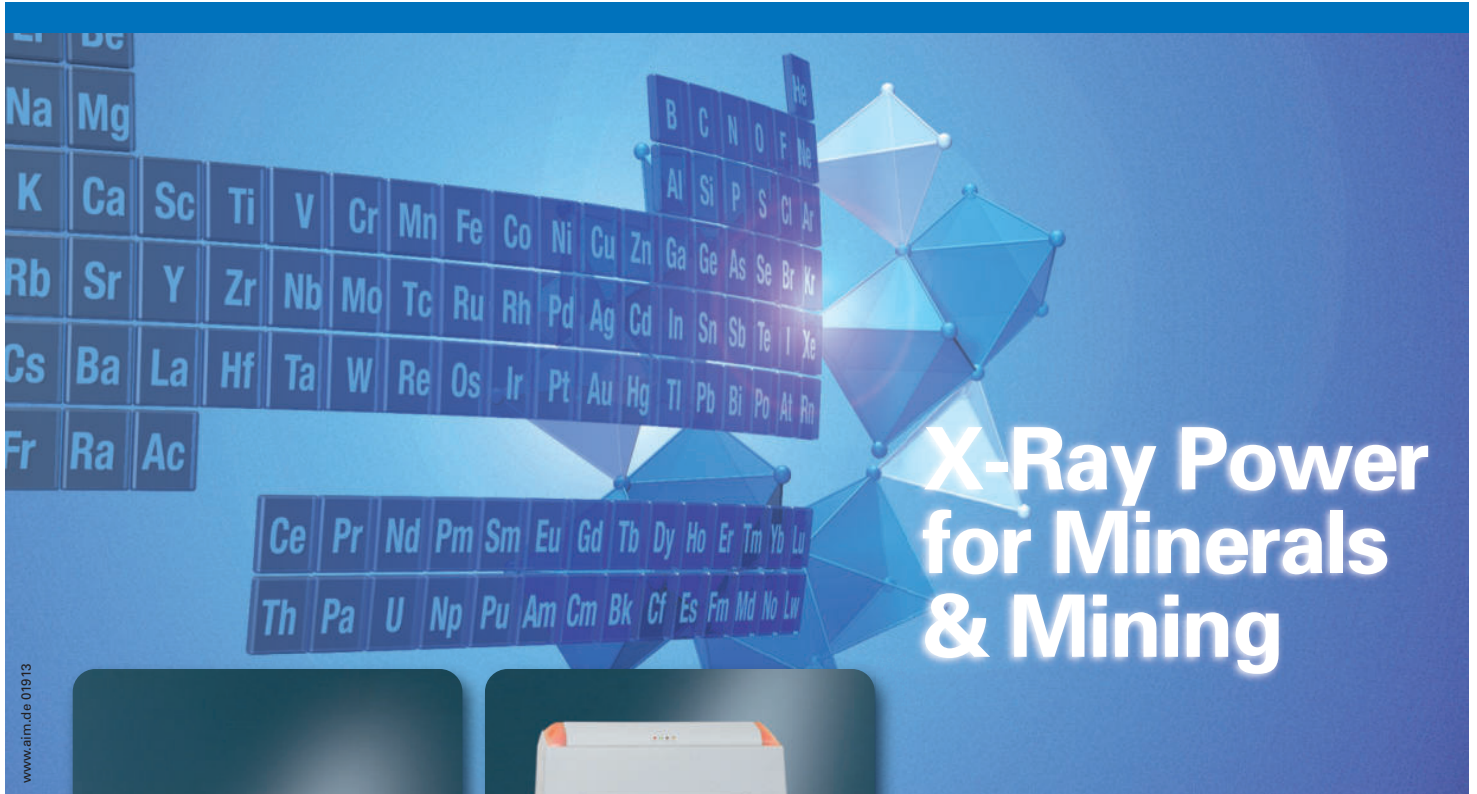
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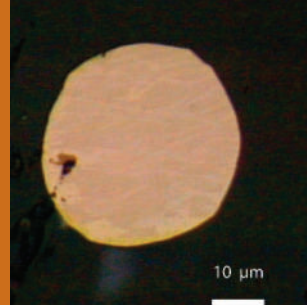
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# Platinum-Group Elements: A New Set of Key Tracers for the Earth's Interior

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Monosulfide solid solution included in a mantle olivine. Plane-polarized reflected light

**Due to their “iron-loving” properties, platinum-group elements (PGE) are expected to be stored in the Earth’s core. Although very low, at a few parts per billion, PGE concentrations measured in mantle-derived rocks are too high to be in chemical equilibrium with the core. The “late veneer” model offers the best explanation for this paradox—it postulates that a flux of primitive meteorites hit the early Earth after core formation had ceased. However, the inferred PGE composition of the hypothetical primitive mantle exhibits slight positive excesses of Ru, Rh, and Pd compared to the canonical chondritic signature. Such deviations have triggered considerable debate about the composition of the late veneer and the extent of reworking of PGE signatures by igneous processes within the Earth’s mantle.**

**KEYWORDS:** platinum-group elements, core, upper mantle, chondrites, base-metal sulfides

## INTRODUCTION

Thanks to advances in analytical chemistry and low-detection multielement analytical facilities, platinum-group elements (PGE) recently joined the panel of geochemical tracers of the Earth’s mantle, thirty years after the rare earth elements (REE) and other lithophile elements that are concentrated in silicates and oxides. In the periodic table of the elements, the PGE are classified, along with Fe, Ni, and Co, as Group VIII transition metals. As transition metals, they possess unfilled high-energy electronic d-orbitals containing unpaired electrons that may be engaged in metal–metal bonding or covalent bonding with electron acceptors like sulfur. Thus PGE display a strong affinity for metallic phases and sulfides, which results in very different properties during planetary differentiation compared to lithophile elements. As such they provide unique clues about processes related to the origin of the terrestrial planets, processes such as core segregation and continuous accretion from primitive meteorites. Recent work has shown that PGE also offer new and complementary perspectives on the relations between the lithophile elements and the geodynamic evolution of the Earth’s mantle and on igneous processes such as melting and magma–rock interaction. However, since most of the PGE information is carried in minerals (sulfides, alloys) representing less than 0.1% by volume of

the Earth’s mantle, understanding the PGE abundance in the mantle requires “sharp” analytical tools and new conceptual frameworks that will allow us to extrapolate from the behavior of trace minerals to evolution at the planetary scale.

## PGE BUDGET OF THE EARTH

The Earth is a differentiated planet with a metallic core (ca. 33% of the Earth’s mass) surrounded by a silicate shell consisting of the mantle (66.4% by weight) and a thin (30–50 km) crust (0.4% by weight). It is generally accepted that the Earth grew by the accretion of a few

tens of protoplanets (bodies up to thousands of kilometers in diameter) within  $10^7$  to  $10^8$  years after the formation of the solar system. Due to their high ( $>10^4$ ) metal–silicate partition coefficients ( $D^{\text{met/sil}}$ , i.e. the concentration of a given element in an Fe–Ni metal alloy divided by the concentration of the same element in molten silicate), it is widely believed that the PGE delivered to the proto-Earth at the accretionary stage were massively sequestered into the metallic core during the core–mantle separation event, more than 4.5 billion years ago. However, as the core cannot be probed directly, information on its composition must be gleaned indirectly by (1) using  $D^{\text{met/sil}}$  for the PGE measured in the laboratory, (2) using the respective masses of the core and mantle, and (3) assuming that chondritic meteorites are the best proxies for the cosmic materials that built up the Earth. A calculation using a conservative  $D^{\text{met/sil}}$  value of  $10^4$  for the PGE shows that more than 99.8% of the PGE were sequestered into the Earth’s core, which is expected to contain ca. 1–3 ppm Os–Ir, 2.2–4.2 ppm Ru, 3.3–5.5 ppm Pt, 1.7–3.15 ppm Pd, and 0.4–0.8 ppm Rh. It can be easily inferred from the mass-balance calculation discussed above that the silicate Earth immediately after core formation was almost completely stripped of PGE.

Unlike the core, the mantle can be sampled directly by peridotites (see page 250) and indirectly by lavas. Both indicate PGE concentrations at levels of a few parts per billion (ppb), two orders of magnitude lower than in chondritic meteorites. Nevertheless, absolute abundances are too high (by several orders of magnitude) and relative abundances too close to ratios measured in chondritic meteorites to be inherited from the core-segregation event. Indeed,  $D^{\text{met/sil}}$  for the PGE are so extremely variable, spanning several orders of magnitude, that for instance the Pd/Ir and Ru/Pt ratios of the silicate Earth should be about 100 times higher than the chondritic ratios (Fig. 1). To account for the near-chondritic relative abundances of the PGE—one of the most elusive

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geochemical aspects of the Earth's mantle—the most popular (but still not universally accepted) model assumes a continuous influx of chondritic materials (the “late veneer” model; Chou 1978) after the Earth had already acquired about 99% of its present mass and core formation was completed. This late extraterrestrial influx (ca.  $10^{22}$  kg) was thoroughly mixed within the silicate Earth but failed to segregate into the core. The Moon has preserved physical evidence of a “late heavy bombardment” (LHB; 4.0–3.8 Ga) that produced large impact basins (lunar maria) (Koeberl 2006). It is widely conjectured that the Earth suffered an LHB at the same time as the Moon. Unfortunately, there is no indisputable record on Earth, because the pre-3.8 Ga crust has been almost completely reprocessed by vigorous geodynamic activity.

Recently, several workers have explored experimentally the possibility that the comparatively high abundances of PGE in the mantle are a result of increasing solubility of these elements in silicate melts at high pressure (Fig. 1). The proponents of this model assume (1) a partially molten proto-Earth and (2) that core-forming metals were able to sink through a magma ocean extending to depths of 800–1800 km, reaching equilibrium with silicate melt at high temperature and high pressure (Righter 2003). Mantle abundances of some transition elements (Ni, Co, Mo, W) showing less affinity for Fe than the PGE have been successfully explained this way (Wade and Wood 2005). The general question of PGE solubility at high pressure remains unresolved, notwithstanding the success of Righter et al. (2007) in approaching the Pd mantle abundance by metal–silicate partitioning at the pressure conditions reigning at a depth of ca. 800 km (Fig. 1). For the same depth, Cottrell and Walker (2006) and Ertel et al. (2006) estimated contrasting  $D^{\text{met/sil}}$  values for Pt, differing by 6 orders of magnitude. To account for chondritic PGE ratios, the metal–silicate partition coefficient of each PGE must converge to the same value for the appropriate pressure range of core formation; this assumption is highly unlikely owing to the vastly different low-temperature geochemical

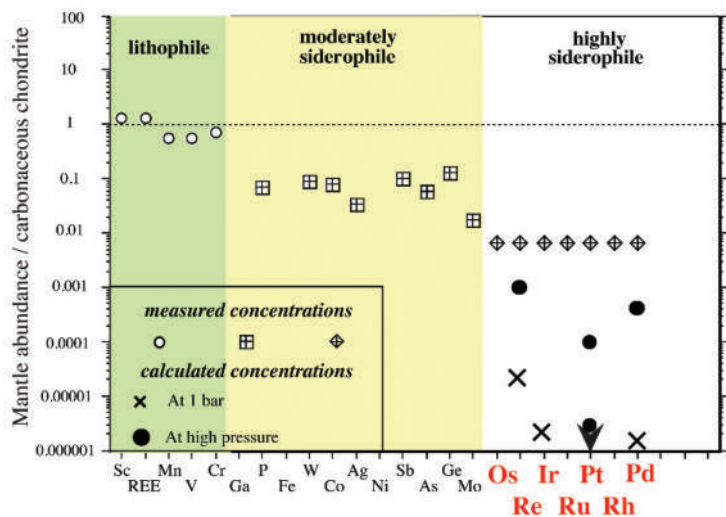
behaviors of the different PGE. In addition to chondritic PGE ratios, the model composition of the Earth's primitive mantle yields a chondritic Re/Os ratio (Meisel et al. 2001). Such a ratio likely would not have survived metal–silicate partitioning at high pressure because Re, another iron-loving element, has a much lower affinity for metal than Os.

## PARTIAL MELTING AND PGE MICRO-MINERALS IN THE TERRESTRIAL MANTLE

Most geodynamicists argue that large parts of the modern mantle have been processed via convection and plate tectonics for the last 3 billion years. Upwelling mantle columns at divergent plate boundaries melt partially, generating magmas enriched in incompatible elements and leaving behind solid mantle residues in which compatible elements are concentrated. Mantle melting is the most important Earth process that fractionates PGE and therefore must be addressed before discussing PGE signatures inherited from the primitive mantle.

If plotted in order of decreasing melting temperature for the pure metal, PGE abundances in magmas produce positively sloped patterns, while restitic mantle rocks show smooth negative slopes (Fig. 2). PGE are unlikely to exist as pure metals in the convecting mantle; thus, the question of which minerals sequester Os, Ir, Ru, and Rh in the mantle—and therefore control their compatible behavior—has been debated for more than 30 years. Olivine and Cr spinel, the two principal minerals that are refractory to mantle melting, are good candidates from a theoretical crystal-chemical point of view. Small divalent Os and Ir ions (0.74 Å) could substitute for base metals in regular octahedral sites in olivine (Brenan et al. 2005), whereas Cr spinel can accommodate Ir, Ru, and Rh substituting for trivalent cations (Capobianco and Drake 1990; Righter et al. 2004). The analysis of PGE in mantle silicates is extremely difficult because concentrations are close to the analytical detection limit and prone to contamination by PGE-rich micro-nuggets, especially in the case of opaque minerals such as Cr spinel. PGE contents ranging between 0.03 and 0.1 ppb have been measured in mantle olivine. Since olivine is the main silicate in the upper mantle (55–90% by volume), less than 10% of the whole-rock PGE budget is believed to reside in silicates (Handler and Bennett 1999; Burton et al. 2002). This percentage does not increase significantly in olivine-rich restitic rocks produced by the loss of 25% of basaltic magma via partial melting (Luguet et al. 2007). Cr spinel may concentrate Ir, Ru, and Rh at tens of ppb levels; however, Cr spinel is present in such small amounts in mantle rocks (<2–3% by volume) that its contribution is negligible.

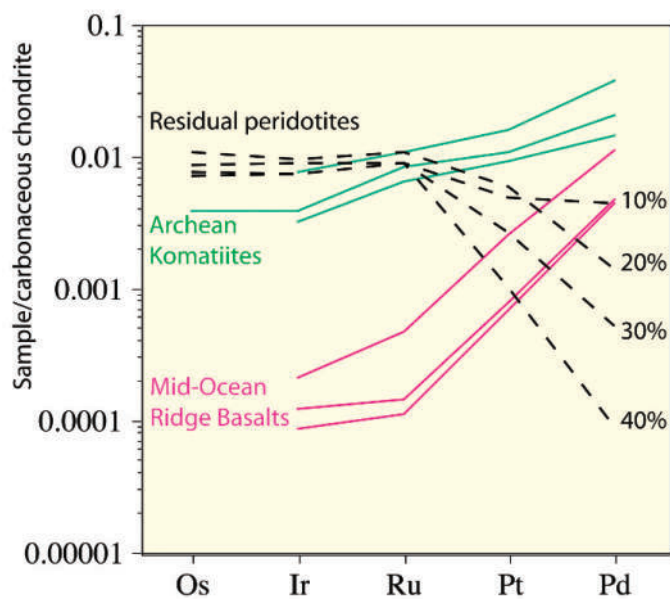
In addition to major silicate and oxide minerals, the upper mantle typically contains about 0.1 vol% of Fe–Ni–Cu sulfides (“base-metal sulfides”). The PGE concentrations measured in base-metal sulfides are at the ppm level, three orders of magnitude higher than those measured in bulk-rock powders of mantle-derived rocks (Morgan 1986; Pattou et al. 1996; Burton et al. 2002). Thus, base-metal sulfides play a pivotal role in controlling PGE abundances in mantle-derived magmas (see Mungall and Naldrett 2008 this issue). Since PGE have an extremely strong affinity for sulfides (sulfide melt–silicate melt partition coefficients of  $10^3$ – $10^6$ ; Ballhaus et al. 2006), magmas in equilibrium with sulfides remaining in the residual mantle (like basalts erupted at ocean spreading centers—MORB; Fig. 2) are PGE poor (Bézos et al. 2005). Magmas formed by a high degree of partial melting, i.e. beyond complete consumption of sulfides, (like Archean komatiites) are PGE rich, their PGE concentrations approaching primitive mantle values (Puchtel et al. 2004; Fig. 2).



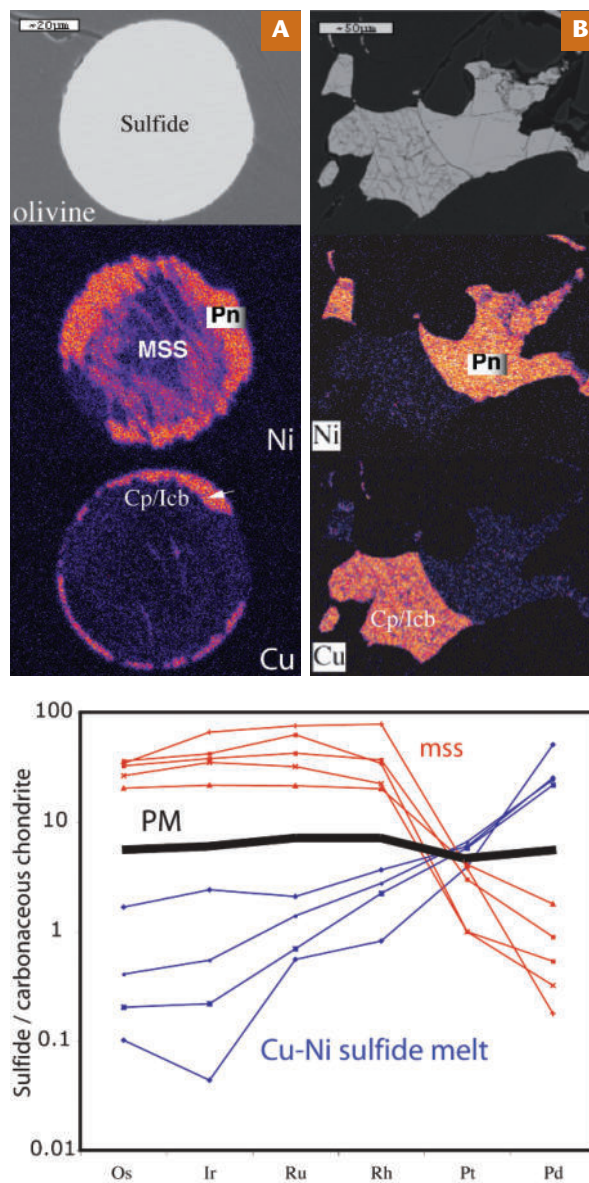
**FIGURE 1** Elemental mantle abundances relative to carbonaceous chondrite. The stair-step depletion pattern is a function of the affinity of each group of elements for iron; thus, lithophile elements, which have no affinity for iron, occur at the chondrite concentration level in the terrestrial mantle, whereas the PGE, Re, and Au, which are “iron-loving elements,” are depleted by two orders of magnitude relative to chondritic meteorites. The uniform depletion of these highly siderophile elements cannot be modelled by metallic melt–silicate melt partition coefficients determined at 1 bar pressure. The use of high-pressure metallic melt–silicate melt partition coefficients can reconcile the abundance of Pd (Righter et al. 2007) but not that of Pt (Ertel et al. 2006). FIGURE ADAPTED FROM DRAKE AND RIGHTER (2002) AND COTTRELL AND WALKER (2006)

However, the model above is unable to explain the fractionated chondrite-normalized PGE patterns that characterize residual mantle rocks and mantle-derived magmas as a whole, because experimental data show that all PGE display equal affinity for sulfide melts (Ballhaus et al. 2006). A possible solution to this conundrum was recently provided by comprehensive mineralogical investigations of PGE mineral carriers in peridotites and by laboratory experiments. In the late 1990s, a major breakthrough resulted from advances in microanalytical tools (especially laser-based microprobes coupled with plasma mass spectrometers). These techniques allowed base-metal sulfides to be analyzed in situ in polished sections, thus eliminating the tedious step of hand picking scarce and tiny (<0.1 mm) minerals, while preserving information on the sulfide minerals to be analyzed, such as their parageneses and their textural relations with respect to mantle silicates and oxides. In situ analyses confirmed conclusions based on previous analyses of separated sulfides, i.e. that more than 90% of the PGE budget of mantle lherzolite resides in base-metal sulfides (Alard et al. 2000; Lorand and Alard 2001). Moreover, Alard et al. (2000) identified two sulfide populations in mantle lherzolite, occupying different sites of crystallization and showing contrasting mineralogical and geochemical compositions (Fig. 3). They found Os–Ir–Ru- and Rh-rich sulfides in the form of rounded Fe–Ni monosulfide solid solution (mss) inclusions in olivine, and these sulfides display the same negatively sloped chondrite-normalized PGE pattern as residual (depleted) mantle peridotites. Palladium is enriched in the second population, consisting of intergranular Ni sulfide

(pentlandite) and Cu sulfide (chalcopyrite–isocubanite), which are the crystallization products of a Cu–Ni-rich sulfide melt with a basalt-like, positively sloped chondrite-normalized PGE pattern. During partial melting, the Pd- and Pt-rich Cu–Ni-sulfide melt is entrained in mantle-derived magmas, whereas mss is trapped in restitic rocks, thus sequestering Os, Ir, Ru, and Rh and producing the typical negatively sloped pattern of the residual mantle (Ballhaus et al. 2006). However, because a silicate melt dissolves thousands of ppm of sulfur, all the mss is expected to be consumed by the magma if the degree of partial melting is sufficiently high (currently estimated at  $\geq 20 \pm 5\%$ ). At this stage, the mss liberates micrometer-scale Ru–Os–Ir sulfides/ alloys and Pt–Ir alloys, which retain the PGE inside the residual peridotite (Luguet et al. 2007).



**FIGURE 2** Chondrite-normalized PGE abundances in residual mantle rocks (dashed lines) and mantle-derived magmas (colored lines). Due to extraction of the low-melting-temperature Cu–Ni-sulfide melt, which concentrates Pt and Pd, the PGE patterns of residual mantle rocks are depleted in Pt and Pd. The depletion factor increases with the degree of melting (10 to 40%), and therefore with the amount of magma extracted from the mantle column, due to the concentration of the PGE in monosulfide solid solution (mss) and to the fact that an increase in the degree of melting decreases the amount of mss remaining in the residual mantle. DATA SOURCES: HANDLER AND BENNETT 1999; PEARSON ET AL. 2004; LUGUET ET AL. 2007). Mantle-derived magmas show the opposite behavior: mid-ocean ridge basalts are IPGE-depleted (IPGE = Ir, Os, Ru) relative to the mantle composition because their mantle source still contains base-metal sulfides. In contrast, the very high (30–50%) degree of partial melting needed to generate Archean komatiitic magma, a now-extinct type of highly magnesian magma, consumed all the base-metal sulfides in the mantle, generating PGE abundances (absolute and relative) close to those of the mantle. DATA SOURCES FOR ARCHEAN KOMATIITES: REHKÄMPER ET AL. (1999b); PUCHTEL ET AL. (2004); AND FOR MORB: REHKÄMPER ET AL. (1999b); BEZOS ET AL. (2005)



**FIGURE 3** Backscattered-electron images, elemental (Ni and Cu) X-ray maps, and in situ analyses of the two populations of base-metal sulfides from mantle-derived rocks. (A) “Residual” Fe–Ni-monosulfide inclusion in olivine. (B) “Basaltic” intergranular sulfide bleb. The color intensity indicates the relative abundance of the element. Mss: monosulfide solid solution; Pn: pentlandite; Cp/lcb: chalcopyrite–isocubanite. The chondrite-normalized PGE patterns are from a combination of different peridotites. Note that a combination of “residual” mss and an appropriate amount of “basaltic” intergranular sulfide produces a primitive mantle (PM)-like PGE pattern. DATA SOURCES: ALARD ET AL. (2000); LORAND AND ALARD (2001)

## THE PGE COMPOSITION OF THE EARTH'S PRIMITIVE MANTLE

PGE in mantle rocks can potentially be used to fingerprint the characteristics of meteorites that hit the primitive Earth during late accretion. The analyses of chondritic meteorites, periodically refined over the past twenty years, indicate differences in absolute PGE abundances among the meteorites, in addition to fractionation between the refractory (Os, Ir, Ru) and the more volatile (Pd) elements (see Fig. 5 in *Palme 2008* this issue). Determining the composition of the late veneer is of prime importance for the early history of the Earth, and it has even been suggested that this event delivered the water and organic molecules that were the precursors of life (*Drake and Righter 2002*). The degree to which PGE signatures of modern mantle rocks provide information on the early Earth depends primarily on primitive mantle (PM, also referred to as “primitive upper mantle”; *Meisel et al. 2001*) compositional estimates, the hypothetical model composition for the silicate Earth before any mantle-crust differentiation and mantle-melting event. Of course, the PM cannot be directly determined from mantle-derived samples. Its composition is based on extrapolations from geochemical trends shown by mantle samples, considering chondrites as the building blocks of the Earth (*McDonough and Sun 1995*). To characterize the PGE content of the Earth's primitive mantle, geochemists analyze lherzolites, i.e. peridotites that have major-element compositions approaching model compositions for the Earth's PM. Lherzolites are brought up from the Earth's interior to the surface as centimeter- to decimeter-sized nodules (mantle xenoliths) included in continental lavas or, less commonly, as kilometer-sized bodies tectonically uplifted through the lithosphere along major faults in Phanerozoic mountain belts (Fig. 4). Until the mid-1990s, PGE were difficult to analyze at mantle concentration levels with an acceptable degree of confidence. Pioneering measurements were accomplished for Ir and Pd, two elements easily detected by radioactivation analysis of rock powders, and the abundances of the other PGE were extrapolated from PGE ratios in carbonaceous chondrites, which are the most primitive meteorites and which are rich in volatile components and organic matter (*McDonough and Sun 1995*).

Compositional data for PGE in the Earth's mantle have accumulated over the past ten years, thanks to advances in mass spectrometry and chemical separation procedures that now allow all PGE to be determined at the ppb level with a precision better than 5%. The quest for the PGE composition of the Earth's primitive mantle has led to contrasting pictures. Many suites of lherzolite xenoliths from basalts erupted on continents display Pd/Ir and Pd/Pt ratios in the range shown by enstatite/ordinary chondrites ( $1.0 \pm 0.3$  and  $0.5 \pm 0.2$ , respectively; *Rehkämper et al. 1997*; *Lorand and Alard 2001*), in good agreement with the chondritic  $^{187}\text{Os}/^{188}\text{Os}$  ratio ( $^{187}\text{Os}$  is a long-term radiogenic decay product of  $^{187}\text{Re}$ ; see *Carlson et al. 2008* this volume) inferred for the primitive mantle ( $0.1296 \pm 0.0007$ ; *Meisel et al. 2001*). Using inductively coupled plasma-mass spectrometry (ICP-MS) and a fire-assay chemical separation procedure, *Pattou et al. (1996)* discovered that orogenic lherzolites from the Pyrénées (France) are characterized by Ru/Ir (2) and Pd/Ir (1.8) ratios that are moderately greater than those of carbonaceous chondrites. By analyzing xenoliths and orogenic lherzolite samples of worldwide provenance, *Becker et al. (2006)* obtained a PGE composition for the primitive mantle that is characterized by broadly chondritic Os, Ir, and Pt relative abundances and 20–30% higher Ru/Ir ( $2.03 \pm 0.12$ ) and Pd/Ir ( $2.06 \pm 0.31$ ) ratios. Such a primitive mantle composition does not match the composition of any known chondrite group. By contrast, it com-



**FIGURE 4** Lherzolite samples from the upper mantle. (A) Yellow-green nodules (“xenoliths”) in a basalt flow (Kerguelen Islands, Indian Ocean). COURTESY OF MICHEL GRÉGOIRE. (B) A kilometer-sized massif composed of orogenic lherzolite in the Pyrenean range (Lherz, southern France)

pares quite well with the PGE composition of Apollo XVII lunar impact melt rocks that formed in conjunction with the large, 4.0–3.8 Ga old lunar impact basins (Fig. 5). Taken at face value, the PGE composition of the impact melt rocks and the PGE signature of the hypothetical primitive mantle suggest that the meteorites that hit the Earth–Moon system had a somewhat different composition from the chondrites in our collections.

### NON-CHONDRITIC PGE RATIOS IN MANTLE-DERIVED PERIDOTITES?

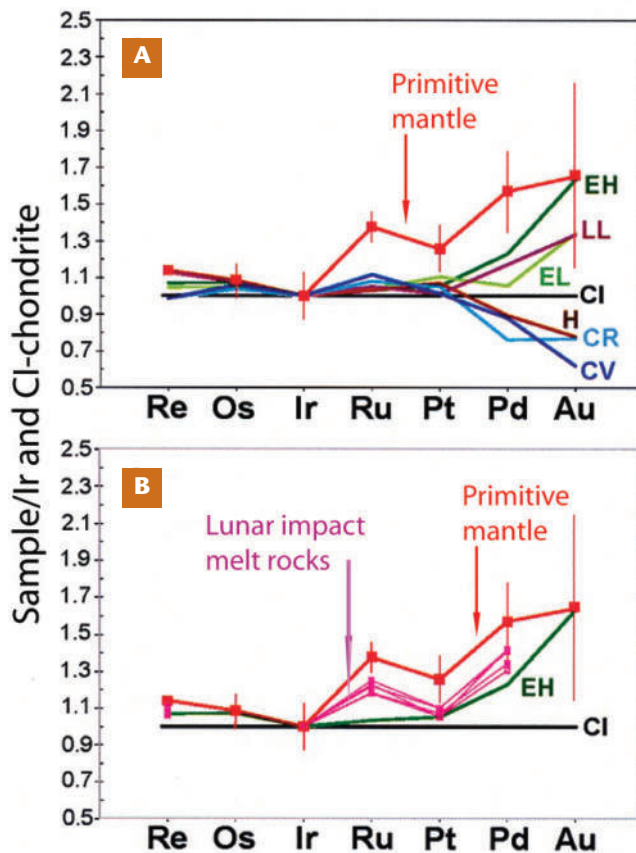
Although they display broadly chondritic PGE ratios (except for Os/Ir), very few lherzolite xenoliths transported by continental basaltic lavas have PGE concentrations similar to those of Becker et al.'s (2006) primitive mantle estimate (Fig. 6). The wide range of PGE concentrations compared to those reported in orogenic lherzolites is puzzling. Some of the lherzolitic xenoliths with low PGE contents may have lost base-metal sulfides via melt rising up through the mantle (*Lorand and Alard 2001*). Osmium concentrations are particularly low compared with the other PGE, which led most authors after *Handler and Bennett (1999)* to postulate selective loss of Os (highly volatile as an oxide) upon eruption or during alteration of the xenoliths by groundwater.

The samples used to constrain the PGE signature of the primitive mantle were stored in the rigid part of the mantle beneath the crust (the lithosphere) long after core separation and meteorite bombardment had ceased. Large volumes of the lithosphere have been affected by magmas “en route” to the Earth's surface. These magmas may have modified whole-rock Pd/Ir and Pt/Ir ratios in the mantle by precipitating Pd- and Pt-rich “basaltic” sulfides within formerly

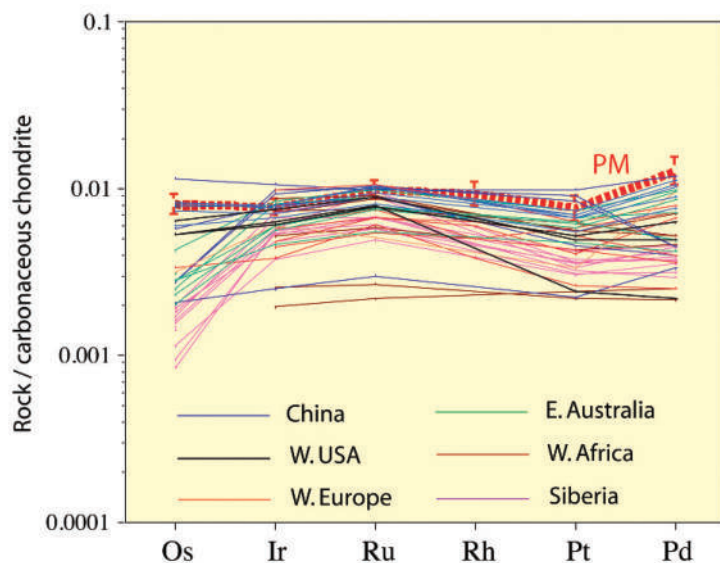
depleted residual peridotites. Physical mixing of the two sulfide populations—"restitic" and "basaltic"—identified in situ can generate whole-rock patterns akin to that postulated for the primitive mantle (FIG. 3). Rehkämper et al. (1999a) were the first to document such mixing in ocean-floor peridotites that have been extensively melted during upwelling and decompression of the mantle beneath mid-ocean ridges. In situ analyses of base-metal sulfides have provided further support for this interpretation. Alard et al. (2000) and Lorand and Alard (2001) found the Pd-rich "basaltic" sulfide population in close association with minerals diagnostic of magma circulation ("metasomatism") in the mantle beneath continents (e.g. diopside, carbonates, feldspar, apatite). Furthermore, Alard et al. (2002) measured the osmium isotope composition of sulfides in situ using a laser probe coupled with a multicollector ICP-MS. They found that the two generations of base-metal sulfides are not contemporaneous: "basaltic" intergranular sulfides are 1–2 billion years younger than "restitic" sulfides. Base-metal sulfides in peridotites from the ocean floor also preserve the two types of complementary PGE patterns, despite substantial mineralogical transformations resulting from alteration of primary minerals by seawater; moreover, "basaltic" sulfides are systematically located within sites of crystallization of magmatic or metasomatic minerals such as spinel and Ca-Al pyroxene (Luguet et al. 2003). Relatively young magmatic events that increased Pd/Ir and Pt/Ir ratios have also been documented in garnet peridotites stored beneath Archean continents (Pearson et al. 2004).

However, some issues regarding the Becker et al. (2006) primitive mantle estimate are still under debate. On the one hand, this estimate is robust because it is supported by evidence from the Moon. The suprachondritic Ru/Ir ratio cannot be explained by any process in which magmas contaminate the mantle because "basaltic" sulfides are too poor in Ir and Ru to contribute significantly to the whole-rock budget of these two PGE (FIG. 3). On the other hand, recent studies cast doubt on the primitiveness of orogenic lherzolites, the cornerstone of the Becker et al. (2006) PM estimate. Rehkämper et al. (1999a), who studied the Horoman lherzolite body (Japan), and Pearson et al. (2004), who examined the Beni-Boussera lherzolite (Morocco), concluded that PGE signatures were modified by magmas because the palladium concentrations (and Pd/Ir ratios) correlate linearly with Ca and Al, in a way not expected for mantle rocks that were processed only by partial melting. In the case of the Lherz body (southern France), the type locality of lherzolite, there is now strong evidence that lherzolites are secondary rocks resulting from the crystallization of magmas that reacted with a 2 Ga residual peridotite body (Le Roux et al. 2007). Of course, such re-enrichment processes ("refertilization") obviously call into question the link between orogenic lherzolites and primitive mantle estimates.

As for continental mantle xenoliths and peridotites from the ocean floor, comprehensive studies coupling geochemical and mineralogical approaches are required for deconvoluting the information from orogenic lherzolites. Such a study performed on a single sample from the Pyrénées identified only intergranular sulfide blebs displaying all characteristics of "basaltic sulfides," except for their PGE contents measured in situ (Lorand et al. 2008). Some blebs effectively showed the Pd-enrichment of "basaltic" sulfides while others were more akin to Pd-poor and Os–Ir–Ru-rich "restitic" sulfides. Although no mss inclusions in silicates have yet been identified, base-metal sulfides commonly enclose micrometer-sized platinum-group minerals (alloys, sulfides) very similar to the mss melting products found in highly depleted residual peridotites. The origin of these PGE micronuggets, as minerals not soluble in the low-temperature base-metal



**FIGURE 5** Ir- and chondrite-normalized PGE composition of the primitive mantle (Becker et al. 2006) compared with the main groups of chondritic meteorites (A) and with impact rocks of lunar maria (B). Note that the primitive mantle estimate does not correspond to any known chondrite composition; only the strongly brecciated rocks in the heights around lunar maria, and contemporaneous with the 3.9–3.8 Ga late heavy bombardment recorded by the Moon's surface, provide a reasonably good match with the Becker et al. (2006) primitive mantle estimate.



**FIGURE 6** Chondrite-normalized PGE abundances measured in basalt-hosted mantle-lherzolite xenoliths collected from five continents. Note that very few analyses match the Becker et al. (2006) primitive mantle estimate. Most xenoliths are significantly depleted in PGE, especially Os. DATA SOURCES: REHKÄMPER ET AL. (1997); HANDLER AND BENNETT (1999); LORAND AND ALARD (2001); PEARSON ET AL. (2004); BECKER ET AL. (2006)

sulfides in the emplaced peridotites or as high-temperature relicts from residual mantle, is a crucial issue in which we are likely to make progress over the next few years.

## CONCLUSIONS

From our knowledge of the fractionation of PGE at the microscopic scale, it seems very likely that the abundances (relative and absolute) of PGE measured in modern mantle rocks were overprinted by magmatic processes, especially melt removal and refertilization. The current primitive mantle estimate for PGE must therefore be considered a work in progress and will need reevaluation as we learn more about the behavior and location of the PGE. Nevertheless, the chondritic to slightly suprachondritic PGE ratios in fertile

lherzolites imply very efficient mixing of basaltic (crustal) material with depleted residual mantle. Our understanding of the identity of the minerals that govern the fractionation of PGE during partial melting and magmatic crystallization in the mantle is also fundamental for using PGE as geochemical tracers, not only for unravelling the early evolution of the Earth and its mantle–core system, but also for understanding the formation of PGE orebodies from mantle-derived magmas.

## ACKNOWLEDGMENTS

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# Ore Deposits of the Platinum-Group Elements

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**The formation of ore deposits of the platinum-group elements (PGE) requires that their concentrations be raised about four orders of magnitude above typical continental crustal abundances. Such extreme enrichment relies principally on the extraction capacity of sulfide liquid, which sequesters the PGE from silicate magmas. Specific aspects of PGE ore formation are still highly controversial, however, including the role of hydrothermal fluids. The majority of the world's PGE reserves are held in a handful of deposits, most of which occur within the unique Bushveld Complex of South Africa.**

KEYWORDS: platinum-group elements, ore deposits, chromite, sulfide, Bushveld Complex

## INTRODUCTION

The concentration of platinum in the parts of the Earth that are exposed on land is about 0.4 ppb (Fig. 1). To be worth mining, Pt ores must contain amounts similar to 4 ppm, a 10,000-fold enrichment over typical crustal rock. However, from 4 ppm, an ore must be further refined until the Pt concentration is 100,000 times higher before this precious metal appears in the jeweler's alloy we call white gold. How can we detect ores with such low concentrations that the metal is invisible except to the most precise geochemical analysis, and how does the metal become 10,000 times more abundant in some rocks than in others? No other commonly used element requires such extreme concentration to become useful, and therefore none pose such extraordinary challenges to petrologists and economic geologists. The reason for the extreme depletion of the platinum-group elements (PGE) in the silicate Earth is the topic of the articles in this issue by Palme (2008) and Lorand et al. (2008). In this article we examine the ways in which that extreme depletion can be undone to the extent that we can mine and extract the PGE for practical uses.

At equilibrium, the concentration of all of the PGE is at least 10,000 times higher in sulfide melt than in coexisting silicate melt, making sulfide an extremely potent agent for the collection and segregation of PGE from magmas in which each PGE normally occurs at concentrations less than 15 ppb (Fleet et al. 1999; Arndt et al. 2005). The extreme enrichment of PGE in sulfide liquid with respect to coexisting silicate melt is a consequence of the preference shown by the PGE for covalent bonding with sulfide ions in sulfide melt over the more ionic character of the bonds formed with oxygen ions in silicate melts. The processes controlling the formation of PGE deposits are therefore inextricably tied to the igneous geochemistry of sulfur.

In most common mantle-derived magmas, sulfur exists as  $S^{2-}$  ions, which dissolve in common silicate melts primarily by forming FeS complexes in which sulfur replaces oxygen in the more common FeO melt species. The sulfur concentration at sulfide saturation in a basaltic melt is increased by increasing temperature and FeO content and decreased by increasing pressure (Wendlandt 1982; Mavrogenes and O'Neill 1999).

Sulfur geochemistry controls the genesis of PGE deposits in two principal ways: first, the presence of sulfide as a restite phase during mantle melting limits the availability of PGE to magmas; and second, the formation of an ore deposit requires the saturation of a magma with immiscible sulfide liquid and the collection of that liquid in structural traps within magmatic systems (Fig. 2).

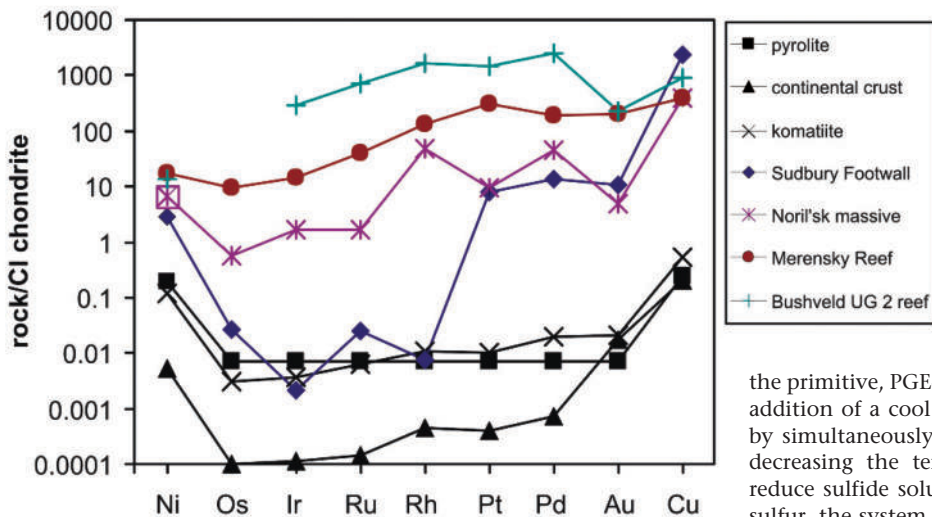
Typical sulfur solubilities range from about 500 ppm in basalts formed by very deep mantle melting to approximately 1000 ppm or more in relatively Fe-rich magmas (Mavrogenes and O'Neill 1999). Since the upper mantle contains about 200 to 250 ppm S, most low-degree mantle melts cannot dissolve all of the S present (Keays 1995). As a result, many basaltic magmas derived by moderate degrees of melting of the mantle, like mid-ocean ridge basalts and common arc or back-arc tholeiites, are formed in the presence of residual Fe-Ni-S liquid that sequesters the PGE. Magmas formed under these conditions have negligible potential to form economic deposits of the PGE.

At the high degrees of melting implicated in the genesis of high-Mg intraplate magmas, including komatiites and picritic flood basalts, all of the sulfur in the mantle is dissolved in the silicate melt prior to magma ascent. In this case, the concentrations of all of the PGE are dictated by mineral-melt partitioning. The IPGE (Os, Ir, Ru) and Rh are mildly compatible with a peridotitic mantle residue, but the PPGE (Pt, Pd) are highly incompatible and therefore are liberated into the silicate melt as soon as the last bit of sulfide has been dissolved (Mungall 2007 and references therein). Alternatively, at oxygen fugacities that are sufficiently high to convert some or all sulfide to sulfate, the net solubility of sulfur in the melt is increased as much as ten fold (Jugo et al. 2005), and any degree of melting of the mantle may permit a mafic magma to form in the absence of a sulfide phase. Magmas formed in the absence of sulfide are fertile potential progenitors of PGE deposits.

Although there are several ways in which PGE-rich magmas may be generated, it appears that all of the major PGE deposits currently known, other than the impact-related deposits of Sudbury, Canada, owe their origins to the

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**FIGURE 1** Compositions of major Earth reservoirs and the principal ore deposits of PGE (recalculated to 100% sulfide) shown as the concentrations of chalcophile metals normalized to those in CI chondrites. Core formation has stripped most of the PGE from the mantle (pyrolite). The formation of continental crust from the mantle has led to even greater impoverishment; it is primarily by high-degree partial melting of mantle rock that PGE-rich magnesian magmas like komatiite can form. The Merensky Reef approaches the maximum possible PGE enrichment in sulfide melts; the sulfide in the UG-2 has probably been enriched by secondary processes. DATA FROM NALDRETT (2004) AND SOURCES THEREIN

formation of intraplate picritic magmas. When these magmas form, the degree of melting is high enough to completely dissolve all the sulfur in their mantle source regions (Arndt et al. 2005; Barnes and Lightfoot 2005).

In order to form a PGE deposit, a fertile magma must become saturated with sulfide melt at a place in the crust where the sulfide can accumulate in a structure that will later be accessible to mining operations. Because primitive fertile magmas must be generated under sulfide-undersaturated conditions and further, because sulfide solubility increases with decreasing pressure, such magmas begin their residence in the crust strongly sulfide undersaturated and hence do not readily produce an immiscible sulfide phase.

Two mechanisms can work, singly or in concert, to provoke sulfide saturation. In the first, because sulfide does not enter any of the common fractionating solid phases in a cooling silicate magma, its concentration increases with progressive cooling and crystallization until the magma eventually reaches sulfide saturation. This might require a large degree of crystallization, so the magma from which sulfide eventually segregates may be as highly evolved as a ferrobasalt. In this case, nucleation of the first immiscible sulfide will be somewhat inhibited due to the large interfacial tension between sulfide and the highly evolved silicate melt. Widely spaced droplets of sulfide will grow by diffusion until they are large enough to settle to the bottom of the magma body; this process can be described as fractional, like a distillation. In a moonshine still, the first fumes to leave contain the highest concentration of those volatile alcohols that are most strongly partitioned into the vapor. Similarly, during fractional removal of sulfide, the first sulfide to fall out will contain the most strongly chalcophile elements. These are the PGE, so the first appearance of sulfide is expected to produce thin layers containing very small amounts of sulfide with extremely high PGE concentrations. Due to the fractional nature of this process, a chromatographic segregation of the chalcophile elements is anticipated as a consequence of the interplay of their parti-

tion coefficients and the rate at which each PGE is able to diffuse towards a growing droplet (Mungall 2002). Important examples of deposits that might have formed in this way are the Main Sulfide Zone of the Great Dyke in Zimbabwe and possibly also the Merensky Reef in the Bushveld Intrusion (see ore deposit models below).

The second mechanism that can produce sulfide saturation involves the assimilation of crustal rocks by

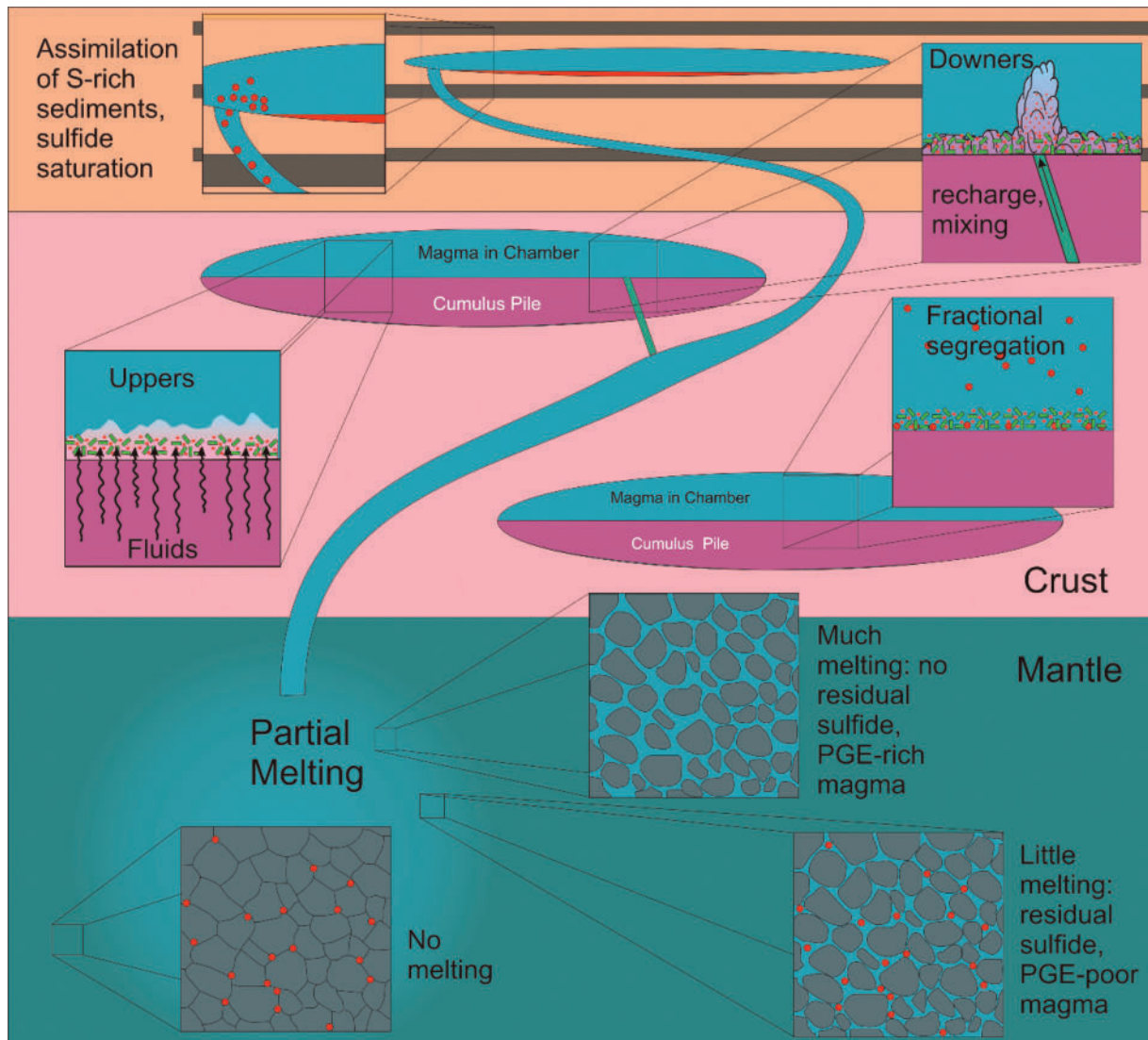
the primitive, PGE-rich, sulfide-undersaturated magma. The addition of a cool assimilant can hasten sulfide saturation by simultaneously increasing the silica concentration and decreasing the temperature, both of which conspire to reduce sulfide solubility. If the assimilant contains crustal sulfur, the system approaches sulfide saturation even more quickly. The formation of immiscible sulfide by crustal contamination is implicated in the generation of all base-metal-dominant magmatic sulfide deposits, but the formation of a PGE-rich deposit by such means requires a delicate balance to achieve the right amount of excess sulfide in the resulting mixture. Addition of just enough crustal sulfur to bring the magma to sulfide saturation can generate small quantities of sulfide with very high PGE tenors. If the magma is just barely saturated with sulfide, then the net amount of PGE sequestered in the sulfide is small compared with the total mass of PGE in the entire system; in such a case the concentration of PGE in the sulfide approximates the product of the partition coefficient and the bulk PGE concentration. However, if the amount of sulfide melt is volumetrically significant, the removal of PGE into the sulfide diminishes the concentration of PGE in the host silicate magma and hence also the concentration in the sulfide phase. The greater the degree of sulfide supersaturation, the higher is the modal abundance of sulfide melt and the lower the concentration of PGE in both the sulfide and silicate phases. As a result, the assimilation of a large amount of crustal sulfur will lead to the segregation of large masses of PGE-poor sulfide melt that may be attractive as sources of Ni and Cu but will not qualify as PGE deposits. This relationship is encoded in a widely used equation (Campbell and Naldrett 1979):

$$C_{sul} = C_0 D^{sul/sil} \frac{R+1}{R+D^{sul/sil}}$$

where  $C_{sul}$  is the concentration of a PGE in the sulfide melt,  $C_0$  is the bulk concentration of that element in the whole system of sulfide + silicate,  $R$  is the silicate/sulfide mass ratio, and  $D^{sul/sil}$  is the partition coefficient for the element of interest.

Once sulfide liquid droplets have formed, they must be collected in order to produce an ore deposit. This is facilitated by their high density (about 4.5 g cm<sup>-3</sup> versus 2.2 g cm<sup>-3</sup> for the silicate melt), which causes the droplets of sulfide to settle to the base of the body of silicate melt. If the sulfide droplets form in a flowing mass of magma in a conduit, they will be entrained and carried in suspension until a change in the flow regime permits them to settle. This process typically occurs where a conduit widens into a larger space, where the flow passes through a portion of the conduit that is choked with unmelted fragments of wall-rock, or both. If the sulfide droplets form in a more quiescent body of magma, such as the liquid portion of a layered intrusion, they can be expected to settle to the bottom. If





**FIGURE 2** Processes governing the formation of PGE deposits. Sulfides (red dots) persist in the mantle during early stages of mantle melting and are not exhausted until much melting has occurred. PGE deposits may form in layered intrusions when magmas reach sulfide saturation during fractional crystallization, by transport of PGE-rich fluids through cumulate crystal piles ("uppers"), or by magma recharge and mixing events ("downers"). The Noril'sk deposit type occurs when fertile magma in a magma conduit encounters sulfide-rich sediments and becomes sulfide saturated.

sulfide liquid begins to segregate in a previously sulfide-undersaturated magma column, then a distinct sulfide-rich layer may form in consequence.

If sulfide droplets accumulate at the base of a melt body in sufficient quantity to form a continuous pool of sulfide melt, they will subsequently undergo a process of magmatic evolution largely or wholly decoupled from the evolution of the parental silicate magma. Although sulfide melt is superheated at magmatic conditions typical of basaltic magmas, a sulfide melt pool will eventually cool to its liquidus temperature and begin to solidify by forming crystals of monosulfide solid solution (mss) or magnetite, or both. Eventually the mss and magnetite are joined on the liquidus by intermediate solid solution (iss; i.e. magmatic cubanite–chalcopyrite solid solution), and during the latest stages of cooling, the sulfide melt may solidify to a variety of phases including pentlandite, millerite, bornite, and a variety of rare copper-sulfide minerals. Platinum, palladium, and gold are rejected by all of these minerals except perhaps pentlandite, with the result that fractionated sulfide melts are highly enriched in these elements compared with the sulfide that initially equilibrated with the silicate magma. As a result, even sulfides that segregate at fairly high sulfide/silicate mass ratios and consequently are not initially very rich in PGE may ultimately generate small volumes of very high-grade PGE mineralization, provided that the residual melts are able to migrate away from the mss–magnetite

cumulates. Examples of this kind of PGE mineralization constitute much of the current ore reserves in the Sudbury district, where their phenomenal contained-metal value allows them to be mined economically at depths where the Ni deposits that spawned them are subeconomic.

In the ultimate stages of sulfide-magma evolution, at temperatures between 200 and 700°C, sulfide melts probably evolve into highly mobile liquid solutions composed of PGE, Au, Ag, S, Te, Bi, Sb, As, and Cl, in which PGE and all of these otherwise rare elements become major elements. The final crystallization products of these very small volumes of melt are composed primarily of platinum-group minerals such as PGE sulfides, intermetallic compounds, and sulfosalts. Widely dispersed disseminations of these minerals occur in the absence of significant base-metal sulfides around the more conventional fractionated sulfide deposits at Sudbury and have recently spurred a major boom in exploration around the Sudbury Igneous Complex.

Aqueous fluids and halide melts contain tens to hundreds of times higher concentrations of the PGE than coexisting silicate melts. Late deuteritic fluids and melts have been identified at Sudbury and in both the Stillwater and the Bushveld intrusions, where they have been found to contain Pt and Pd concentrations comparable to experimentally measured values, on the order of several ppm (Hanley 2005). The possible role of these fluids in the generation of the truly vast ore deposits of the Bushveld and Stillwater intrusions remains a topic of vigorous debate, as described below.

## ORE DEPOSIT MODELS

We recognize several basic types of PGE deposits (FIG. 2).

### Peripheral To or Within Accumulations of Sulfide Liquid

This style of deposit forms as a result of the crystallization of a sulfide liquid that has already been concentrated from mafic or ultramafic silicate magma. Characteristically, these ores are rich in Cu, Pt, Pd, and Au and relatively poor in Rh, Ru, Ir, and Os. They are thought to have resulted from the cooling and crystallization (fractional, equilibrium, or a combination of both) of the sulfide liquid, with the separation of a fractionated component and its migration and concentration away from the early-crystallizing pyrrhotite-dominant component (Naldrett et al. 1982; Naldrett 2004; Mungall 2007). Classic examples of this style of mineralization are found at Noril'sk-Talnakh in Siberia, where they constitute zones within the massive ore, veins in the foot-wall, and peripheral disseminations; and at Sudbury, Canada, where they form massive, chalcopyrite-rich veins. In the latter example, Farrow et al. (2005) showed that a zone of veinlets containing Ni- and Cu-rich sulfides (millerite, bornite, and others) and associated high concentrations of PGE surround many of the chalcopyrite-rich veins. This peripheral mineralization is almost certainly a hydrothermal phase either imposed on, or originating from, original Cu-rich magmatic sulfides, combined with widely dispersed late sulfosalt melts that migrated along grain boundaries and microfractures through the host rock.

### Layers of Very High-PGE-Tenor Sulfides Within a Layered Intrusion

#### Without Substantial Chromite

These constitute stratiform accumulations of PGE-rich, sparsely (0.5–3 vol%) disseminated sulfides such as those in the Merensky and J-M reefs of the Bushveld and Stillwater complexes. The PGE contents correlate closely with the sulfide content of the rock. Because of their importance as sources of PGE (FIG. 3), Bushveld deposits are discussed in greater detail below. The Great Dyke differs from the deposits of the Bushveld Complex in that PGE, Ni, and Cu are not associated with a distinctive horizon (i.e. “reef”) but occur as a zone of sparsely disseminated sulfide, approximately 1–5 m thick, within uniform pyroxenite (the Main Sulfide Zone). The metals show a vertical zoning, with the concentrations of Pd and Rh in 100% sulfides being highest near the base of the sulfide zone and decreasing sharply upward, followed sequentially by the concentrations of Pt, Au, Cu, and Ni (Naldrett and Wilson 1990). This zonation is thought to be the consequence of the ease with which the PGE are concentrated within segregating sulfide droplets, which is, in turn, a function of (1) the respective partition coefficients between the sulfide liquid and the silicate magma and (2) their diffusivities within silicate magma (Mungall 2002).

#### Associated with Chromitite Horizons

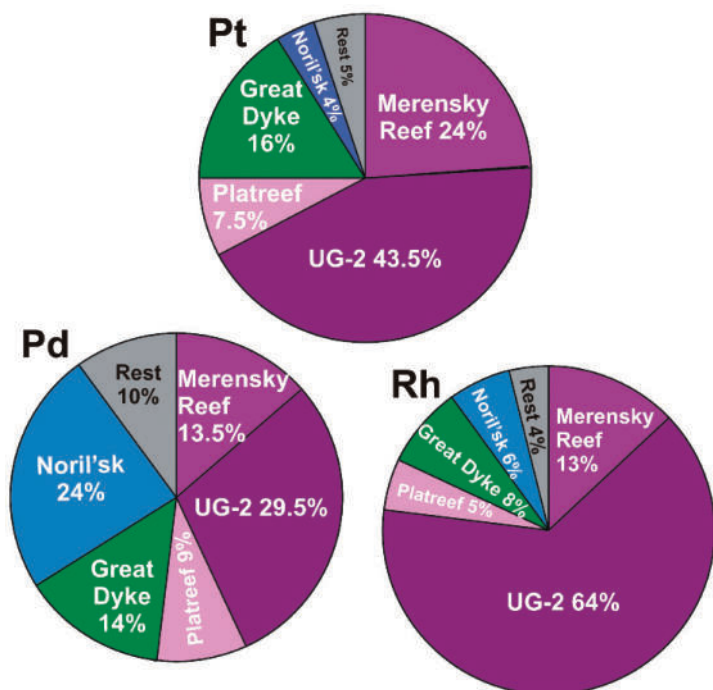
These are also stratiform accumulations of PGE and include the UG-2, UG-1, MG-3, and MG-2 chromitites of the Bushveld Complex (Scoon and Teigler 1994; FIG. 4). The UG-2 chromitite is the world's largest single accumulation of PGE (FIG. 3) and extends for nearly the entire 400 km strike length of the eastern and western limbs of the Bushveld Complex.

### Development of PGE-Rich Immiscible Sulfides Prior To or During Emplacement into Their Present Locations

This process has given rise to weak marginal accumulations of sulfide in intrusions in northern Finland, in the Kola Peninsula of Russia, and in Ontario, Canada. As is also discussed below, the Platreef and Sheba's Ridge deposits of the Bushveld Complex are likely also of this type (Kinnaird et al. 2005). Typically the mineralized zones are characterized by numerous inclusions of cognate, mafic/ultramafic xenoliths and/or country rocks.

### Delayed Separation of Sulfide during the Crystallization of a Layered Intrusion

Examples include the Rio Jacaré intrusion of Bahia, Brazil (Sá et al. 2005), and the Platinova Reef in the Skaergaard intrusion (Andersen et al. 2002). This mechanism gives rise to deposits that are relatively rich in Cu, Pt, Pd, and Au and much poorer in Ru, Ir, and Os. For example, Sá et al.'s (2005) average Pd/Ir and Cu/Ni ratios for the Rio Jacaré intrusion are 206 and 3.10, respectively, compared to 16.4 and 0.31 for the Merensky Reef (Merensky data are an average of analyses from Naldrett 2004, appendix to chapter 1). The Volkovsky deposits, which are associated with titaniferous magnetite, apatite, and Cu-sulfides in the calc-alkaline gabbros of the Urals Platinum Belt, also belong to this group, as does the Stella intrusion of South Africa (Maier et al. 2003).



**FIGURE 3** Contributions of different ore deposits to global production and reserves of Pt, Pd, and Rh

## Chromite Crystallization Without the Development of Sulfide Immiscibility

Deposits formed in this way tend to be enriched in Ru, Ir, and Os and relatively poor in Ni, Cu, Pt, Pd, and Au and are mostly found within ophiolite complexes. While examples of this association do not constitute economic in situ PGE resources, they give rise to important placer deposits in the Urals and elsewhere.

## Hydrothermal Redistribution of PGE

Examples of this type were reviewed by Wilde (2005) and include the New Rambler mine in Wyoming, U.S.A., the Waterberg deposit, Transvaal, South Africa, and the Coronation Hill deposit, Australia. The genesis of hydrothermal ores is not well understood as yet, but most appear to be the result of highly oxidized Cl-rich aqueous fluids concentrating PGE that occur dispersed in host intrusions. Depositional sites are controlled by abrupt changes in fluid pH or redox state that are caused by changes in wall-rock chemistry. Under conditions of 1.5 kb total pressure, oxygen fugacity equal to that of the Ni-NiO buffer, and 600–800°C, NaCl brines can dissolve very high concentrations of Pt. For example, Pt-saturated brines containing 20 wt% equivalent NaCl contain typically 1000–3000 ppm Pt (Hanley 2005). Pt solubility increases with increasing temperature but decreases markedly with increasing NaCl concentration, suggesting that under these conditions the main ligand is hydroxyl.

## Secondary Concentration of PGE Associated with Chromite Schlieren in Zoned Dunite-Pyroxenite Intrusions

These intrusions are commonly referred to as “Alaskan” or “Alaskan-Ural” type, and deposits include the PGE mineralization at Nizhny Tagil in the Urals. Similar deposits occur in Koryakia, northeastern Russia (Nazimova et al. 2003), and in the Kondyor intrusion within the Siberian platform. Platinum is the principal PGE that is concentrated. Some in situ mining has occurred in this environment in the Urals (Nizhny Tagil-Soleviev Hills), but the main importance lies in the major Pt-rich placer deposits that result from erosion of these intrusions.

## Hydrothermally Concentrated PGE (Principally Pt) in Black Shales, Often in Association with Au

A classic example of this type is the Sukhoi Log gold deposit in Siberia (Distler and Yudovskaya 2005). It is important to note that the concentration of Pt does not covary with that of Au at Sukhoi Log, implying that the two metals were concentrated by different mechanisms.

## PGE MINERALIZATION OF THE BUSHVELD COMPLEX

The Bushveld Igneous Complex contains by far the majority of PGE mined today (Fig. 3). The mechanism by which PGE were concentrated in the Merensky Reef has given rise to considerable debate. Hypotheses fall into two principal groups: (1) those (christened “uppers”) according to which the PGE were scavenged from the underlying cumulates by ascending, chloride-rich, aqueous fluids that had been released as anhydrous minerals segregated from trapped, intercumulus magma (Boudreau and McCallum 1992); and (2) those (christened “downers”) that maintain that the PGE were scavenged from overlying magma by settling sulfides that had segregated in response to either magma mixing (Campbell et al. 1983) or pressure change (Cawthorn 2005). These hypotheses are illustrated in FIGURE 2. Recently, Naldrett et al. (2008) pointed to marked upward decreases in PGE tenor and Pd/Cu in sulfides, which they



**FIGURE 4** Field exposure of the UG-1 chromitite in the vertical wall of the Dwars River gorge, Upper Critical Zone of the Bushveld Complex, South Africa. Chromitites in the Bushveld Complex supply a significant amount of the world’s platinum, palladium, and rhodium (UG-2; FIG. 3). The UG-1 chromitite, which is interlayered with plagioclase-rich rocks (predominantly anorthosite), is laterally extensive across the Bushveld Complex and is noted for its unusual bifurcating layers. PHOTO COURTESY OF CRAIG FINNIGAN

documented in 22 profiles across the Merensky cyclic unit; they ascribed these trends to fractional segregation and settling of sulfide from the Merensky magma.

Based on our understanding of the causes of sulfide immiscibility, chromite precipitation may well be accompanied by the segregation of immiscible sulfide. Silicate zones within the UG-2 are marked by very radiogenic Sr (Seabrook et al. 2005), indicating that the energetic introduction of fresh magma and the mixing of this magma with melted roof rocks may have caused chromite to crystallize and sulfides to segregate. However the sparsity of sulfide and the high Ni/Cu ratio of the UG-2 in comparison with the Merensky Reef have raised doubts as to whether sulfides are in fact the principal collector. Magnetite can contain excess O<sub>2</sub> at high temperature, but its composition narrows to stoichiometric Fe<sub>3</sub>O<sub>4</sub> by 900°C; it is thought that the resulting chemical potential gradient of Fe into the magnetite component of chromite is sufficient to destabilize adjacent pyrrhotite, resulting in an overall loss of Fe (and S) from the sulfide phase (Naldrett 2004). Sulfide with a composition like that of the Merensky Reef could have been the principal collector of the PGE in the UG-2 but has been lost as a result of this reaction, leaving the PGE isolated in platinum-group minerals.

The Platreef is the third main source of PGE in the Bushveld. It is a zone of pyroxenite with similarities to the pyroxenites occurring within the Bushveld Critical Zone (the zone that hosts the chromitite seams and the Merensky Reef). The Platreef forms the floor of the Bushveld along the northern limb, where it has reacted extensively with country-rock dolomites, iron formation, and shale of the Transvaal Supergroup. PGE-, Ni-, and Cu-rich sulfides occur within it, forming 40–100 m thick zones as a result of repeated injections of magma along the contact. Some of the sulfide tenors are very similar to those of the Merensky Reef, perhaps as a result of Critical Zone magma escaping up the sloping contact of the Bushveld magma chamber as fresh magma entered at depth.

In all three examples of PGE mineralization hosted by the Bushveld Intrusion, there is a distinctive association of very high PGE tenor with minor quantities of sulfide liquid in equilibrium with silicate melt, underscoring the ultimate importance of sulfide melt as a collector phase for the PGE in a variety of magmatic environments. Both the “uppers” and “downers” models require the existence of sulfide melt as the final resting place of the PGE that make up the deposits, despite differences in opinion regarding the proximal sources of the PGE. Also, in both models, the ultimate source of the PGE is the mantle source region of the mafic or ultramafic rocks hosting the deposits.

## FUTURE OUTLOOK

Future prospects for the discovery of PGE ore deposits are interesting to contemplate. Discoveries of relatively small PGE deposits in mafic and ultramafic rocks continue to be made every year; however, it is unlikely that another layered intrusion of the stupendous scale of the Bushveld Complex remains to be found. We suspect that if a future discovery of another group of deposits on a scale approach-

ing that of the Bushveld is made, it is likely to be in a setting sufficiently different from the Bushveld that such deposits have hitherto escaped serious attention; however, their origin will most likely be related to the concentration of PGE by aqueous fluids or sulfide melts derived from a very large mafic magmatic province. The extremely high prices of the PGE make it possible for ore-grade accumulations to be completely invisible to the naked eye in the absence of accessory sulfide minerals; there is therefore ample reason to think that unsuspected deposits of considerable size might remain for future discovery.

## ACKNOWLEDGMENTS

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# Environmental Relevance of the Platinum-Group Elements



Automobile exhaust is a major source of platinum-group elements in the environment.

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**Platinum-group elements (PGE) are used in an increasing number of applications, and emissions are resulting in elevated environmental concentrations of these normally rare metals. Automobile exhaust catalysts, which use Pd, Pt, and Rh as active components, are the main source of PGE emitted into urban and roadside environments, and they contribute to a global increase in PGE concentrations. Emitted PGE are found in urban air and accumulate on the road surface and in roadside soil. Transport of PGE via stormwater is resulting in contamination of aquatic environments. There is now mounting evidence that a fraction of PGE in the environment is bioavailable, and potential uptake into the biosphere is raising concern over potential risks for humans and the environment.**

**KEYWORDS:** platinum-group elements, automobile catalyst, urban environment, bioavailability, risk assessment

## INTRODUCTION

Platinum-group elements (PGE; i.e. Ir, Os, Pd, Pt, Rh, Ru) are concentrated in the Earth's core and mantle and have low natural abundances in the continental crust. Average concentrations in the upper continental crust range from 0.02 ng g<sup>-1</sup> (ppb) for Ir to 0.5 ng g<sup>-1</sup> for Pt and Pd and represent <0.01% of the Earth's PGE budget. As a result, the cycling of PGE in surface environments is limited in importance, and associated risks for humans and the environment are generally considered to be inconsequential. However, reports of increasing PGE concentrations in the environment are raising concern that this situation is changing.

Worldwide PGE production has steadily increased since the 1970s because of increasing use in applications such as automobile exhaust catalysts, industrial process catalysts, jewelry, dental implants, and electronics (Fig. 1). The subsequent release of PGE into the environment is causing a redistribution of PGE, and increasing concentrations of these elements have been reported in surface environments. It is now important to assess the potential impacts of this new contamination on humans and the environment. This review presents the current knowledge about PGE emissions, accumulation, dispersion, and impacts.

## ANTHROPOGENIC PGE EMISSIONS

PGE emissions might occur during PGE production, manufacture of PGE-containing products, and use and disposal of these products. At present, the only documented anthropogenic PGE sources are metal production (Niskavaara et al.

2004; Rodushkin et al. 2007), automobile exhaust catalysts (Artelt et al. 1999a; Moldovan et al. 2002), and medical applications (Esser and Turekian 1993; Kümmerer et al. 1999). Although additional sources of PGE to the environment may exist, they have not been characterized or reported to date.

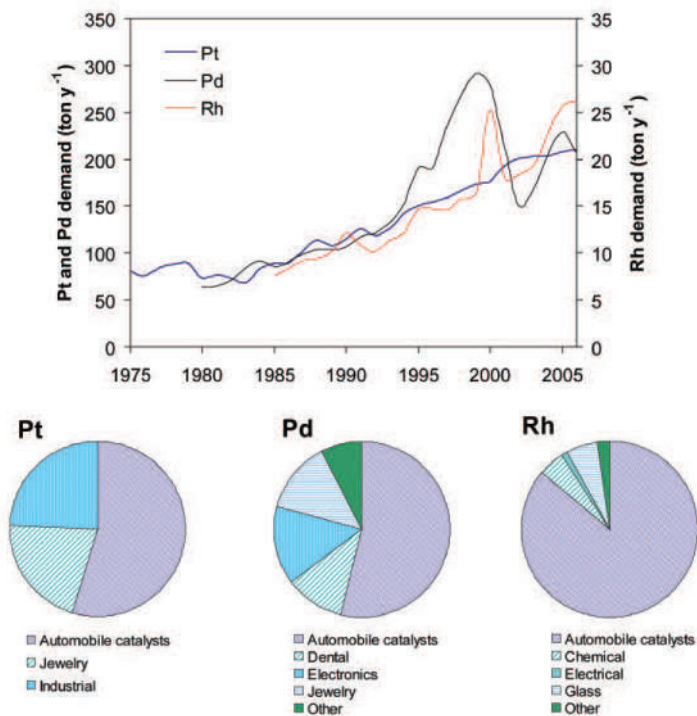
## PGE Emissions from Automobile Catalysts

Automobile catalysts are generally believed to be the main source of PGE emitted into the environment. These catalysts use Pd, Pt, and Rh to promote the removal of gaseous pollutants in vehicle exhausts, and a fraction of the PGE in catalysts is

emitted into the environment during vehicle operation (Moldovan et al. 2002). In addition, catalysts contain Os, Ir, and Ru impurities, and these metals are released into the environment alongside Pd, Pt, and Rh (Fritsche and Meisel 2004; Rauch et al. 2004a; Poirier and Garipey 2005). Direct measurements of PGE emissions from automobile catalysts provide emission estimates in the nanogram per traveled kilometer range. Emissions from gasoline catalysts are expected to be in the low nanogram per kilometer range, whereas 10–100-fold higher Pt emissions have been measured for diesel catalysts (Moldovan et al. 2002). In contrast, an emission rate of 0.8 μg km<sup>-1</sup> has been inferred from indirect measurements based on the analysis of environmental samples and traffic information (Helmert 1997). This higher emission estimate has been attributed to conditions encountered in real life, for example, engine ignition problems, that are not taken into consideration in bench tests used for direct measurements. Emission rates depend on factors like engine and catalyst types, the PGE content of the catalyst, the mileage of the catalyst, engine condition, vehicle speed, and driving conditions (Ravindra et al. 2004). A global catalyst emission of 0.8–6.0 metric tons of Pt per year can be inferred, assuming that 500 million vehicles are equipped with catalysts, that the average yearly mileage is 15,000 km per vehicle, and that the average emission rate is 0.1–0.8 μg km<sup>-1</sup> (Rauch et al. 2005).

The emission mechanism and the form of PGE in automobile exhaust are still unclear. It is generally believed that mechanical erosion of the catalyst surface is the major cause of PGE emissions, although thermal and chemical processes may also contribute. Pd, Pt, and Rh occur in particle sizes ranging from <1 μm to >63 μm (particle size defined by sampling device) in automobile exhaust and in the urban environment, supporting the idea that emission is a combination of processes such as chemical and thermal

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**FIGURE 1** Changes in total Pt, Pd, and Rh demand for 1975–2006 and distribution by sectors for 2006 (source: Johnson Matthey 2007)

aging. In addition, chemical transformation is suggested by the occurrence of soluble PGE in automobile exhaust. Whereas soluble Pt represents less than 10% of total Pt emissions, soluble Pd and Rh fractions might be greater than 50% of total emissions. The occurrence of fine PGE-containing particles and soluble PGE species in the environment raises concern about potential environmental and health risks.

### PGE Emissions from Mining and Metal Production

Metal production in northern Europe has also been reported to result in PGE emissions. Nickel smelters in the Kola Peninsula in northwestern Russia have been identified as an important regional source of Pt and Pd, based on the spatial distribution of these metals in environmental samples (Niskavaara et al. 2004). Chromium smelters in the Kemi district in Finland have been identified as a source of Os (Rodushkin et al. 2007). However, emission rates have not been determined, and data from other metal production sites are needed to assess the extent of PGE emissions resulting from metal production activities. Furthermore, emissions from PGE production activities in South Africa, the leading PGE producer, need to be determined.

### PGE Emissions from Medical Facilities

Platinum-containing drugs, including cisplatin [cis-diamminedichloroplatinum(II)] and carboplatin [diammine(1,1-cyclobutanedicarboxylato)platinum(II)], are used in the treatment of several forms of cancer. Platinum is excreted by the patients after administration of Pt-based drugs and is found in hospital effluents at concentrations ranging from  $<10 \text{ ng l}^{-1}$  (ppt) to  $3.5 \text{ } \mu\text{g l}^{-1}$  (ppb), but Pt is diluted in the municipal wastewater system, and concentrations are  $<10 \text{ ng l}^{-1}$  in sewage effluents (Kümmerer et al. 1999). Emission is expected to be in the form of soluble compounds, including administered drugs and their derivatives. Osmium is also believed to be emitted from medical facilities where it is used as a stain fixative in electron microscopy applications (Esser and Turekian 1993).

### Other Potential Anthropogenic Sources

Today PGE are used in a wide range of applications, and emissions might occur during PGE production, manufacture of PGE-containing products, and use and disposal of these products. Although emissions from PGE production and manufacture are expected to be limited or relevant to specific sites, the use and disposal of PGE-containing items are of concern because of the potential leaching of PGE. Emissions from these sources, however, have not been determined.

The contribution of natural sources, including erosion and volcanic emissions, and the potential impact of human activities on some natural sources also need to be investigated. Increased erosion resulting from agriculture or deforestation may, for instance, contribute to elevated concentrations at remote sites where no direct anthropogenic sources are present.

### PGE ACCUMULATION AND DISPERSION

PGE emissions into the environment are causing an increase in the concentrations of these normally rare metals. Most studies to date have focused on roadside and urban sites, where elevated Pd, Pt, and Rh concentrations have been attributed to automobile catalyst emissions. Typical concentration ranges are presented in FIGURE 2. Automobile catalyst emissions are also believed to be responsible for elevated Ir, Os, and Ru owing to the occurrence of these elements as impurities in catalysts (Fritsche and Meisel 2004; Rauch et al. 2004a).

Emitted PGE are found in airborne particles where they occur at the picogram per cubic meter level (Ravindra et al. 2004). The concentrations of Pt and Rh in airborne particles increased 46 and 27 fold, respectively, over a 10-year period (1988–1998) near a heavy-traffic road in Germany (Zereini et al. 2001). Particles are deposited on the road surface or roadside soil, and their concentration decreases as the distance from the road increases. During rain events, the accumulated PGE can be transported to rivers or water bodies where they accumulate in sediments, while concentrations in the water remain low. An increase in Pd, Pt, and Rh deposition was found in lake sediments in the United States, where deposition increased by factors of 15, 8, and 6, respectively, following the introduction of automobile catalysts (Rauch et al. 2004a). Further transport of sedimented PGE via resuspension might also result in the contamination of coastal environments. Input from medical facilities due to sewer overflow might be an additional source of PGE in the aquatic environment, but it is expected to be of limited importance relative to automobile catalyst input.

While the greatest occurrence is in the urban and roadside environment, a significant fraction of PGE emitted by automobile catalysts is dispersed at regional and global scales owing to their occurrence in fine particles (Rauch et al. 2005). PGE are found in particles with diameters ranging from less than  $1 \text{ } \mu\text{m}$  to over  $63 \text{ } \mu\text{m}$  (Gómez et al. 2002). Whereas relatively large particles are expected to be deposited close to their source, a significant fraction of particles containing PGE in automobile emissions has a sufficiently long atmospheric residence time to be transported over long distances (Rauch et al. 2005). Elevated PGE concentrations at remote sites support suggestions of widespread atmospheric dispersion of emitted PGE (Barbante et al. 2001; Barbante et al. 2004; Rauch et al. 2004b). Increasing PGE concentrations have been reported as far from automobile traffic as central Greenland (Barbante et al. 2001). Although recent results raise concern over the validity of reported Greenland concentrations (De Boni 2007), the possibility of widespread dispersion of PGE is also sup-

ported by increasing accumulation in Alpine glaciers (Barbante et al. 2004) and in a remote peat bog located approximately 300 m from automobile traffic (Rauch et al. 2004b). In the latter study, Pd, Pt, and Rh deposition was determined to be of almost exclusively anthropogenic origin by estimating the natural input using Os isotope composition as a proxy.

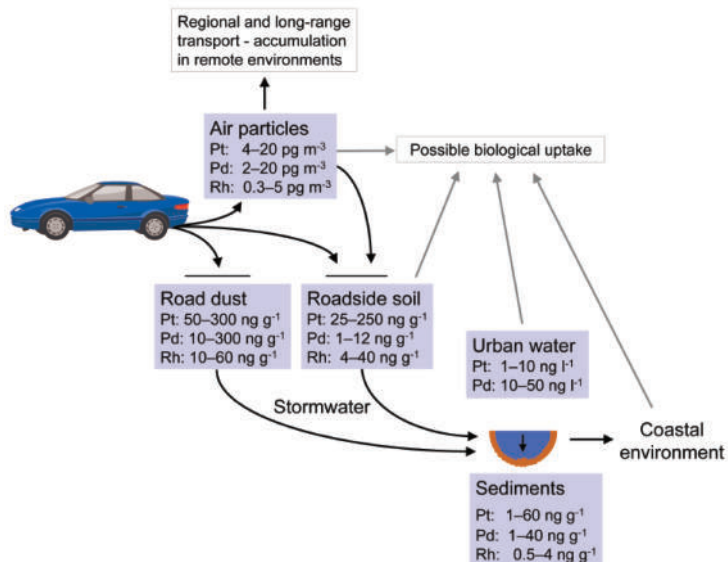
## PHYSICOCHEMICAL FORMS AND TRANSFORMATION

The chemical form of PGE in the environment depends on the form in which PGE are emitted and on subsequent transformations. In the environment, PGE are generally associated with the particle phase as a result of their emission as particles or their interaction with environmental components.

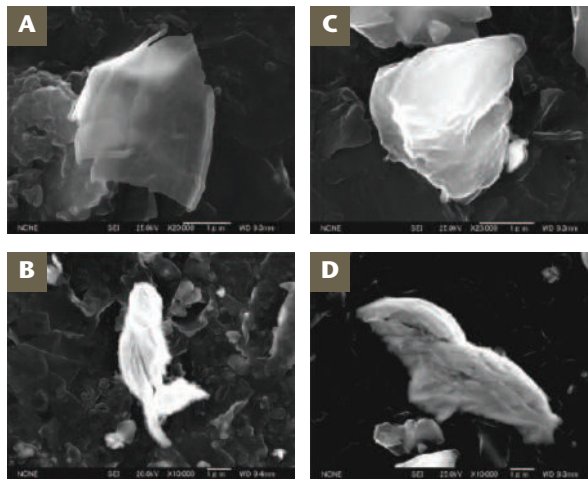
PGE are present as finely dispersed nanoparticles in catalysts and are likely to be emitted in the form of PGE nanoparticles or as PGE attached to washcoat particles of  $\gamma\text{-Al}_2\text{O}_3$ . Sintering may also result in the emission of PGE particles in the micrometer range. Subsequently different types of PGE-containing particles are expected to be found in the environment, resulting in differences in their environmental reactivity (FIG. 3). In addition, soluble PGE species have been found in automobile exhaust, although there is no clear agreement on the amount in such emissions. Moldovan et al. (2002) reported that the soluble fraction represents approximately 10% of total Pt emissions, while as much as 40% of Pd and Rh may be soluble in a weak acid solution. The remaining fraction is expected to be in metallic form. Because the soluble fraction is obtained by filtration at  $<0.45\ \mu\text{m}$ , soluble PGE may also include PGE nanoparticles. Hospital emissions are an additional source of soluble Pt emitted into the aquatic environment as a result of the excretion of platinum-based drugs and their derivatives by patients.

Particle size and especially the occurrence of PGE as nanoparticles may also play a major role in the presence and formation of soluble PGE species. As mentioned earlier, soluble PGE may include nanoparticles if the soluble fraction is determined by filtration at  $<0.45\ \mu\text{m}$ . In addition, fine particles have relatively large surface areas and offer more possibility for reactions with environmental substances. Larger particles are likely to be composed of catalyst washcoat, and PGE nanoparticles may be released under conditions that promote the dissolution of  $\gamma\text{-Al}_2\text{O}_3$ .

PGE in automobile emissions are predominantly in metallic form. Metallic PGE are usually considered to be inert and environmentally unreactive, and it may be reasoned that they cannot be oxidized. Oxide and hydroxide forms also have limited solubility. Studies on the solubility of PGE provide an unclear picture of the amount of soluble PGE compounds in the environment. Differences are likely due to the form of PGE in different environmental compartments, as well as to the presence of reaction promoters and the readsorption of soluble PGE onto solid surfaces. It is clear, however, that Pd has a higher solubility than Pt and Rh (Jarvis et al. 2001; Moldovan et al. 2001). Naturally occurring complexing agents may play an important role in the solubilization of PGE and their fate in the environment. Such complexones are widely found in many soils and freshwater systems. The presence of humic acids, as well as triphosphate, pyrophosphate, and L-methionine, increases the solubility of platinum (Lustig et al. 1998). Siderophores (organic ligands secreted by microbes and plants to extract metal nutrients from soil) also have the potential to solubilize PGE metals and oxides, thereby increasing their environmental mobility and enabling their uptake by plants (Normand and Wood 2005; Dahlheimer et al. 2007). The extraction of PGE is in



**FIGURE 2** The fate of PGE from automobile catalysts in the urban environment. Concentration ranges typically found for selected compartments (compiled from general literature data) are shown. Equivalent units:  $1\ \text{ng g}^{-1} = 1\ \text{ppb}$ ;  $1\ \text{ng l}^{-1} = 1\ \text{ppt}$



**FIGURE 3** Field-emission scanning electron microscope images of PGE-containing particles in urban air in Göteborg, Sweden. Particles **A** and **C** contain only traces of Pt, with main components being Al, Si, and C. Particles **B** and **D** are enriched in Pt and Rh, and particle **B** is also rich in C. (IMAGES A, C AND D REPRODUCED WITH PERMISSION FROM ENVIRONMENTAL SCIENCE & TECHNOLOGY 2005, 39, 8156. COPYRIGHT AMERICAN CHEMICAL SOCIETY; PHOTOS COURTESY OF M. OWARI, UNIVERSITY OF TOKYO, JAPAN)

the order  $\text{Pd} > \text{Pt} > \text{Rh}$  (Dahlheimer et al. 2007). Experiments on the interactions of PGE with humic soils indicate that Pt is subject to complex transformations in soil. Pt is oxidized and released from the particle surface by a complexing agent, leaving the surface free for further oxidation (Lustig et al. 1996). However, the formation of organic complexes may also explain the relatively low mobility of PGE in soils (Lustig et al. 1996).

Emitted PGE particles may reach aquatic environments, where they are expected to remain largely insoluble. The soluble fraction may react with particles or form complexes with inorganic or organic ligands. The input of particulate or particulate-reactive PGE to aquatic systems has been demonstrated using sediment cores (Rauch et al. 2004a). A study of the behavior of soluble PGE in river water showed that a significant fraction of PGE binds to particulate matter

(>45  $\mu\text{m}$ ). The speciation of Pt, Pd, and Rh is controlled by different mechanisms. Palladium is complexed by small hydrophobic organic ligands (<0.1  $\mu\text{m}$ ); Rh is complexed to these organic ligands, but also forms hydroxychlorides; Pt forms inorganic aqueous species, and the particle-water reactivity of Pt is controlled by electrostatic interactions (Cobelo-Garcia et al. 2008). The behavior of PGE in natural waters results in increasing solubility in estuarine mixing (Cobelo-Garcia et al. 2008).

## BIOAVAILABILITY AND TOXIC EFFECTS

The emission and increasing environmental concentrations of PGE raise concern over the potential risks for humans and the environment. Risk depends on exposure, bioavailability, and toxicity.

### *Uptake by Flora and Fauna*

Transformation of PGE and the occurrence of soluble species in the environment indicate that a fraction of PGE is in a bioavailable form. It follows that exposure to PGE may result in uptake and eventually in toxic effects.

Roadside vegetation is exposed to relatively high PGE concentrations owing to proximity to automobile traffic. Elevated PGE concentrations have been found in roadside grass (Zimmermann and Sures 2004). However, elevated concentrations are largely due to PGE deposition on the plant surface and actual uptake from soil is relatively limited, possibly due to exposure routes. Uptake from soil requires the remobilization of deposited PGE, whereas atmospheric deposition results in direct contact for adsorption. Accumulation of PGE on the plant surface is likely the result of such particle adsorption. PGE uptake from soil has also been demonstrated in laboratory experiments and may contribute to internal PGE accumulation (Zimmermann and Sures 2004). The uptake mechanism is believed to be linked to complexones (siderophores) used by plants for the extraction of metallic nutrients from soil. The highest concentrations are generally found in the roots, followed by the shoots and the leaves, indicating uptake but limited transport in the plants (Zimmermann and Sures 2004).

Aquatic organisms have been reported to take up and accumulate PGE under environmental conditions. Freshwater benthic organisms were found to contain 38.0  $\text{ng g}^{-1}$  Pt, 155  $\text{ng g}^{-1}$  Pd, and 17.9  $\text{ng g}^{-1}$  Rh. These organisms feed on sediments, and the uptake route is believed to be dietary intake and dissolution of PGE in the digestive system (Moldovan et al. 2001). Laboratory exposure (typically performed in ligand-free water using soluble compounds at high concentrations) supports the idea that PGE are present in a bioavailable form in the aquatic environment and can be taken up by aquatic fauna, including invertebrate and fish species (Zimmermann and Sures 2004).

Studies on higher organisms are scarce. Exposure of rats to model Pt-containing particles resembling automobile emissions indicate that Pt can be taken up through inhalation or intratracheal intake (Artelt et al. 1999b). A substantial fraction of Pt was found to be bioavailable as a result of *in vivo* solubility. Increased concentrations were found in the blood, urine, and feces; in organs like the liver, spleen, kidneys, stomach, and adrenal, and in the femur. Over 90% of the bioavailable Pt is bound to proteins, and the remaining fraction possibly corresponds to low-molecular-weight ionic complexes (Artelt et al. 1999b). Binding to proteins is believed to play a major role in PGE accumulation in organisms (Zimmermann and Sures 2004).

In general, Pd is found to be more bioavailable than Pt and Rh. Experimental studies also reveal that uptake and accumulation depend on the chemical speciation of PGE in the environment (Zimmermann and Sures 2004); at present, knowledge about the chemical form of PGE in the environment is very limited. Further characterization of PGE in the environment and in the biosphere is needed to understand uptake and accumulation mechanisms.

### *Human Exposure and Health Effects*

Human exposure to PGE is most likely to be through inhalation of fine PGE-containing particles, skin contact, and dietary intake. Human exposure and uptake have been investigated in studies comparing populations with different exposures to automobile traffic. Adults from a large city with dense traffic had greater urinary Pt and Rh concentrations than adults from a smaller town with relatively low traffic density, but no clear trend was found for Pd (Bocca et al. 2004). In contrast, a significant correlation between urinary Pd and Rh concentrations and traffic density was found in children, but no correlation was observed for Pt (Caroli et al. 2001). Despite some inconsistencies, these studies clearly show that human exposure, possibly through inhalation, results in the uptake of PGE, although PGE may not be transferred to organs.

Toxic effects at high concentrations reported in medical and occupational studies include sensitization, mutagenic effects in bacterial and mammalian cells, and increased tumor incidence. PGE effects have been observed in medical or occupational settings where exposure is high. However, effects have not been determined under environmental conditions as concentrations are generally considered too low for any effect to occur. While a no-effect limit concentration of 1.5  $\text{ng m}^{-3}$  has been set for exposure to Pt salts in a catalyst-manufacturing plant (Merget and Rosner 2001), airborne Pt concentrations typically do not exceed 100  $\text{pg m}^{-3}$  and only approximately 10% may be in the form of soluble salt. Available data on Pd and Rh are still insufficient to determine the likelihood of effects on human health, but effects from PGE exposure in the environment are considered unlikely (Merget and Rosner 2001). Further characterization of exposure, uptake, and effects are needed.

## CONCLUSIONS

Reports of elevated PGE concentrations and uptake by biota are raising concern over the potential risks from PGE emitted by automobile catalysts and other sources. Emissions are expected to increase in the near future owing to greater PGE loading resulting from increasingly stringent emissions regulations in developed countries and the introduction of catalysts in developing countries. New uses for PGE may also result in additional emissions. The use of Ru in consumer electronics (hard drives and plasma screens) has soared in recent years, and increased emission of this metal may also occur in the future.

Despite increasing concentrations, current environmental PGE levels remain low, and risks for humans and the environment are therefore expected to be limited. However, it is important to stress that currently available data are not sufficient for an accurate assessment of potential risks. Studies on the effects of PGE are sparse and do not generally provide environmentally relevant information; studies on chronic effects at low-exposure concentrations are insufficient at present. The physicochemical form of PGE, including the occurrence of PGE as nanoparticles, and the higher bioavailability of Pd need to be taken into consideration.



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

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# 24<sup>th</sup> International Applied Geochemistry Symposium 2009

Monday, June 1 to Thursday, June 4, 2009  
Hosted by the University of New Brunswick  
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THE 2009 BIENNIAL ASSOCIATION OF APPLIED GEOCHEMISTS (AAG) MEETING IS CONVENED BY THE INTERNATIONAL ASSOCIATION OF GEOCHEMISTRY (IAGC) AND THE INTERNATIONAL ASSOCIATION OF GEOANALYSTS (IAG) AND WILL INCLUDE THE NORTH ATLANTIC MINERALS SYMPOSIUM (NAMS).

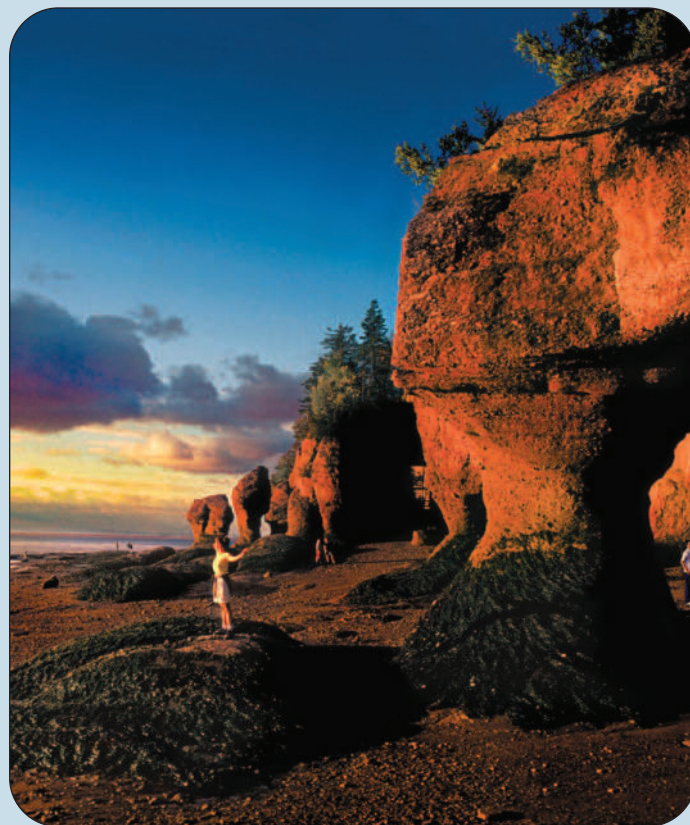


The meeting will be preceded by 5 different professional-development workshops, which will be held on Sunday, May 31. There will also be 3 premeeting field trips (Wednesday, May 27 to Saturday, May 30) and 4 postmeeting field trips (Friday, June 5 to Monday, June 8). These trips will run throughout the Maritimes (Atlantic Canada) and each will leave from and return to Fredericton.

All sessions will consist of 15-minute presentations, with 5 minutes between presentations for questions and moving between rooms. Keynote and guest presentations (35 minutes each) will be featured at each half-day session. Tuesday afternoon will be reserved for poster presenters, who will have the opportunity to give 5-minute oral presentations (4 slides) to introduce their poster; Beth McClenaghan (GSC) has kindly agreed to host this very special session.

We will be producing an extended - abstracts volume, in which authors will be allowed 2 to 4 pages in *GEEA* format. Both the abstract volume and the accompanying CD will be included in the normal registration package. The final deadline for submitting extended abstracts is **February 15, 2009**.

This IAGS 2009 meeting is jointly organized by geoscientists from the University of New Brunswick (UNB), the New Brunswick Department of Natural Resources, the New Brunswick Research and Productivity Council, the New Brunswick Department of the Environment, and professionals drawn from the consulting engineering and mineral exploration industry in New Brunswick, in conjunction with a professional conference organizer (PCO) from UNB.



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## DON'T PANIC! HOW NOT TO WRITE YOUR THESIS IN ONE WEEK



Nicholas S. Wigginton

I think there comes a point during every PhD student's graduate career when they feel overwhelming panic about writing their thesis. Whether that moment comes during the first week of classes or in the last year of research, it can be paralyzing and debilitating, and result in abnormal behavior, even for a graduate student.

My first experience of this kind occurred during a geochemical thermodynamics course taught by Prof. Don Rimstidt at Virginia Tech. As usual, my mind had drifted away while Don waxed ecstatic about Eh-pH diagrams. Like a typical delusional PhD student, I was daydreaming about the glory of papers, conferences, and talks, without even having written so much as my name on my thesis yet. I eventually started thinking to myself: writing this up might require a smidgen of actual effort. In fact, writing might actually be just as hard as—if not *harder* than—the lab work itself! Panic hit me like it does a freshman geology student with a rock hammer at his first outcrop: how on Earth was I going to write my thesis? My eyes widened and I nervously fidgeted in my seat, rocking my head from side to side. Unfortunately for me and the rest of the class, Don interpreted my awkward behavior as me being exasperated with the material. So upon my "request," he decided to spend the next 20 minutes discussing the merits of a logarithmic scale when plotting activity coefficients. Needless to say, that wasn't what I was looking for at that moment.

For most students, the realization that writing may not be as easy or as straightforward as originally planned is a difficult pill to swallow. Oftentimes, writing takes much, much longer than originally anticipated. The reason is simple: writing at a high level is extremely difficult. On top of that, most graduate curriculums do not emphasize technical writing at all, so we have to learn how to write as we go. Unfortunately, many students don't realize this fact until it's too late.

But do not fear geochemists and mineralogists of tomorrow! There is hope! You can avoid becoming one of the many horror stories everyone has heard about. After all, nobody *wants* to become engrained in lab folklore for staying up for 72 hours straight, surviving only on coffee and jelly beans, to finish the last chapter of their thesis. Of course that isn't to say there won't be a few late nights on your computer with deadlines looming fast, but the thesis-writing process can be easier, less stressful, and more educational if you start preparing early.

So how does one actually prepare for such a task early? Well, for me, the best piece of advice I received was from a thesis committee member. He told me to start writing as early as possible, as often as possible. It's almost a guarantee that your best writing won't happen under the pressure of finding a job, wrapping up experiments, and preparing your defense presentation. To avoid writing everything at the end, it makes sense to do little tasks along the way. For example, write the methods section(s) of your thesis as soon as the work is done. One student told me that one of her methods sections was completely written by her second year. It doesn't seem like much at the time, but even a little step like that goes a long way towards easing the pressure at the end.

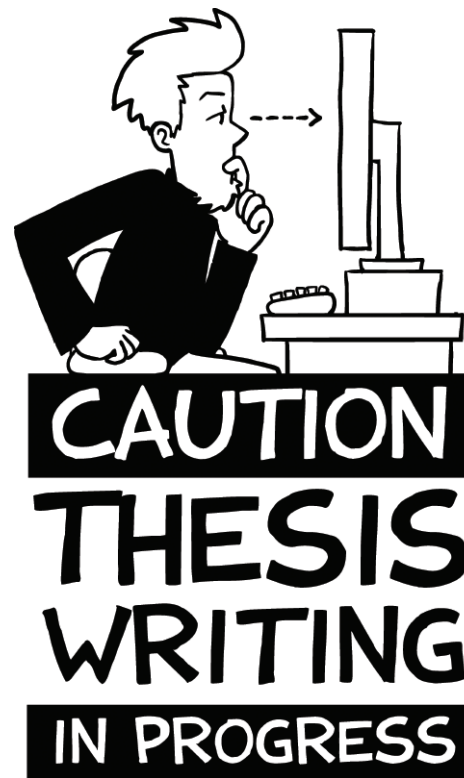
But everyone's PhD experience is a little different—among countries, universities, departments, and even within one's research group—and some of you might not have the luxury to write very much material early. Therefore it doesn't make sense for just one person (i.e. me) to give advice. To help provide additional insight, I asked a few other recent geochemistry PhD grads to share the best piece of advice they received during their writing process. Here are their helpful responses:

Kelly Johnson (PhD 2006, Notre Dame), now a geochemist at USGS in Menlo Park, California, says, "*If your university is very particular about formatting, use an old thesis as a template. That way you aren't wasting a lot of time fighting with word processing software and the auto-format shenanigans. However, if you are going to do that you should double/triple check to make sure you don't leave any of the old text in the middle of your thesis.*" I hope that last part isn't from personal experience!

Deric Learman (PhD 2008, Virginia Tech), now a postdoc at Harvard University, warns that "*thesis writing (and approval) involves bureaucracy. Just like science, make a schedule but be prepared to have your schedule changed for unforeseeable reasons.*" So don't get too stressed out over circumstances that you cannot control.

Kate Tufano (PhD 2008, Stanford University), now a geochemist working with Tetra Tech-MM in Fort Collins, Colorado, advises that "*if you're going around in circles and can't seem to get anything down on paper, write conversational style then go back and 'science-it-up.'* Once you have an idea on the page, at least you have something to work with." Good advice for getting a lot of thoughts on paper quickly.

Frannie Skomurski (PhD 2007, University of Michigan), now a postdoc at Pacific Northwest National Laboratory in Richland, West Virginia, suggests, "*Make a big pot of tea, sit down, and write. It has to get done one way or another, so just block out the time and get it done, but try to make it kind of pleasant for yourself.*" I wish I was bet-



"PLED HIGHER AND DEEPER" BY JORGE CHAM  
WWW.PHDCOMICS.COM

ter about doing this. I found many excuses to check e-mails or wander around the halls instead of actually writing. Don't procrastinate!

So there you have it. No matter how daunting a task it may seem, or how overwhelmed you may feel, you can get through writing your thesis. You might not be able to avoid the initial panic, but you'll be better prepared to overcome it fast. In the end, you'll not only be proud of your work, but you'll have a lot less stress when graduating and be a better writer because of it.

**Nicholas Wigginton\***

#### NOTE FROM THE MANAGING EDITOR

When I took a writing class, I was surprised to discover that the teacher treated writing very much like exercising: we did warm-up exercises — short periods of writing — before we got to the main writing period of the class, and it worked. I also recommend the following books: *A Manual for Writers of Research Papers, Theses, and Dissertations* (7<sup>th</sup> Edition) by Kate L. Turabian, published by the University of Chicago Press, and *A Writer's Coach*, by Jack Hart (Anchor Books).

\* Nicholas Wigginton completed his PhD in geochemistry from Virginia Tech in April 2008. He is now a postdoctoral researcher at École Polytechnique Fédérale de Lausanne, Switzerland.



<http://geoanalyst.org>

## International Association of Geoanalysts

### GGR SUBMISSION BECOMES FULLY ONLINE



Ed Williams

*Geostandards and Geoanalytical Research*, in conjunction with its publisher Wiley-Blackwell, has now introduced online submission for all scientific articles through Manuscript Central. Several benefits are anticipated, from both the author's and journal's point of view. Authors now have a simple and rapid system available to upload electronic versions of their articles. This centralised point for the submission and the sophisticated capability for the management of articles will simplify their administration, leading to

shorter peer-review times and more timely publication of the latest results in both online and print formats. Authors will also have the opportunity to monitor their submission(s) by visiting their 'author centre' within Manuscript Central; the centre will be accessible following initial registration with the system. Further details can be found on the *Geostandards and Geoanalytical Research* Synergy homepage at <http://www.blackwellpublishing.com/ggr>. Manuscript Central for the journal can be accessed directly at <http://mc.manuscriptcentral.com/ggr>.

**Ed Williams**  
Managing Editor, *GGR*

### IAG GOVERNING COUNCIL

In the October 2007 issue of *Elements*, we introduced half of the members of the IAG's Governing Council. In this issue, we introduce the remaining members. As always, we encourage all analytical geochemists, whether IAG members or not, to contact any member of Council if they have any questions or suggestions, or if they wish to become more active in our society.



#### JENNIFER COOK (JMC@BGS.AC.UK)

Honorary Secretary of IAG since its creation in 1997, Jennifer is the manager of the ICP laboratories at the British Geological Survey and quality manager for the ISO 17025 accreditation of the Survey's geochemistry laboratories. Her main interests are the development of methods for the analysis of geological and environmental materials

by ICP spectrometry, proficiency testing and laboratory accreditation. She is the author of an annual review on the analysis of geological samples by atomic spectrometric techniques published in the *Journal of Analytical Atomic Spectrometry*.



#### CHRIS JACKSON (CRJ2508@NTLWORLD.COM)

Honorary Treasurer of IAG since its creation in 1997, Chris is a member of the Royal Society of Chemistry and has managed mining chemistry laboratories for Anglo American and Rio Tinto. He is currently a consultant working for clients worldwide concerned with laboratory design and procurement, quality assurance and staff

training. He has over 35 years of experience in analytical chemistry.



#### KLAUS PETER JOCHUM (KPJ@MPCH-MAINZ.MPG.DE)

Member of IAG since 2006; member of the IAG Council since 2006; member of the Editorial Board of *GGR* since 1997; member of the IAG Certification Committee since 2005. Klaus Peter is a physicist and geochemist with a special interest in mantle geochemistry and cosmochemistry, but he now focuses his research on environmental geochemistry using LA-ICP-MS. He is the leader of the ICP-MS group of the Max-Planck-Institut für Chemie in Mainz, Germany, and is the lead coordinator of the GeoReM database for geological and environmental reference materials. He is active in the development and certification of reference materials for in situ microanalytical techniques.



#### PHIL POTTS (P.J.POTTS@OPEN.AC.UK)

Member of IAG and IAG Council since 1997; President of IAG from 2000 to 2006; Editor-in-Chief (joint) of *GGR/Geostandards Newsletter* since 1995; member of the IAG Certification Committee since its creation in 2002. Since 2004, Phil has been Dean and Director of Studies of the Faculty of Science at the Open University (Milton Keynes, UK). His main research interests are the development of techniques for the chemical analysis of rocks and minerals and the characterisation of geochemical reference materials. He has worked on developing portable X-ray fluorescence instrumentation and its application to environmental contamination and archaeological provenancing issues.



#### PETER WEBB (P.C.WEBB@OPEN.AC.UK)

Member of IAG since 2007; member of Council since 2007; member of the Steering Committee of GeoPT, the IAG's proficiency testing programme for geoanalytical laboratories, since its inception, and coordinator of GeoPT since 2004. Peter is a geologist who has been involved in geochemical, mineralogical and geoanalytical research at the Open University (UK) since 1977. He set up and has managed the XRF laboratory at the OU and has developed systems for ED-, WD- and portable-XRF analysis. His research has also involved the geothermal potential of radiothermal granites, hydrothermal alteration and mineralization and, more recently, the non-destructive analysis and provenancing of archaeological artifacts. He has been involved in the production of geoanalytical proficiency testing materials for the GeoPT programme since 1994.



#### MICHAEL WIEDENBECK (MICHAWI@GFZ-POTSDAM.DE)

Member of IAG since 2000; member of IAG Council since 2002; President of IAG since 2006; member of the Editorial Board of *GGR* since 2004; member of the IAG Certification Committee since its creation in 2002. Since 1998, Michael has managed the SIMS laboratory at the GeoForschungsZentrum Potsdam, Germany. His main interests are the development of new reference materials and improved analytical techniques for in situ geochemical analyses. His recent research has investigated the influence of atomic structure on the calibration of microanalytical methods.



#### STEPHEN WILSON (SWILSON@USGS.GOV)

Member of IAG since 2000; member of IAG Council since 2007; member of IAG's Certification Committee since 2002; member of the Editorial Board of *GGR* since 2001. Since 1985, Stephen has served as coordinator of the U.S. Geological Survey's reference materials project. His responsibilities include the distribution of historical USGS materials as well as the development of new materials required by the scientific community. He serves as liaison with other scientific organizations needing USGS assistance in the development of quality control and reference materials. His current interests focus on the development of a new generation of reference materials with application to the micro-analysis of geological, industrial and biological samples.

Cont'd on page 267



<http://simp.dst.unipi.it>

## Italian Society of Mineralogy and Petrology

### 2007 SIMP PRIZES FOR PhD STUDENTS

Every year SIMP awards prizes for the best PhD dissertations by young researchers who have completed their doctorate. The winners for 2007 were Nadia Malaspina (University of Milano) and Federica Schiavi (University of Pavia).



#### NADIA MALASPINA

*Ultrahigh Pressure Metamorphism and Metasomatism in Mafic-Ultramafic Rocks from Eastern China: Implications for Fluid Release and Volatile Transfer at Subduction Zones.* This PhD thesis focused on crust-to-mantle element transfer in subduction zones. Garnet orthopyroxenes from Maowu (China) were derived from a LILE-enriched hydrous melt that reacted with garnet peridotite at ultrahigh pressures. New orthopyroxene and garnet accommodate some LREE, while H<sub>2</sub>O and LILE partition into a residual fluid phase trapped in the garnet, forming polyphase inclusions. The experimental homogenization and geochemical analyses of these inclusions indicate that this aqueous fluid may transfer its LILE-enriched signature to the mantle wedge.



#### FEDERICA SCHIAVI

*Geochemical Study of Melt Inclusions and Ashes from the Recent Activity of Stromboli and Etna Volcanoes: Inferences for Magma Origin and Evolution.* For her PhD thesis, Federica Schiavi characterized, by means of geochemical and isotopic (Li, B, Pb) microanalytical investigations, volcanic ashes and melt inclusions hosted in olivine and clinopyroxene phenocrysts recovered from tephra and lava samples erupted from Stromboli and Etna. A melt-inclusion study provided constraints on the nature of the mantle sources and, in particular, on the subduction-related metasomatic processes affecting the mantle wedge beneath Stromboli. The investigation of ashes provided information on the degassing-induced crystallization processes and magma dynamics occurring within the shallow plumbing systems.

### HP-HT MINERAL PHYSICS: IMPLICATION FOR GEOSCIENCES – BRESSANONE, 11–15 FEBRUARY 2008

On February 11–15, 2008, at Bressanone-Brixen (Italy), the Italian Mineralogical Group (GNM) held an International Mineralogical School entitled “HP-HT Mineral Physics: Implication for Geosciences.” About sixty participants from countries all over the world attended the school. Theoretical and practical lectures covered the principal aspects of mineral physics under high-pressure and high-temperature conditions. The school was sponsored by institutions, academies and corporations from several countries, which provided ten grants for young scientists.

The school focused on mineral physics and its role in understanding and interpreting geological and geophysical observations. Modern experimental techniques now allow the determination of physical-chemical parameters that were previously extremely difficult to obtain. Their evolution as a function of pressure and temperature can now be defined with great detail, allowing the construction of an accurate model of the Earth's system. Moreover, computational calculations now represent a valid counterpart to the experimental approach, and not only help to go beyond the limits of experimental techniques but provide a theoretical validation of the experimental results. At the school, a number of modern techniques for collecting physical parameters on geological materials over a large pressure and temperature range using both experimental and computational methods were presented. It was also shown how the data obtained by means of such methods are used to understand phase equilibria and to predict phase relationships under different P–T gradients and, in turn, to formulate geodynamical models at large scales (e.g. subduction and exhumation processes).

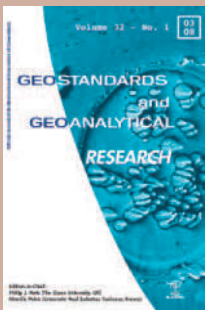


In addition to several theoretical lessons, three afternoons were dedicated to practical sessions. The lecturers were among the major international experts in their fields and were always available at the school, where they spent many enjoyable moments with the students.

Thanks to the success of the school, we proposed that a “Special Issue of the School” containing papers presented by the students and teachers be published. Our proposal was enthusiastically accepted by the management of the *European Journal of Mineralogy*. We, as guest editors (together with Ross J. Angel), are collecting manuscripts until the end of September with the expectation to publish the issue at the beginning of 2009.

**Paola Comodi** (University of Perugia, Italy)  
**Fabrizio Nestola** (University of Padova, Italy)

IAG (cont'd from page 266)



*Geostandards and Geoanalytical Research* is the official journal of the International Association of Geoanalysts. Since January 2007, *GGR* has been published by Wiley-Blackwell Publishers in collaboration with the IAG. Here are some key achievements from the first 12 months of this new collaboration:

Legacy files available for the period 1977–2007: 697  
Research articles published in 2007: 37  
Member of Wiley-Blackwell Earth Pages,  
total visits in 2007: >55,000  
Impact factor in 2007: 2.049





[www.iagc.ca](http://www.iagc.ca)

## International Association of GeoChemistry

### SERVING THE GEOCHEMISTRY COMMUNITY WORLDWIDE



The mission of the International Association of GeoChemistry (IAGC) is to foster international cooperation that leads to scientific advancement in the broad field of geochemistry. This remains as much a challenge today as it was when IAGC was formed 40 years ago. This objective is accomplished through a variety of means, for example, sponsoring scientific conferences and educational activities, establishing internal specialty-area working groups, and disseminating new geochemical knowledge through scientific publishing. IAGC is probably best

known through publication, since 1986, of the monthly geochemical journal *Applied Geochemistry*. During most of its history, IAGC has functioned primarily through its working groups, which are affiliations of geochemists interested in a particular area of geochemistry. IAGC has several long-established working groups: Applied Isotope Geochemistry (Chair: Jodie Miller, University of Stellenbosch, South Africa), Geochemical Training in Developing Countries (U. Aswathanarayana, Mahadevan International Centre for Water Resources Management, India), Global Geochemical Baselines (David B. Smith, USGS, USA), Geochemistry of the Earth's Surface (Sigurdur Gislason, University of Iceland, Iceland), Thermodynamics of Natural Processes (German Kolinin, Russian Academy of Sciences, Russia), and Water-Rock Interaction (Halldor Armansson, Iceland). In 2007, the IAGC Council accepted a membership petition to admit a seventh working group, Urban Geochemistry, which will be chaired by Rolf Tore Ottesen and Morten Jartun of the Geological Survey of Norway. The periodic conferences of the Applied Isotope Geochemistry, Geochemistry of the Earth's Surface, and Water-Rock Interaction working groups are premier international meetings.

During the past eighteen months, IAGC has embarked on several new initiatives to more fully address its international mission. An awards program was begun in 2006, with the first set of awards conferred at the 2007 Goldschmidt Conference in Cologne, Germany. Fred Mackenzie of the University of Hawai'i was the recipient of the Vernadsky Medal, which is awarded for a distinguished record of scientific accomplishment in geochemistry over the course of a career. Seifu Kebede of the University of Addis Ababa and Dana Royer of Wesleyan University shared the Ebelmen Award, which recognizes a geochemist of particular merit and outstanding promise who is less than 35 years of age. Keara Moore, Brenda Ekwurzel, Bradley Esser, Bryant Hudson, and Jean Moran were the recipients of the Hitchon Award for the most significant paper published in *Applied Geochemistry* during the previous two years. A new IAGC Fellow Award will be implemented in 2008 to recognize outstanding scientists who, over the course of some years, have made significant contributions in the field of geochemistry, with particular emphasis on applied geochemistry. In addition, the Faure Award is bestowed at IAGC-sponsored conferences for the best student paper/poster presentation. Finally, perhaps the most important new IAGC initiative is the Student Research Grant program (see accompanying article).

IAGC is also interested in working cooperatively with its "sister" geochemistry societies. IAGC has sponsored sessions at the annual GS-EAG Goldschmidt Conference for a number of years and advertises the conferences of other geochemical societies in the IAGC Newsletter and on its website. Next year, IAGC will partner with the Association of Applied Geochemists to organize and conduct the 24<sup>th</sup> International Applied Geochemistry Symposium, which will be held on the campus of the University of New Brunswick in Fredericton, New Brunswick, Canada, from 1 to 4 June 2009. This conference is the world's premier forum for exchange of ideas on a broad range of issues related to the use of geochemistry in the mineral resources industry and is an increasingly important meeting for geochemists working in environmental geochemistry. Conference information is available on the website [www.unb.ca/conferences/IAGS2009](http://www.unb.ca/conferences/IAGS2009) (see also advertisement on page 264).

**Russell Harmon**  
Interim President, IAGC



### IAGC STUDENT GRANTS

In order to recognize and promote the work of young scientists in the field of geochemistry, the International Association of GeoChemistry initiated a Student Research Grant program in 2007. The objective is to assist PhD students in geochemistry worldwide to undertake and acquire geochemical analyses as part of their dissertation research. This award consists of a grant of up to \$3000 (US), a certificate, a complimentary membership to IAGC for the year following receipt of the award, and an article profiling the recipient in the IAGC Newsletter and posted on the IAGC website. Up to three grants will be awarded each year. The deadline for applications is **15 October**. Additional information and application forms are available at the IAGC website [www.iagc.ca](http://www.iagc.ca).

The Student Research Grant Committee (R. Harmon, chair; E. Galimov, K. Notsu, and A. Parker) has completed its review of the 11 applications received for 2008 and is pleased to announce the recipients:

**Bryn Kimball** – an award of \$3000 for "Copper Isotope Fractionation During Sulfide Mineral Dissolution," Pennsylvania State University, supervisor: Prof. S. Brantley

**Ibrahim Barrie** – an award of \$1000 for "Tectono-thermal Evolution of the Sierra Leone Passive Continental Margin: Constraints from Thermochronology," University of Amsterdam, supervisor: Prof. P. Andriessen

**Alejandro Villalobos-Aragón** – an award of \$1000 for "Using Chromium Stable Isotopes to Monitor Reactive Transport of Chromium in Leon, Gto., Mexico," University of Texas at El Paso, supervisor: Dr. A.S. Ellis

**Lindsay MacKenzie** – an award of \$1000 for "Sedimentology and Geochemistry of the Chengjiang Formation, China," University of Montana, supervisor: Dr. N. Hinman

We wish the grantees successful research work that will significantly contribute to the field of geochemistry!

**Clemens Reimann**  
Vice President, IAGC

Cont'd on page 271



www.sfmc-fr.org

## Société Française de Minéralogie et de Cristallographie

### 2008–2010 SFMC BOARD ELECTION RESULTS

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The Society thanks outgoing councilors Pierre Barbey, Olivier Grasset, Jean-Louis Hazemann, Gérard Panczer, Gian Carlo Parodi and Jacques Roux for four years of dedicated service.



Patrick Cordier  
SFMC President



Anne Marie Karpoff  
Vice-President



Christian Chopin  
Second Vice-President

### The European Journal of Mineralogy on GEOSCIENCEWORLD

The *European Journal of Mineralogy*, the journal of SFMC (France), DMG (Germany), SIMP (Italy) and SEM (Spain), joined GeoScienceWorld and can be accessed at

<http://eurjmin.geoscienceworld.org>



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

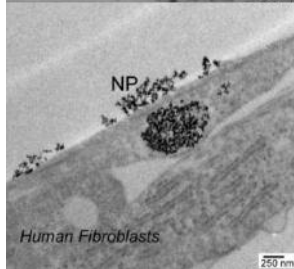
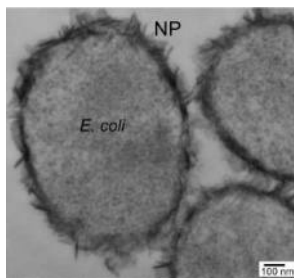
### PRIX HAÛY-LACROIX 2008

The Prix Haüy-Lacroix recognizes a young scientist for the quality of his or her PhD research in the fields of mineralogy, petrology, geochemistry, or materials science. This year it was awarded to Mélanie Auffan, on 10 June 2008 during the SFMC 2008 general assembly in Paris.



Mélanie Auffan obtained her PhD from the Paul Cézanne University at the CEREGE (Aix-en-Provence) with a thesis entitled "Metal Oxide Nanoparticles: Relations between Surface Reactivity and Biological Effects." Jean-Yves Bottero and Jérôme Rose were her advisors. A summary of her work follows.

Nanotechnology as a branch of engineering deals with producing objects approximately 1–100 nm in size. Activities spawned by nanomaterials will affect the social, economic, and environmental dimensions in ways that are unanticipated. Along with the benefits provided by nanomaterials (e.g. medical sciences and environmental protection), there are potential adverse effects that need to be considered. The high level of production fueled by growing markets for products incorporating these materials will inevitably lead to their appearance in air, water, soils, and organisms. It would be naïve to imagine that this emerging industry will not leave unforeseen traces in our environment. Research is needed to ensure that this industry evolves in a context of environmental sustainability and not as an environmental liability.



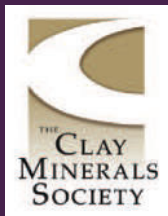
TEM photomicrographs of human dermal cells internalizing nano-CeO<sub>2</sub> and nano-Fe<sup>0</sup> adsorbed on the membrane of *Escherichia coli*

Nanoparticles (NP) cannot be considered as typical chemical compounds or particles. They have a high surface/volume ratio: more than ~35% of the atoms are localized at the surface of a 6 nm NP. This high ratio generates unique extrinsic (large specific surface area) and intrinsic (strong surface reactivity) properties for very small NP. NP smaller than 20 nm are able to react differently than bulk materials. For instance, iron oxide particles between 300 and 20 nm in size adsorb similar amounts of arsenic per unit of surface area (~6 mmol/m<sup>2</sup>), suggesting similar adsorption mechanisms. But the adsorption capacity of NP smaller than 20 nm increases drastically: 11 nm iron oxide NP adsorb 3 times more As per unit area (~18 mmol/m<sup>2</sup>) than do 20 nm iron oxide particles (e.g. Yean et al., *J. Matter Res.* 2005). These results highlight different adsorption mechanisms at the surface of very small NP and a true nano-size effect. For the first time, we have related this enhanced adsorption to a significant decrease of the surface free energy and to size-dependent change of

the crystalline structure of the surface. For instance, as the size decreases, the occupancy of the tetrahedral site of  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> decreases, leaving vacant highly reactive sites at the surface, which are available to adsorb As. For larger  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> particles, all tetrahedral sites are occupied, which decreases the number of possible adsorption sites. This structural change allows the adsorption of a large amount of As at the surface and induces a significant decrease of the surface energy. Hence, whereas in macroscopic systems adsorption is mainly governed by chemical affinity and electrostatic strength, for NP smaller than 20 nm, the decrease of the surface free energy is a supplementary driving force.

Below a critical size, it is not possible to simply scale the physicochemical, thermodynamic, and toxicological data for bulk materials and thus predict the biological activity of NP. A number of studies have suggested that some NP can cause adverse biological effects. But a serious lack of characterization of the NP tested makes it difficult to identify which key characteristics determine the hazard documented in nanotoxicological

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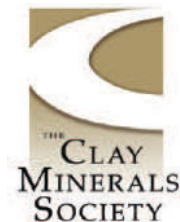


[www.clays.org](http://www.clays.org)

## The Clay Minerals Society

### PRESIDENT'S CORNER

In the last *Elements* issue, I mentioned that the CMS membership had evolved from a US majority to an international majority. The Clay Minerals Society is changing, and we have to be cognizant of where our membership is and where our future lies. We welcome our international members and value their opinion. Our next president, Scotland's Derek Bain, will lead us boldly into this new era. To highlight this transformation, we have taken another step that recognizes the changed CMS.



#### The all-new CMS logo

The new CMS logo that you see here is our way of expressing our newness. This logo represents the efforts of many dedicated souls and is the product of much discussion. The work was done beautifully by Mr. Timothy Phillips, a graphics designer at the University of Cincinnati. To some the logo appears as a C and represents the clays and their mysteries that we spend time pondering, while to others it

conjures a more future-related context. Some have said that it looks like a road—I like this image as it conveys continuously changing scenery and a journey. Whatever it conveys to you, we hope you enjoy The Clay Minerals Society. We look forward to seeing you in 2009 at the annual meeting in Montana, U.S.A.

**Andrew Thomas**

President, The Clay Minerals Society  
Chevron Energy Technology Company, Houston, Texas  
[andrew.thomas@chevron.com](mailto:andrew.thomas@chevron.com)

### ELECTRONIC COMMUNICATION

CMS is making progress in the areas of electronic communication and online conduct of its business. We'd like to encourage feedback about what works and what doesn't, and we welcome suggestions for improvement. The electronic ballot introduced this year produced a higher-than-expected return of votes, and it will soon be possible to conduct all of the business related to membership and purchase of publications directly online. A major overhaul of the website is in the works. The chief goal of revision is to improve navigation from the home page to linked pages and other sites. We would

like CMS members to send us a list of the tasks they most often try to accomplish when visiting the website. We plan to modify the site to make the most frequently visited sections easier to reach from the home page. Are there other topics or areas of interest that you would like to have added to the primary navigation buttons? Any opinion regarding items that make our site useful to non-members would also be appreciated. Send your comments via e-mail to [rferrell@lsu.edu](mailto:rferrell@lsu.edu). If you are impressed by another society website, send us the URL so that the committee may study its organization scheme. Thanks.

### BENTONITES

A proposal by The Clay Minerals Society for a thematic issue of *Elements* devoted to bentonites has been accepted by the journal's editorial board, and this issue is scheduled to be published in February 2009. Of all naturally occurring clays, bentonites are arguably the most interesting and versatile. Articles will cover the nature and occurrence of bentonites, geological aspects, exploration, mining, production, medical applications, environmental applications, chemically modified bentonites, and nanocomposites. The authors include Malek Bouazza, Richard Brown, Katie Carrado, George Christidis, Jock Churchman, Don Eisenhour, Ray Ferrell, Will Gates, Necip Güven, Shelley Haydel, Warren Huff, Peter Komadel, and Lynda Williams, with Derek Bain acting as guest editor. There should be something of interest to all readers of *Elements*!

### JOURNAL SCRIPTS

The following are some papers that have been accepted for publication in future issues of *Clays and Clay Minerals*:

- H.-R. WENK, M. VOLTOLINI, M. MAZUREK, L.R. VAN LOON, AND A. VINSOT – Preferred orientations and anisotropy in shales: Callovo-Oxfordian shale (France) and Opalinus clay (Switzerland)
- ALI GÜREL AND SELAHATTIN KADIR – Geology and mineralogy of Late Miocene clayey sediments in the southeastern part of the central Anatolian volcanic province, Turkey
- ALAIN DECARREAU, SABINE PETIT, FRANÇOIS MARTIN, FRANÇOIS FARGES, PHILIPPE VIEILLARD, AND EMMANUEL JOUSSEIN – Hydrothermal synthesis between 75 and 150°C of high-charge ferric nontronites
- STEPHAN KAUFHOLD, REINER DOHRMANN, DIETRICH KOCH, AND GEORG HOUBEN – The pH of aqueous bentonite suspensions
- MARIA DOLORES RUIZ CRUZ – Na-bearing white micas from Triassic rocks of the transition between Maláguide and Alpujarride Complexes (Betic Cordillera, Spain)
- DOUGLAS K. MCCARTY, BORIS A. SAKHAROV, AND VICTOR A. DRITS – Early clay diagenesis in Gulf Coast sediments: new insights from XRD profile modeling
- CELIA MAQUEDA, AGUA SANTAS ROMERO, ESMERALDA MORILLO, JOSÉ L. PÉREZ-RODRÍGUEZ, ANTON LERF, AND FRIEDRICH ERNST WAGNER – The behavior of iron in ground and acid-treated vermiculite from Santa Olalla
- MIGUEL ÁNGEL MARTÍN AND CARLOS GARCÍA-GUTIÉRREZ – Log self-similarity of continuous soil particle size distributions estimated using random multiplicative cascades



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

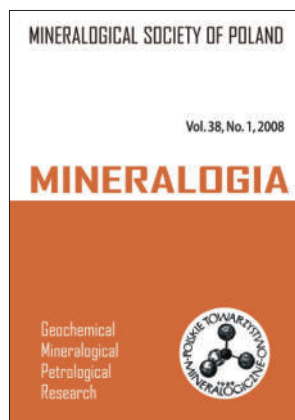




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## Mineralogical Society of Poland

### MINERALOGIA POLONICA JOURNAL CHANGES ITS TITLE AND COVER



*Mineralogia Polonica*, the official journal of the Mineralogical Society of Poland, was founded in 1970. Two issues have been printed every year to date. *Mineralogia Polonica*, publishing in English from its beginning, has been very important for the development of mineralogical science in Poland. Based on a long discussion with our foreign contributors and other colleagues from abroad, we have concluded that the title suggests that the journal is focused on local mineralogical problems in Poland. To avoid this misunderstanding, we decided to modify the title and, accordingly, the journal cover. The new and simple title *Mineralogia* (with subtitle *Geochemical, Mineralogical, and Petrological Research*) indicates the open character of the journal. Our intention is to publish original papers, review papers, and short notes from the broad fields of geochemistry; mineralogy; petrology; technical, experimental and applied mineralogy; and environmental geochemistry and mineralogy. We also decided to introduce changes in the review and preparation of papers to ensure a high scientific level and a relatively short time span between paper submission and publication (electronic and paper versions). The regular series *Mineralogia* will be accompanied by the irregular one (*Mineralogia – Special Papers*), containing conference abstracts.

*Mineralogical, and Petrological Research*) indicates the open character of the journal. Our intention is to publish original papers, review papers, and short notes from the broad fields of geochemistry; mineralogy; petrology; technical, experimental and applied mineralogy; and environmental geochemistry and mineralogy. We also decided to introduce changes in the review and preparation of papers to ensure a high scientific level and a relatively short time span between paper submission and publication (electronic and paper versions). The regular series *Mineralogia* will be accompanied by the irregular one (*Mineralogia – Special Papers*), containing conference abstracts.

It is our deep conviction that the journal published by our scientific society should be accessible freely to the whole scientific community. Similarly to the former *Mineralogia Polonica*, all full-text papers in the new journal will be accessible via the society website (www.ptmin.agh.edu.pl), Direct Open Access Journals (www.doaj.org), Metapress (www.metapress.com), and via the *Mineralogia* webpage (www.mineralogia.pl).

We invite you to publish your papers in *Mineralogia*, and we hope you will like the experience.

**Marek Michalik**

President of the Mineralogical Society of Poland

### 4<sup>th</sup> MID-EUROPEAN CLAY CONFERENCE MECC'08

Zakopane, Poland  
22–27 September 2008  
www.mecc08.agh.edu.pl  
e-mail:mecc08@agh.edu.pl

IAGC (cont'd from page 268)

### Special Offer for IAGC Members: 10 Years of the Kola Project



In 1998, the Geological Survey of Norway (NGU) published the now-classic *Environmental Geochemical Atlas of the Central Barents Region* or, in short, *The Kola Atlas*. The atlas presents the results of an international (Finland–Norway–Russia) multimedia (terrestrial moss, topsoil and the O-, B- and C-horizon of podzol profiles), multi-element (more than 60 chemical elements, radioisotopes and other parameters), geochemical mapping project, covering 188,000 km<sup>2</sup> in the European Arctic. IAGC members who do not yet have the atlas in their library can now get it free of charge, provided they pay the postage (the book weighs 2.5 kg). The official sales price of the book is 450 NOK, about US\$90. The NGU still sells about one copy every three months or so but wants to reduce the stock substantially. Orders should be sent to Clemens.Reimann@ngu.no.

### START-UP MEETING FOR EUROPEAN-SCALE GEOCHEMICAL MAPPING PROJECT

The EuroGeoSurveys Geochemistry Working Group met in Berlin, March 5–7, 2008. At this meeting the GEMAS Project (Geochemical Mapping of Agricultural Land and Grazing Land Soils of Europe) was officially started. Thirty-four European geological survey organizations have agreed to collect samples of arable land (ploughing layer, 0–20 cm) and of land under permanent grass cover (0–10 cm) at a density of 1 site per 2500 km<sup>2</sup> in their territory. The total area covered will be about 5.8 million km<sup>2</sup>. The project is a continuation and extension of the Baltic Soil Survey, which resulted in a very successful geochemical atlas. The project is led by Clemens Reimann, IAGC Vice-President. The European metals industry, represented by EuroMetaux of Brussels, will support this project with a contribution of 130,000 Euros per year, over a four-year period.

**Clemens Reimann**

SFMC (cont'd from page 269)

### PRIX HAÛY-LACROIX 2008



Mélanie Auffan receiving the Prix Haüy-Lacroix 2008 from Patrick Cordier, SFMC President

studies. Our goal was to develop appropriate methods to assess the safety of NP. Using a standardized bio-physicochemical approach controlling the properties of NP all along their interactions with biological targets, it is possible to compare toxicological data and to identify mechanisms of toxicity. We propose a classification of the potential toxicity of metallic NP related to a redox sensitivity that predisposes them to induce an oxidative stress towards biological targets.

Indeed, chemically stable metallic NP in physiological redox conditions do not exhibit any cytotoxicity in our experimental conditions, whereas metallic NP with strong oxidative (e.g. CeO<sub>2</sub>) or reductive (e.g. Fe<sup>0</sup> or Fe<sub>3</sub>O<sub>4</sub>) power appear cytotoxic for *Escherichia coli* and genotoxic for human fibroblasts. The main source of toxicity is the electronic and/or ionic transfers during oxidation (e.g. Fe<sup>2+</sup> and/or Fe<sup>0</sup>) or reduction reactions (e.g. Ce<sup>4+</sup>, Mn<sup>3+</sup>, Co<sup>3+</sup>) either within the NP lattice or on release to solution. These results raise many questions concerning the toxicity of nanometric crystallites. While this redox activity may be desirable for several applications (e.g. catalysis, sensors), we have pointed out that this same trait can also have negative implications in an environmental context.



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## Geochemical Society

### FROM THE PRESIDENT

#### *The Present and Future of the Goldschmidt Conference*



The 2008 Goldschmidt Conference in Vancouver, Canada, is now history. With a scientific program of exceptional breadth and high quality, a large number of registrants, and exciting social events, this conference was one of the best ever and continued the long-term systematic growth in size and scope of the North American and European Goldschmidt Conferences. This growth is gratifying. The success of each meeting is due in large part to the dedication

and hard work of a group of scientists who put the meeting together. The continued growth and impact of the Goldschmidt Conference is also a reflection of both its international impact and the vitality of the field of geochemistry. Innovative science is present in every session. Meeting participants realize that the key colleagues in their field are more likely than not to be present. The emphasis on student involvement always keeps the energy level high. A number of exhibitors find this meeting a great way to communicate with leaders in the field of geochemistry. Our ventures to meeting sites in Australia and Japan have yielded a positive impact in the form of increased scientific contributions to the meeting from these nations. The North American conference is also profiting from a new memorandum of understanding with the Mineralogical Society of America that recognizes MSA as an official sponsor. Overall, both the present and the future of the Goldschmidt Conference look bright.

With the growing success of the Goldschmidt Conference come some challenges. The increasing size is one of these. The number of participants and space requirements for oral and poster sessions, the space needed for exhibitors, and the realities of feeding and housing so many participants make the meeting a tight fit for the university campuses at which many of the previous meetings have been held. The complexity of the meetings means that, although we have had extremely competent and experienced commercial help in many aspects of the planning process, the workload of the local organizing committee is still very high. We also face a situation in which a new group of volunteers organizes each meeting. We suffer from a lack of continuity between meetings, so we tend to solve many of the same problems each time. For these reasons, the Geochemical Society is now considering giving an expanded role to a professional meeting organizer. Having a professional organizer would relieve the local committee of dealing with many of the non-science meeting details and allow more focus on the program. Part of this meeting-planning role might be to help select a suitable venue and deal with many of the on-site logistical details. Because the Goldschmidt Conference is such a key function of our Society, I intend to make easing the meeting-planning burdens on scientists one of the focuses of my presidency. If you have your own ideas as to how we can better plan future Goldschmidt Conferences, please let us know by sending your suggestions to our business manager, Seth Davis, at [seth.davis@geochemsoc.org](mailto:seth.davis@geochemsoc.org).

**Marty Goldhaber**  
President

### NOTES FROM ST. LOUIS

#### *Goldschmidt 2008*

Congratulations to Dominique Weis and her dedicated staff at the University of British Columbia and to Cambridge Publications for a great conference. Look for highlights from the 2008 Vancouver Goldschmidt in the December issue of *Elements*.

#### *Goldschmidt 2009*



June 21–26, 2009 – Davos, Switzerland  
[www.goldschmidt2009.org/](http://www.goldschmidt2009.org/)

Organizers: Chris Ballentine (University of Manchester),  
Philippe van Cappellen (Utrecht University), Janet Hering (EAWAG)

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#### *GS at the 2008 Joint Meeting*

October 5–9 2008  
– Houston, Texas, USA  
[www.acsmeetings.org/2008/](http://www.acsmeetings.org/2008/)

#### *GS Exhibit*

Booth 956, next to MSA and MAC

#### *GS Events*

MSA/GS Joint Reception  
Tickets will be available at the door.  
2008 F. Earl Ingerson Lecture  
presented by Dr. John Morse  
(see inset, page 273)

#### *GS (co)sponsored sessions*

T119 – The Science of Oil Shale –  
Chairs: Alicia Sanchez, John  
Kaszuba

T122 – Soil Geochemistry:  
Databases and Applications at  
Regional to Continental Scales  
– Chairs: David B. Smith, Andrew  
Rencz, Juan Carlos Salinas (Orals  
& Posters)

T123 – Real-Time, In-Field  
Geochemical Analysis: Current  
Capabilities and Future Prospects  
(Posters) – Chairs: Nancy J.  
McMillan, Russel S. Harmon,  
April L. Ulery

T124 – Roles of Speciation and  
Molecular Structure in Soil  
Processes – Chairs: Owen  
Duckworth, Alan T. Stone

T127 – Geochemical Tracers of  
Changes in Seawater Chemistry  
– Chairs: E. Troy Rasbury, Franco  
Marcantonio

T130 – Opportunities at the  
Interface: Minerals, Bugs, and  
Aqueous Solutions – Chairs:  
Maria Dittrich, Andreas Lutttge

#### *Call for 2009 Award Nominations*

Once again it is time to ask for nominations for the Goldschmidt Medal, Clarke Medal, Patterson Medal, Treibs Medal, and GS/EAG Geochemical Fellows Awards. **November 15, 2008** is the deadline for nominations for these awards. For information on nomination requirements, visit the Geochemical Society website at [www.geochemsoc.org/awards](http://www.geochemsoc.org/awards). Please take the time to highlight the accomplishments of your valued friends and colleagues by nominating them. With your help, we can ensure that all of geochemistry is recognized and all deserving geochemists are considered.

**The V.M. Goldschmidt Medal** is awarded for major achievements in geochemistry or cosmochemistry, consisting of either a single outstanding contribution or a series of publications that have had great influence on the field.

**The F.W. Clarke Medal** is awarded to an early-career scientist for a single outstanding contribution to geochemistry or cosmochemistry, published either as a single paper or a series of papers on a single topic.

**The C.C. Patterson Medal** is awarded for a recent innovative breakthrough in environmental geochemistry of fundamental significance, published in a peer-reviewed journal.

**The Alfred Treibs Medal** is awarded by the Organic Geochemistry Division for major achievements, over a period of years, in organic geochemistry.

**The GS/EAG Geochemical Fellows Award** is bestowed upon outstanding scientists who have, over some years, made a major contribution to the field of geochemistry.

**Time to Renew?**

It is not too early to start thinking about renewing your membership for 2009. Go ahead and get it out of the way by renewing online at [www.geochemsoc.org](http://www.geochemsoc.org). And remember, if you enjoy *Elements*, your conference discounts, and/or your publication discounts, please encourage your students or colleagues to join and to help make a difference in geochemistry globally.

**How Are We Doing?**

As always, we at GS want to hear from you about our programs and services. Send comments and/or suggestions to Seth Davis at the contact information below.

**Seth Davis**  
GS Business Manager  
([seth.davis@geochemsoc.org](mailto:seth.davis@geochemsoc.org))

**2008 F. EARL INGERSON LECTURE**



**Session T130 - 2008 Joint Meeting in Houston, TX**

Nanoscale Insights into the Mechanisms Responsible for the Strange Kinetics and Solubility Behavior of Aragonite in Seawater

Dr. John Morse (Texas A&M University)  
PHOTO COURTESY TEXAS A&M

For close to 50 years the precipitation kinetics and solubility behavior of aragonite in seawater have been observed to be unusual. Examples include precipitation on ooids where "resting periods" are needed between periods of growth, "kinetic solubilities," aragonite mud porewaters and inner Great Bahama Bank waters all yielding an IAP about twice the thermodynamic solubility of aragonite, and the observation that for experimental time periods less than months the apparent equilibrium IAP is strongly time dependent. This behavior clearly points to complex reaction processes occurring on and near the aragonite-seawater interface.

In this study, single aragonite crystals were exposed to seawater for time periods ranging from hours to months. The morphologies of the surface precipitates were studied using SEM and the overgrowths were analyzed using a variety of TEM techniques, which provided very detailed information on growth patterns, structure, and composition. For normal seawater (~4x supersaturated), the initial precipitate consisted of widely scattered submicron individual spherulitic crystals. With time their density increased to multiple layers composed of submicron crystals. After ten days, and increasingly to 50 days, compact fibrous arrays of crystals started to appear, which probably were composed of aragonite. TEM studies of the early-formed material indicated that it had an amorphous calcium carbonate near-surface region about 80 nm in thickness underlain by aragonite that was crystallographically contiguous with the host aragonite crystal. Both contained Mg, which was absent from the substrate. These observations demonstrate the complexity of the reactions taking place between aragonite and supersaturated seawater.

**THANK YOU VOLUNTEERS!**

What we do at GS day after day to impact the direction of geochemistry at a global level is only possible through the herculean efforts of our volunteers. Thank you!

Johnson Haas and Carla Koretsky of Western Michigan University have decided to step down from the helm of *Geochemical News* after eight years of service. Their perennial talent and dedication to the Society is greatly appreciated.

\* Indicates the committee chair.  
Terms ending this year are in blue.

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**GOLDSCHMIDT2008**

Many people put in hours upon hours of work to make this year's meeting in Vancouver a success.

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## Mineralogical Society of Great Britain and Ireland

### THE UK'S SCIENCE COUNCIL



Sir Tom McKillop

As an umbrella organisation, the Science Council's membership is a wide collection of different bodies representing chemistry, biology, physics, mathematics, Earth science, psychology and many other professional groups. We need to bring all of these groups together around common issues and deliver a much more coherent, aligned presentation of our interests to government and others, with the aim of enhancing the status of science and scientists. Our role in the Science Council is very much to make the sum of the parts more effective in representing what science can do; so having that breadth of membership is absolutely vital.

We certainly have some big issues to face. How do we make science more relevant to society? How do we pull in youngsters and get them excited about science? And how can we ensure that the professional standing of scientists and the credibility of science are maintained? In that context, building the importance of the chartered scientist is pivotal.

There are many organisations in the science world, some of which are very closely affiliated with a particular discipline or community, such as mathematics, engineering, or physics, for example. Knowing just who should be doing what and who can be most effective is an issue of discussion, and it will often be best for the specialist organisation, such as the Royal Society of Chemistry or the Institute of Physics, to speak about or lead on a topic. The Science Council is definitely not going to usurp the role of its individual member bodies. But we can help them and those wishing to consult the science community by bringing together the appropriate groupings on a topic, by spreading the net broadly across science, and by helping to evaluate the issues and provide advice or guidance that is broadly based and consensual. In my view, it is multi-disciplinarity that lies at the heart of the Science Council and is the key to our potential roles. We must also get much more effective in aligning all of our interests and agreeing what we should be saying to government or to society on any particular matter.

We have spent recent months sorting out the mechanics of the organisation to ensure we have effective governance and accountability in the Science Council, something that is very important to get right in an umbrella body. We are now moving on to an agenda which is much more about the presentation of science to society and particularly to youngsters. One of our key programmes is *Careers from Science*, a project that includes a website for young people showing the wide range of exciting careers open to those who have studied science and mathematics at A level. We are also developing our special interest groups in health and sustainability to enable us to consider these issues from a truly multi-disciplinary perspective. And we are building our representative role working with government and others to ensure that we have the right levels of investment and support for science and scientists so that science can really make a difference to people's lives.

It is a great honour to have been elected President of the Science Council. I am enjoying the role and look forward to contributing whatever I can to advance the role of science and scientists in society.

**Sir Tom McKillop**  
President of the UK Science Council

### BURSARY REPORT



First, I would like to thank the Mineralogical Society for supporting my attendance at the AGU Fall Meeting 2007. I was very pleased to have the opportunity to present my poster at the largest international gathering of geophysical researchers in the world. But I was also happy to represent a community of mineral scientists who seek answers to the major questions about the Earth's deep interior.

I really enjoyed attending the meeting because I learned much about the most recent scientific advances and the most innovative research projects in geophysics, in its widest sense. Furthermore, it provided me with an excellent forum in which to present my results and draw the community's attention to my work in mineral-physics simulations, which is particularly relevant to seismologists.

My research is focused on the implementation of force-field simulations in order to understand structural, elastic and transport properties of mantle-related perovskites, for which extreme conditions are difficult to achieve experimentally. This could provide seismologists with new ideas and more information about the physical properties of these minerals and their influence on the amplitude attenuation of seismic waves when they travel through the lower mantle.

This meeting also allowed me to share different opinions about my project and gave me the opportunity to interact with other researchers in the same field, including the leading players in the mineral-physics community.

I also had the chance to get involved in different activities in the Education and Careers section, where I met other research students from other countries and interacted with representatives of organisations where I could pursue my career interests in geophysics, particularly in rock and mineral physics, in the near future.

**Liliana Goncalves-Ferreira**

Department of Earth Sciences, University of Cambridge, UK

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## Landmark Papers

### Metamorphic Petrology

} NUMBER

The key benefit in the Landmark series is the commentaries by guest editors.

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

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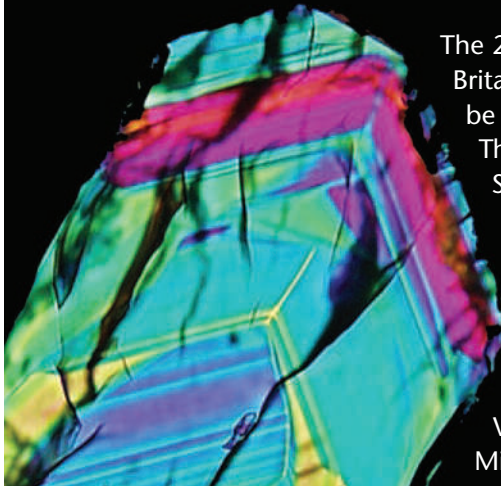
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## MAPT MEETING • AUGUST/SEPTEMBER 2009



The 2009 Annual Meeting of the Mineralogical Society of Great Britain and Ireland, 'Micro-Analysis, Processes, Time' (MAPT) will be held at Edinburgh University from Sunday, 30 August to Thursday, 4 September 2009. The lead convenor is Professor Simon Harley, chair of the Metamorphic Studies Group of the Mineralogical and Geological Societies. Other international and national bodies which are co-convening or contributing to the meeting and its workshops include the Société Française de Minéralogie et de Cristallographie, the Deutsche Mineralogische Gesellschaft, the International Association of Geoanalysts, and the Geochemistry and Volcanic and Magmatic studies Groups, also of the Mineralogical and Geological Societies.

**M**icro-analytical information is now central to many new observations in the Earth sciences, and it is critical to the testing and development of hypotheses related to Earth processes and behaviour on all time and length scales. In the last ten years, new developments in instrumentation have led to considerable improvement in very high spatial resolution micro-analysis in the mineralogical-geological sciences. For example, stable and radiogenic isotopes can now be determined by ion microprobe (SIMS), laser ICP-MS, electron backscatter diffraction (EBSD), SEM, and controlled ion thinning accomplished with the TEM. The new methods, in concert with longer-established techniques (e.g. electron microprobe analysis, petrographic analysis using optical microscopy, cathodoluminescence imaging and backscattered imaging) enable more-detailed and higher-resolution chemical and textural observations to be made in situ. These in turn provide more powerful and stringent tests of models of Earth's behaviour.

MAPT will provide a forum for the presentation and discussion of the many recent advances in micro-analytical techniques. The meeting will focus also on how these advances impact on our under-

standing of mineralogical-geochemical processes, their timescales of development, and the consequences for the measurement of time in the Earth sciences. MAPT will address the current development of new micro-analytical instrumentation and techniques as well as the new information and ideas that are arising from application of these techniques and older techniques of microscopic observation and analysis. We will welcome symposia and sessions and contributions on the nature of geological materials, the microscopic analysis of those materials, and the application to deciphering geological processes and the timing of those processes. MAPT will welcome and promote sessions that bridge the sub-disciplines by focussing on, for example, mineral behaviour in super-critical fluids or the applications of mineralogy in waste management and containment.

A list of suggested sessions is given below. MAPT will welcome both oral presentations and posters to these sessions, and will also welcome proposals for other sessions within the broad theme of the meeting. Please contact Simon Harley ([simon.harley@ed.ac.uk](mailto:simon.harley@ed.ac.uk)) if you are interested in any of these, or if you would care to offer a session for consideration.

### Suggested Sessions

- The deep Earth and mantle processes: Experiments and implications
- Mineral physics and experimental petrology at high pressure: A window into the deep Earth
- Formation, growth and differentiation of the continental crust: Insights from accessory minerals and isotopes
- High-precision (low-uncertainty) geochronology: Ar-Ar and U-Pb and their implications for the geological record
- LA-ICP-MS isotopic and trace element analysis: Techniques and applications to solid Earth studies
- Advances in the application of accessory mineral analysis to understanding crustal processes
- Polymetamorphism, orogenic belts, and thermal modelling from P-T-time records
- Deep subduction and exhumation of continental and oceanic crust
- General metamorphic petrology
- Light-element isotopes: Analysis and applications to mass fluxes in the Earth
- Frontiers in microanalysis and microtextures as applied to magmatic processes
- Fingerprinting exhumation: Advances in thermochronology and sediment provenance analysis
- New advances and applications in electron microscopic techniques
- EBSD, microstructural analysis and grain-scale processes: Insights and frontiers
- New advances in transmission electron microscopy characterisation and preparation of minerals
- Mineral microstructures: Their implications and applications
- Micromechanical properties of minerals: Applications in the Earth and construction sciences
- Environmental mineralogy: From science to solutions
- Mineralogy and global waste problems: Nuclear waste disposal and carbon capture
- Environmental mineralogy of mineral deposits
- New advances in mineral deposit geology and genesis

Please check the conference website for information:

[www.minersoc.org/  
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## Mineralogical Society of America

### PRESIDENT'S LETTER

#### Farewell to a Master of New Minerals



Pete Dunn

1984 seems like a long time ago. It was the year the first Apple Macintosh was sold. *Terms of Endearment* won the Academy Award for best picture. The Soviet Union boycotted the Summer Olympics in Los Angeles. And Ronald Reagan beat Walter Mondale by a landslide. 1984 also started a 23-year mineralogical streak that came to an unexpected close in December 2007. Dr. Pete Dunn, museum specialist at the National Museum of Natural History, announced his retirement as the United States' voting member on the International Mineralogical Association's Commission on New Minerals, Nomenclature, and Classification (CNMNC).

To appreciate the extent of this achievement, you may need some background information. The CNMNC is universally recognized as the final arbiter for issues involving mineral taxonomy; it was founded in 1959 with "the purpose of controlling the introduction of new minerals and mineral names, and of rationalizing mineral nomenclature." Worldwide, the communities of professional researchers and amateur collectors have come to rely on the expertise of this group to bring order to our mineralogical vocabulary. The workload is heavy and never ending. Every month, each member receives a mailing of between five and eight proposals to review, and the documentation in each package is daunting.

The work of the CNMNC flies under the radar screen of many MSA members for two reasons. The first involves the status of mineral nomenclature as a science in the United States. The *American Mineralogist* has carried a regular section entitled "New Mineral Names" since 1917, and until the 1990s, U.S. authors contributed routinely to this effort. Over the past 15 years, however, the declining American participation in the identification of new minerals has been steep and unambiguous. Nevertheless, it is an activity that continues to thrive outside the United States. Second, Pete Dunn performed his duties so ably and steadfastly that the challenges were resolved with little fuss or fanfare. His extraordinary aptitude for this work should not be surprising. Pete himself has identified more new minerals than any other person; to date he has published over 133 new minerals, representing ~3% of all those known.

We are lucky that Dr. Anthony Kampf, curator at the Natural History Museum of Los Angeles County, has agreed to succeed Pete. Tony has a long and distinguished history with IMA, and he has authored many publications on new minerals. We all wish Pete a long and happy retirement, with sincere thanks for his enduring service to MSA and the field of mineralogy.

Peter J. Heaney

### NOTES FROM CHANTILLY

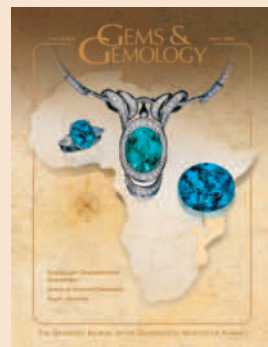
- Regular member dues were last increased in 2004 by \$5 to \$55, but this was offset by a \$5 discount for early renewal. Because of the considerable time lapse since that increase, MSA Council voted at its 2008 Spring Meeting to increase regular member dues in 2009 by \$10 to \$65. Members who renew online before October 31, 2008, will receive a \$5 dues discount; the discount reflects cost savings for online renewal. Student dues remain at \$10 because they were raised to that level only last year. Sustaining membership will remain at \$150 + regular dues.

Domestic and foreign member subscription rates to *American Mineralogist* will continue to be different in 2009 to reflect actual costs of mailing and in order to shift a portion of first-copy costs from institutional subscribers to individual subscribers, as was begun last year. The U.S. member subscription price (paper and electronic) will be \$70 (currently \$60), and foreign member subscription price will be \$80 (currently \$70). Member electronic-only subscription will remain at \$30. The U.S. institutional subscription price (paper and electronic) will be raised to \$825 (from \$775), and foreign institutional subscription will be raised to \$850 (from \$800). Included with the institutional subscription are all the current-year issues of *Reviews in Mineralogy and Geochemistry* and *Elements*, as well as access to the electronic journal on the MSA website.

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

- MSA 2009 membership renewals will start by October when membership renewal notices will be sent electronically. This will be followed by electronic reminders, and then a paper copy will be sent to those who do not renew online by the end of October.

- If you subscribe to other journals through MSA (*Journal of Petrology*, *Physics and Chemistry of Minerals*, *Mineralogical Record*, or *Rocks & Minerals*), please renew early. MSA needs to forward your renewal to these publishers before your subscription runs out.



- MSA will offer another journal to its members at a reduced rate on the renewals: *Gems & Gemology*. This is the quarterly journal of GIA (The Gemological Institute of America), which presents up-to-date technical information about diamonds and colored stones—where they are found, their special characteristics, simulants and synthetics, treatments, and identification techniques.

J. Alex Speer

[j\\_a\\_speer@minsocam.org](mailto:j_a_speer@minsocam.org)

### IN MEMORIAM

EDWARD J. MARCIN

(Life Fellow – 1947)

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Many members contribute to MSA each year by including a contribution with their dues. Depending on the wishes of the member, the money is deposited with the principal of the MSA Endowment, MSA Mineralogy/Petrology, MSA Outreach, Edward H. Kraus Crystallographic Research, or Bloss Funds. The income from these four funds supports MSA's research grants in crystallography, mineralogy, and petrology; publishing the *American Mineralogist*; the American Mineralogist Undergraduate Awards; the Mineralogical Society of America Award; the Distinguished Public Service Award, the Dana Medal, the Roebling Medal; the website, and the lectureship program.

Between June 1, 2007 and May 24, 2008, 609 MSA members and organizations contributed \$78,829.36 to MSA Funds: Endowment (\$28,073), Kraus (\$2321), Mineralogy/Petrology (\$8441), Outreach (\$5086), Bloss (\$32,427), Sustaining (\$2455), and *American Mineralogist* (\$25). If you have not done so previously, you might want to consider contributing at the next opportunity. Here we want to extend our gratitude to the following individuals and organizations:

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## Mineralogical Association of Canada

### INTRODUCING NEW VP AND COUNCILORS

#### Vice-President Iain M. Samson



Iain Samson graduated from the University of Strathclyde with a BSc in applied geology in 1979 and a PhD in 1983. He then became a research associate with the Mineral Exploration Research Institute at McGill University in Montreal. In 1986 he joined the Department of Geology at the University of Windsor where he is now a full professor in the Department of Earth and Environmental Sciences. From 1998 to 2003 he was chair of the department. Dr. Samson's research interests revolve

around the geochemistry and mineralogy of hydrothermal systems and the origin of hydrothermal mineral deposits. He uses a variety of approaches to understanding such systems, including mineral chemistry, isotope geochemistry, fluid inclusion studies, and thermodynamic modeling. He is also interested in improving analytical techniques for minerals and fluid inclusions, including laser ablation ICP-MS and Raman spectroscopy. His research has involved a variety of system types, including sediment-hosted base-metal mineralization; magmatic-hydrothermal W, Mo, Cu, and rare-element deposits; and disseminated PGE mineralization. He has also been involved in studies of diagenetic fluids. Dr. Samson was MAC's finance chair, served on its Council and Executive for 9 years from 1998 until 2007, and previously chaired the Hawley Medal committee. During this period, he was the lead organizer and editor for MAC short course 32 on fluid inclusions. He was formerly the short course coordinator for the Mineral Deposits Division of GAC.

#### Councillors 2008–2011

**DANIELLE FORTIN** has been a professor in the Department of Earth Sciences at the University of Ottawa since 1997. Dr. Fortin did her graduate studies in Quebec City where she obtained her BSc and MSc degrees at Laval University and her PhD in aqueous geochemistry at INRS-EETE (Université du Québec). Prior to joining the University of Ottawa, Dr. Fortin was a postdoctoral fellow in the Department of Microbiology at the University of Guelph and in the Department of



Geology at the University of Toronto. Her field of research is environmental geomicrobiology. Her ongoing research focuses on the microbial diversity of various groups of bacteria present in extreme environments (mine tailings, deep-sea vents, cold environments, etc.) and on the role of bacteria in the formation of biogenic nanominerals. She is also interested in using biogenic minerals as potential biosignatures in the search for past and present life on Earth and other planetary bodies. Dr. Fortin is an associate editor of *Applied Geochemistry* and *Geochemical Journal* and has coedited several special issues on bacteria-mineral interactions in various peer-reviewed journals. She is also a regular panel member of the NASA exobiology program.



**DAVID PATTISON** is a professor in the Department of Geoscience at the University of Calgary. He received his BSc from Queen's University, Kingston, Ontario, and his PhD from Edinburgh University, Scotland. He undertook postdoctoral work at the University of Chicago before arriving at the University of Calgary in 1987. His research interests are primarily in the field of metamorphic petrology. Specific areas include metapelitic phase equilibria, geothermobarometry, granulites, metamorphosed ore deposits, petrogenesis of accessory phases used for geochronology, and application of metamorphic petrology to tectonics. He is in charge of the microprobe lab at the University of Calgary.

### YOUNG SCIENTIST MEDALIST



Every year, the Mineralogical Association of Canada presents its Young Scientist Medal to an individual who has, in the early stages of his or her career, distinguished themselves as a researcher. The medalist for 2007 was Dr. Laurence Coogan, of the University of Victoria. As he could not attend last year's ceremony, we were glad to have the opportunity to recognize Dr. Coogan's achievements during the award presentations at the 2008 Goldschmidt Conference.



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## "LASER ABLATION ICP-MS IN THE EARTH SCIENCES" SHORT COURSE FOLLOWING GOLDSCHMIDT 2008

One can always depend on enjoying five stimulating days of geochemistry at the annual Goldschmidt Conference, but for some enthusiasts even five days is not enough! Following this summer's Goldschmidt Conference, held in a sunny Vancouver, British Columbia, Canada, eighty professional and student geochemists from nineteen countries stayed on for two additional days (19–20 July) to immerse themselves in the world of laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). There, sixteen of us who have been toiling at this method for years, some since the early 1990s, presented a short course sponsored by the Mineralogical Association of Canada, with generous financial contributions from Agilent Technologies and Varian Canada, and flawless logistical assistance from the local Goldschmidt organizing committee at the University of British Columbia. In some ways the course was an updated version of a similar one given seven years ago in conjunction with an annual meeting of the Geological Association of Canada–Mineralogical Association of Canada held in St. John's, Newfoundland and Labrador; many of the same lecturers participated in both courses, for instance. But in other ways this was a brand new course, focusing on technical issues and geological applications that have come to the fore only in the last few years.

Those familiar with LA-ICP-MS know it as a powerful technique capable of providing micron-scale analyses of trace-element concentrations and isotopic ratios in minerals, melt inclusions, fluid inclusions, corals, and other objects of geological interest. They also know that it can be both utterly frustrating and completely rewarding all in the span of one afternoon's work. Frustrating because when the instrument is not set up just right, results can be not only incorrect but incorrect in unexpected ways. On the other hand, when the system is operating properly, large amounts of very useful data can be collected to solve geological problems that could not be addressed nearly as easily using other analytical tools. And therein lies the reason why so much energy has been spent by so many creative people to understand how best to set up an LA-ICP-MS lab and to carry out effective analytical sessions. The Vancouver short course aimed to pass on this knowledge as efficiently as possible in two intensive days of lectures and discussions. Numerous topics were described and debated, including reviews of basic instrumentation and principles, as well as new technologies such as ultrafast (femtosecond) lasers, rapid-washout ablation cells, multiple ion-counter devices for U–Pb geochronology and low-level isotopic analyses using magnetic sector ICP-MS instruments, synthetic standard reference materials, and the latest computer software packages for data reduction.

It is clear from the level of enthusiasm shown by course lecturers and participants that LA-ICP-MS is still a very popular method for geochemical applications, as well as being an intrinsically interesting technology itself, and will remain so for some time to come.

**Paul Sylvester**

Memorial University of Newfoundland (pauls@esd.mun.ca)



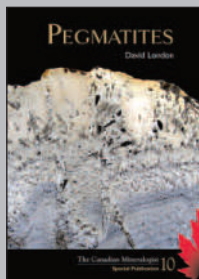
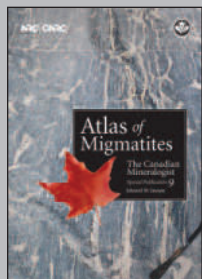
Some lecturers and participants at the LA-ICP-MS short course in Vancouver. Left to right – back row: Thomas Pettke, John Cottle, Matthew Horstwood, Simon Jackson; middle row: Detlef Günther, Klaus Peter Jochum, Paul Sylvester, Norman Pearson, Ingo Horn; front row: Davide Bleiner, Rebecca Lam, Brigitte Stoll, Michael Tubrett, Henry Longrich, Jan Košler, Amanda Kate Souders. Lecturers missing from photo: Thomas Chacko, Paul Mason, Chris McFarlane, Antonio Simonetti, Jon Woodhead. PHOTO COURTESY OF DETLEF GÜNTHER

### Pinch Medal – Call for Nominations

The Pinch Medal has been awarded every other year since 2001 to recognize major and sustained contributions to the advancement of mineralogy by members of the collector–dealer community. The 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. Previous recipients include William Wallace Pinch (2001), Mark Feinglos (2003), Charles Key (2005), and László (Les) Horváth and Elsa Pfenninger-Horváth (2007).

Nominations for the 2009 Pinch Medal should be submitted to Peter Burns (Department of Civil Engineering and Geological Sciences, University of Notre-Dame, 156 Fitzpatrick Hall, Notre-Dame, Indiana 46556-0767, USA; phone: 219-631-7380; fax: 219-631-9236; e-mail: pburns@nd.edu) by October 30, 2008. Each nomination should consist of a letter describing in detail the contributions of the nominee and a list of publications resulting from the nominee's contributions (the nominee is not required to be an author of these publications); additional supporting letters are welcome. The medal is typically awarded at the Tucson Gem and Mineral Show, following the selection of the recipient by the award committee and approval by MAC Council.

## We have new publications for you!



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ISBN 978-0-92129-446-7, 168 pp
- SC 40 Laser Ablation ICP-MS in the Earth Sciences – EDITOR: PAUL SYLVESTER (2008)  
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## German Mineralogical Society

### EXCELLENCE AND DEFICITS



In June 2005 the German federal and state governments agreed to initiate an exciting new type of research funding, the so-called Excellence Initiative. The Excellence Initiative “aims to promote top-level research and improve the quality of German universities and research institutions, thereby making a significant contribution to strengthening science and research in Germany in the long term, improving

its international competitiveness and raising the profile of the top performers in academia and research.” International and national review panels became involved to select the very best researchers and to support

them with 1.9 billion Euros in the period 2006 to 2011. The most recent funding decisions were made in October 2007. Special research clusters, graduate schools, and “elite universities” were selected. Details and selected sites can be downloaded from [www.dfg.de/forschungsfoerderung/koordinierte\\_programme/exzellenzinitiative/index.html](http://www.dfg.de/forschungsfoerderung/koordinierte_programme/exzellenzinitiative/index.html).

This program will clearly strengthen German science and compensate for an earlier period of insufficient funding. It will also help universities to compete with well-equipped research centers, where researchers have essentially no teaching load. However, the new funds do not benefit all universities. Several universities have had to cut positions over a period of many years, and in some cases the smaller programs in Earth science were strongly affected or even closed down through consolidation. These universities now are at a disadvantage in competing for funds from the Excellence Initiative.

And what comes now? Recently the demand for specialists in the field of mineral deposits with a background in mineralogy, geology, geo-engineering, or related fields has risen tremendously, but in Germany the number of universities with such programs has decreased so strongly that the local demand is far from being satisfied. When I was recently in Chile talking to the chief executive officer of a major copper mine, he mentioned that European graduates in this field are basically nonexistent and that his company hires Canadian and Australian graduates, and even those candidates are more and more difficult to attract. Within the next ten years about 50% of the skilled employees in such positions will retire and a shortage of staff seems obvious. For our junior scientists this ballooning deficit is and will remain for a long time an “excellent” springboard into industry—again we talk about “excellence.”

**Ulrich Bismayer**

### MEETING OF THE DMG PETROLOGY/PETROPHYSICS SECTION IN TÜBINGEN

This year’s traditional meeting of the DMG petrology/petrophysics section took place at the Institute for Geoscience in the picturesque town of Tübingen in southern Germany. It was well organized by Gregor Markl and Michael Marks with help from many other members of the Tübingen petrology group. The meeting began on Friday evening with a warm buffet, where the participants had the opportunity to discuss informally and exchange scientific and other news. The attraction of this meeting within the German petrology/petrophysics community was underlined by the presence of more than 60 participants from all over Germany, with travel times in excess of 8 hours being no obstacle for groups from Berlin, Potsdam, Kiel, and Bremen.

The scientific part of the meeting started on Saturday with the presentation of the invited speaker, Prof. Ron Frost from the University of Wyoming, U.S.A. Prof. Frost presented a talk entitled “Petrology of Serpentinization,” in which he provided an excellent overview of serpentinization processes. Prof. Frost emphasized the importance of low silica activities for the distinctive petrological and geochemical properties of serpentinites, such as the reducing conditions as evidenced by rare iron alloys, the presence of unusual minerals like hydrogarnet and jadeite, and the formation of calcic, high-pH fluids. Following on this theme, the subsequent contributions presented constraints on the phase relations in the system Fe-Ni-O-S during serpentinization and the formation and alteration of plagiogranites at mid-ocean ridges. The second part of the morning session focused on



Prof. Ron Frost conversing at the petrology/petrophysics meeting in Tübingen. PHOTO CREDIT: A. DORN

hydrothermal activity, including tectonic, magmatic, and experimental aspects, as well as on experimental work on ferropicicase and grain-boundary diffusion. The lunch break gave the participants an opportunity to venture out on a perfectly sunny day and get a brief glimpse of the half-timbered buildings of Tübingen’s old-town district.

The afternoon session covered a wide variety of petrological and petrophysical investigations. In the first part, subjects as diverse as CO<sub>2</sub> sequestration on a laboratory scale, experimental constraints on solubilities and partitioning behavior of trace elements in melts and aqueous solutions, and geochronological and field-based petrogenetic studies on mantle xenoliths and alkaline rocks were presented and discussed. In the second part, the importance of modeling in petrology was stressed by contributions on isotope fractionation during crystal growth and P-T paths. The session was completed by experimental work on rhyolites and

field-based studies on various metamorphic rocks. The different topics and the diverse analytical methods covered by the talks prompted the audience to look beyond their own interests and stimulated many to envisage new aspects or directions for their research.

Like previous section meetings, this one was no exception in providing an excellent opportunity for mostly young researchers to get together, present their work, and discuss scientific themes in a friendly and somewhat informal setting without the stress associated with big conferences. In particular, many PhD and diploma students contributed oral presentations. In addition, several posters were presented in the coffee lounge, stimulating further discussion. After the scientific part of the meeting, discussions continued in the backyard of the institute during a delicious barbecue that included beer and bratwurst, and some participants were not willing to stop talking science until the early hours of the next morning—indisputable evidence for the success of the meeting. The organizers are thanked for the great job they did, and the contributions by all participants were greatly appreciated. Last but not least, we acknowledge the financial support of the DMG that made the participation of Prof. Frost possible and provided travel grants to PhD and diploma students who presented their results at the meeting. Not surprisingly, the overwhelming mood at the end was anticipation for next year’s section meeting.

**Ralf Halama**  
Universität Kiel



[www.appliedgeochemists.org](http://www.appliedgeochemists.org)

## Association of Applied Geochemists



### INTERNATIONAL YEAR OF PLANET EARTH AND AAG

So why does it matter that the United Nations General Assembly has proclaimed 2007–2009 as the International Year of Planet Earth (IYPE)? The IYPE Global Launch Event by UNESCO at the UN Headquarters (Paris, France) in February 2008 was quite an event, underscoring the UN's high expectations. IYPE has honorable goals indeed: "Earth Sciences for Society – The International Year of Planet Earth aims to capture people's imagination with the exciting knowledge we possess about our planet, and to see that knowledge used to make the Earth a safer, healthier and wealthier place for our children and grandchildren."

About 70 countries are members of IYPE. The two main activities of IYPE are its science and outreach programs. Funding for projects in these two areas comes from industry, foundations, and governments around the world, although implementing them has mainly been at the grassroots level by volunteers; and as there are more than 400,000 Earth scientists worldwide, the UN is hoping we have a broad-based impact. The science programs fall into ten broad, societally relevant, multidisciplinary themes: health, climate, groundwater, oceans, soils, deep Earth, megacities, hazards, resources, and life. There is even an IYPE online book that has lots of "gift ideas."

So what are we going to do about it?, I asked the AAG executive before I headed out as the AAG representative for the IYPE launch. Here is some feedback I received. AAG members are actively engaged in outreach in schools where they live, like members of many other active geoscience organizations. Here in Canada, our IYPE focus is on outreach. Our national committee is planning a major book, as well as making grassroots efforts to talk to kids in schools. I am very proud to say my colleagues and I are actively engaged in these



outreach efforts, because science literacy, and especially Earth science literacy, is a national disaster, a disgrace.

Because AAG is an international organization, however, the impacts of the various science components of IYPE were of most interest to us; our group's expertise lies in over half the science theme areas. Our society plans on being engaged in them all, from grassroots efforts through to lobbying industry and governments, particularly on issues pertaining to world health and poverty. Dr. Hugh de Souza noted that AAG members can do a lot to improve world health and alleviate poverty by encouraging the broad-based application of geochemistry, which goes to the very heart of AAG's twin mandates of environmental and exploration geochem-



istry. By championing detailed regional geochemical mapping, AAG members know we can identify areas where potentially toxic elements can have an impact on health. For example, the British Geological Survey's efforts (international regional geochemistry baselines) in Bangladesh to identify areas of arsenic accumulation have a direct impact on health. Another example is Dr. Reimann's group's efforts to develop Scandinavian geochemical maps, in which one can see the effects of industrial and natural pollution and perhaps link them to health problems, particularly cancers and malnutrition; however, this is possible only where epidemiological databases are available to correlate with the geochemical data. Such correlations are impossible to prove when we don't have adequate geochemical data. I personally know of several cases where such surveys and even geochemical mineral exploration programs have led to awareness of health problems related to high natural abundances of As, Hg, Cd, Pb, Ra, and Rn, and not to anthropogenic contributions; problems can arise when *some* bureaucrats inhibit the process of informing the proper environmental and health authorities and (or) the public. The FOREGS Geochemical Baseline Mapping Program for sediment, water, and soil recognized and addressed these issues by doing the research, building the protocols, and then the databases covering much of Europe. The North American Soil Geochemical Landscapes Project represents a comprehensive trilateral soil sampling effort involving multiple agencies. IUGS-IAGC's Working Group on Global Geochemical Baselines is also contributing to this important

effort. Numerous websites detail these baseline studies and explain method development and protocols for sampling through to analysis.

On the poverty side, the same regional geochemical maps provide a boost to mineral exploration and, in rare cases, mining development. Recently published statistics from Northern Ontario quantify the huge economic impact mining has had in generating wealth in local communities. Dr. Olle Selinus (Geological Survey of Sweden) has long been working on issues related to world health and poverty in Sweden and around the Third World. For some time, Ollie's group has focused on medical geology in developing nations and, unlike in most developed countries, their international IYPE efforts attract the Swedish king's attention. The International Medical Geology Association (IMGA) is focused on these issues—they have lots of pertinent material, and many AAG members are actively engaged in this field, where the lines between disciplines tend to blur. Currently, the IMGA is developing a web-based education package for use by anyone.

So why does it matter? Well we have a lot of volunteer work ahead of us if we wish to achieve the level of impact that the UN wants and needs. A major grassroots effort from members from all Earth-science associations can change the world, if we really want to.

For more information on the International Year of Planet Earth, visit <http://yearofplanetearth.org/index.html>

**David Lentz**  
AAG IYPE Representative



S.E.M.

[www.ehu.es/sem](http://www.ehu.es/sem)

## Sociedad Española de Mineralogía

### MINERALOGY AND RELATED SCIENCES IN THE 21<sup>st</sup> CENTURY

On June 11, 2008, the Mineralogical Society of Spain held a one-day seminar to discuss the future of teaching and scientific research in mineralogy in Spain. About thirty participants from all over the country attended the meeting, most of them actively involved in graduate and postgraduate courses and programs, including crystallography, mineralogy, petrology, and geochemistry.

Professors Sol López Andrés (Complutense University of Madrid), Salvador Morales Ruano (University of Granada), and Fernando Rull Pérez (University of Valladolid) gave three talks covering topics like the impact of the European Space for Higher Education on scientific research in mineralogy and related disciplines; the need for academics to adapt to an apparently new teaching paradigm: skill development via a student learning-based approach; and how to include new concepts and techniques in modern, university-level teaching of mineralogy. To discuss in greater detail the issues emerging from the talks, an open debate followed each presentation.

Many interesting questions were raised in the discussions. Worth noting were thoughts on the perception the practitioners of mineralogy have with respect to their own contribution to geosciences and collateral fields (engineering, materials science, biomedicine, historical science, law, climate change, etc.) and on the question of whether their work is adequately acknowledged by the scientific community and society. Interesting reflections were also made on the fading-out tendency of classical, Earth science-based mineralogy and on how in past decades the environmental and technological applications of mineralogy have taken off. Although the participants generally agreed that this is a global tendency, not much agreement was found regarding the causes: Is this the normal evolution of a mature scientific field that is spontaneously merging with neighbor disciplines? Are we suffering pressure from other productive and expanding fields (chemistry, physics, biology), which may be widening the frontiers of their knowledge at our expense? As scientists, should we accept the situation and carry on, facing the challenges and opportunities provided, or should we try to strengthen our position within the rest of science?

The translation of the previous discussion to the practical arena was centered on the two main topics of the seminar: funds for research and the elaboration of new academic curricula. With respect to project funding, the participants observed that, in Spain, it is true that funds available for scientific research or for the acquisition of costly equipment have greatly increased in past decades. However, the funds addressed specifically to geoscientific fields, including mineralogy, have clearly declined, and it is perceived that there is a tendency toward their complete disappearance. For instance, in the present National R&D Program (2008–2011), our government has identified research needs in food, farming and fisheries; environment and eco-innovation; energy; security and defense; construction and cultural heritage; tourism; aerospace; infrastructures and transport; pharmacy; and industry. It also provides for strategic actions in human health, bio- and nanotech-



Professor Fernando Rull, from the University of Valladolid, giving his talk on modern concepts and techniques applied to teaching mineralogy.

nology, nanoscience, energy and climate change, telecommunications, and new materials. A similar situation can be found in the case of the 7<sup>th</sup> European Framework Programme. Thus, although there is money available to work, a great deal of imagination is needed to fit many geoscientific proposals into the present funding system. To the participants in the seminar, this may reflect the lack of influence of our scientific realm compared with the dominant positions of other disciplines, which are favored by science metrics and the higher social impact of their research. A more worrying concern was the perception of the prevalence of certain interests, not strictly scientific or academic, associated with lobbies and pressure groups. A great deal of effort is necessary to improve our communication skills and to highlight past, present, and future achievements.

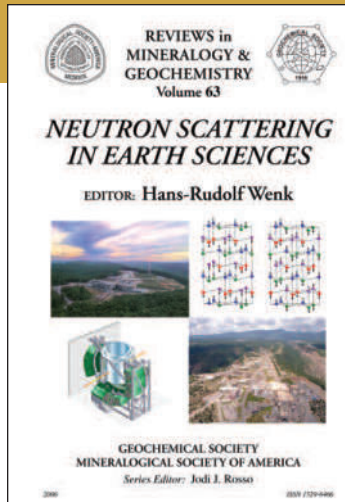
Another key battleground is the adaptation of academic curricula in accordance with the Bologna converging process. European experts say that new graduate programs must stress the development of key qualifications, like communication and team work. In fact, that means the reduction of lectures in favor of more time for students to develop given skills (or competencies). Like many other titles in Spain, our future geologists will enter the labor market after completing a four-year degree (now five), including instruction in crystallography and significantly shorter inputs from mineralogy, petrology, and geochemistry. However, the problem deepens because in Spain, since the nineties, geology is not taught at pre-university levels.

Some of the participants called attention to the leadership role that scientific institutions, like the Mineralogical Society of Spain (SEM), should play in order to face these challenges. In any case, we cannot expect that any short-term action will dramatically improve the present situation. It is necessary, however, to construct a long-term strategy based on the coordination of groups and activities, information dissemination (talks, educational materials, etc.), and public communication (mass media). Within the context of university education, SEM should help to assess the minimum background levels required in crystallography, mineralogy, petrology, and geochemistry for geoscientists, as well as to identify key content in related disciplines (chemistry, physics, engineering, etc.). On the other hand, in order to foster research in mineralogy, SEM should be present in the corresponding scientific policymaking scenarios. Most of these actions should be taken within a transnational context because it is acknowledged that a similar situation has developed in other countries.

The meeting was convened by Drs. Lurdes Fernández Díaz and José Fernández Barrenechea, both in the Crystallography and Mineralogy Department of the Complutense University of Madrid. As an outcome of the seminar, a summary report is being coordinated by Dr. Salvador Morales Ruano (University of Granada). The full report will be included in the next regular issue of *Macla* (i.e. the SEM's magazine) and distributed to departments, universities, and accreditation agencies, as well as to local and national educational administrations.

**Jordi Delgado**

## Neutron Scattering in Earth Sciences<sup>1</sup>



The availability of specialised structural and analytical techniques at central facilities (e.g. synchrotron and neutron laboratories) has revolutionised materials (*sensu lato*) research over the last 10–20 years, but Earth scientists as a whole have been slow to ‘dip their toes’ into such exciting waters. However, the synchrotron radiation, element-specific X-ray absorption spectroscopic technique (EXAFS) is becoming increasingly popular among environmental scientists studying the cycling of toxic elements. By contrast, some mineral physicists carry out challenging

synchrotron X-ray and/or neutron diffraction experiments, often at controlled temperatures and pressures. However, the time is ripe to emphasise the wider importance of neutron methods for a wide range of Earth science research and to expand the user-base. Thus the short course entitled Neutron Scattering in Earth Sciences (December 2006) was held to try to stimulate new research areas and to attract more Earth scientists to this exciting cross-disciplinary research community.

The book contains 17 chapters with an impressive list of authors covering a wide range of scientific and experimental expertise but, perhaps inevitably, not many have a mainstream Earth science background. Chapter 1 (Parise) is an excellent introduction to the special properties of neutron radiation and emphasises the advantages compared to equivalent X-ray techniques. Chapter 2 (Vogel and Priesmeyer) provides background information on neutron sources and associated equipment, distinguishing between reactors and spallation sources and between monochromatic and polychromatic (time-of-flight) techniques. These articles introduce terminology, concepts and experiment types which are more fully covered in the other contributions.

Chapter 3 (Ross and Hoffmann) deals with single-crystal diffraction and gives useful examples for location of light elements (mainly hydrogen and deuterium). The low-key nature of this article perhaps reflects the paucity of single-crystal mineralogical studies using neutron diffraction. Chapter 4 (Von Dreele) describes how Rietveld refinement of powder data can be used to obtain full structures, and this analysis method provides the basis for the contributions given in chapters 5 (Knorr and Depmeier) and 7 (Redfern), the latter reviewing studies of the temperature dependence of cation order–disorder in a range of petrologically important minerals. Chapter 6 (Harrison) is an authoritative treatment of neutron diffraction of magnetic minerals, providing useful summaries for magnetite spinels and hematite–ilmenite solid solutions.

Chapter 8 (Kuks and Hansen) is another excellent contribution which deals with time-resolved, controlled pressure/temperature studies of water ices and clathrates. The higher flux from a reactor source with a specialised beamline (D20 at ILL) allows reactions to be studied on sub-second time scales. Chapter 9 (Parise) also deals with water-ice polymorph stabilities as part of a useful review of high-pressure experimental equipment. The final section is particularly interesting and deals with new plans and developments, particularly on the SNS at Oak Ridge. In the next chapter, Chun-Keung Loong shows that neutron inelastic scattering provides information on spatial-temporal interactions of atoms and electrons. The next three chapters deal with studies of disordered/amorphous solid materials and fluids. Chapter 11 (Proffen) shows how total-scattering methods and pair-distribution functions can be

used to obtain ‘true’ atomic structures for amorphous and poorly crystalline or strained materials. Chapter 12 (Wilding and Benmore) summarises neutron-diffraction and data-reduction methods used in the study of silicate glasses. The use of levitation techniques for in situ studies of oxide melts seems particularly promising. The next chapter (Cole, Herwig, Mamontov and Larese) is wide ranging and shows how neutron diffraction has been used to provide important data on the structure of liquid water and aqueous electrolyte solutions.

The last few chapters deal with macro- and micro-structural features of ‘real’ rocks and related mineralogical samples. In chapter 14 (Radlinski), the technique of small-angle neutron scattering (SANS and ultra-SANS) is described, and it is shown how these techniques can be used to characterise the porosity (and fractal properties) of sandstones and coal, and to study micro-structures of shales and clays at length scales between 1 nanometre and 20 microns. Chapter 15 (Wenk) is the most persuasive, which is appropriate as it is written by the editor of this book – a pioneer in the use of neutrons for studying textures of deformed rocks. Examples of work dealing with real petrological problems are clearly explained. In chapter 16 (Daymond), the study of deformed aggregates is described with the example of in situ measurements of strain partitioning in multi-phase mineral mixtures being particularly interesting. In the last chapter (Winkler), applications of neutron radiography and tomography are covered, with examples including study of rock cores, experiments to measure melt viscosity, and fossil conifers. These techniques have a huge potential in Earth science, and this chapter is just too brief.

This is a typical volume in the Reviews in Mineralogy and Geochemistry (RiMG) series – it is packed with important information and is excellent value at \$40. However, it is not user friendly, as there is much repetition of basic concepts, and background information is scattered through the different articles in the volume. The lack of an index makes it difficult to dip into and cross-check between chapters.

It is pertinent to compare this book with the thematic issue of the *European Journal of Mineralogy* (*Neutron Scattering in Mineral Sciences*, editor R. Rinaldi, *EJM*, volume 14(2), 2002). On the whole, the *EJM* papers are authored by mainstream mineralogists and, overall, this is reflected in a better coverage of significant mineralogical examples. However, the RiMG book has a wider scope and includes chapters dealing with amorphous materials (glasses, melts and fluids) and magnetic samples, and has more detailed information on techniques. Potential users could consult both of these, but wise researchers might already have RiMG volume 63 on their shelves along with the rest of this excellent series.

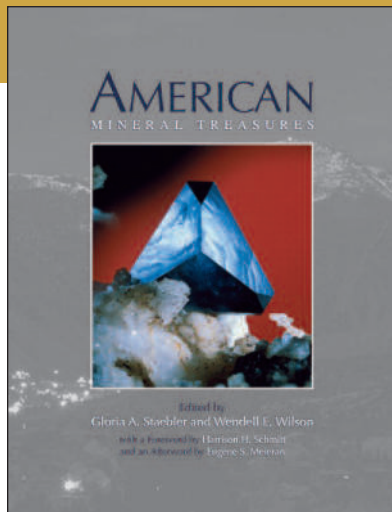
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<sup>1</sup> Wenk H-R (editor) (2006) *Neutron Scattering in Earth Sciences*. Reviews in Mineralogy & Geochemistry 63, Mineralogical Society of America Chantilly, VA, USA, ISBN: 978-0-939950-75-1, 471 pages, US\$40 25% discount for MSA and GS members

## American Mineral Treasures<sup>2</sup>



At the 2005 Tucson Gem and Mineral Show, mineral collectors Gene Meiran and Shields Flynn were discussing ideas for future shows. Past Tucson show themes usually revolved around a particular country or continent, a particular suite of minerals, or a particular mineral, such as gold. Meiran and Shields wanted to have a show theme involving some of the finest mineral specimens from some of the United States of America's premier specimen-producing localities. Seven other people were brought into the discussion, and the American Mineral

Treasures project developed. Queries were put forth as to which localities should be targeted, and a short list was determined. This book is a part of that project.

The book's principal editors are Gloria Staebler and Wendell Wilson; however, seven other people also became contributing editors. The book starts with an eleven-page chapter summarizing the history of mineral collecting in America. Then the fun begins. What follows are 44 chapters written by experts on each locality. Some of the localities encompass more than one mine or area. The chapter entitled "California Gold," for example, zeroes in on four gold specimen-producing localities, and the chapter "Celestine from the Findlay Arch District" includes localities in Ohio and Michigan.

The book has over 60 authors, some of whom contributed to more than one chapter. What results are wonderful stories of personal discoveries. Some of the stories sound like "whoppers," except that there are many

photographs to back up the tales. The specimen photography, mostly by Jeff Scovil, the recent recipient of the Carnegie Award, is excellent. But being a field collector, two of my favorite images are Jones' Meikle mine pocket of barite crystals (page 206) and Jack's Bunker Hill mine pyromorphite pocket (page 151). Most of the specimens shown in the book were collected in the last 50 years, some as recently as 2007. This is current stuff! I want to go out and find some of these rocks myself! The book is so full of wonderful stories and photographs that people might get the impression that anybody can find such specimens. However, the book is more than personal stories and pretty pictures: many of the chapters include geological and historical information.

Most of the 60+ authors were present at the Tucson show, and many people, including myself, were getting the various chapters autographed by as many of the authors as they could find. By the end of the show I had 39 autographs in my copy.

I have only a few trivial negative comments. I was surprised that the Butte chapter had a one-page historical summary that did not mention the mine fire of 1917, which killed 163 miners. The map of Hiddenite did not include the Rist mine location. I recall seeing one typo where a space did not exist between sentences (okay authors—go nuts looking for the missing space). My only serious complaint is the title of the book. Correctly used, "America" extends from Canada to Argentina. However I must admit that even I get lazy and sometimes refer to my country as "America." Still, in a book that deals with a specific geographic area, one should get that area correctly labeled.

This book had many sponsors, which resulted in a low retail price of US\$85 —far less than expected for a 24.6 × 33.5 cm biggest-book-in-your-library book. Thank you sponsors! The last book the likes of *American Mineral Treasures* I saw was Bancroft's *Gem and Crystal Treasures*, which included worldwide localities and was published in 1984. So many rocks have been found since then. This new book is most welcome.

When I came back from the Tucson show, I attended a social/professional meeting and showed off my new book. After a few minutes someone remarked that it was the best book he had ever seen. From a mineral collector's point of view, he was right! This is not an academic book, but I highly recommend it to all geologists and mineral collectors.

**Patrick Haynes**  
Las Vegas, USA

<sup>2</sup> Staebler G, Wilson WE (editors) (2008) *American Mineral Treasures*. Lithographie, LLC, East Hampton, Connecticut, USA, 354 pages, US\$85

<sup>3</sup> Patrick Haynes has discovered several new mineral species and is busy looking for more. The mineral haynesite is named after him.

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## 2008

**September 22–27 4<sup>th</sup> Mid-European Clay Conference**, Zakopane, Poland. E-mail: mecc08@agh.edu.pl; www.mecc08.agh.edu.pl

**October 5–8 Geological Society of America Annual Meeting**, Houston, TX, USA. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings/2008

**October 5–9 Materials Science & Technology 2008 Conference and Exhibition** – MS&T '08 combined with the American Ceramic Society (ACerS) 110<sup>th</sup> Annual Meeting, Pittsburgh, Pennsylvania, USA. Web page: www.matscitech.org/2008/home.html

**October 8–10 Federov Session 2008**, Saint Petersburg, Russia. E-mail: fs2008minsoc.ru; web page: www.minsoc.ru/fs2008

**October 13–16 Chapman Conference on Biogeophysics**, Portland, ME, USA. E-mail: chapman-help@agu.org; web page: www.agu.org/meetings/chapman/2008/fcall/

**October 21–23 Workshop on Martian Phyllosilicates: Recorders of Aqueous Processes?**, Paris, France. Web page: www.ias.u-psud.fr/Mars\_Phyllosilicates/main\_1st.php

**October 26–29 AAPG International Conference and Exhibition: African Energy - Global Impact**, Cape Town, South Africa. Phone: +1 918 560 2617; web page: www.aapg.org/capetown

**October 28–31 Lunar Exploration Analysis Group (LEAG), International Lunar Exploration Working Group (ILEWG), and Space Resources Roundtable (SRR) meeting**, Cape Canaveral, FL, USA. Web page: www.lpi.usra.edu/meetings/leagilewg2008

**November 6–7 Joint Mineralogical Societies of Australasia – 31<sup>st</sup> Annual Seminar**, Zeehan, Tasmania. R. Bottrill; e-mail: rbottrill@mrt.tas.gov.au; web page: www.mineral.org.au/seminar/seminar08.htm

**November 12–14 ACROFI-2: Asian Current Research on Fluid Inclusions**, Kharagpur, India. Details: M.K. Panigrahi; e-mail: mkp@gg.iitkgp.ernet.in; web page: www.iitkgp.ac.in/acrofi

**November 14–20 International Workshop on Exploration and Mining Geochemistry**, Perth, Western Australia. E-mail: workshop@ioglobal.net; web page: www.ioglobal.net

**November 17–19 Workshop on Postmining Problems from the Exploitation of Polymetallic Sulfides**, Seville, Spain. Details: Dr. Antonio Romero; e-mail: aromo@us.es

**December 1–5 Materials Research Society Fall Meeting**, Boston, MA, USA. Web page: www.mrs.org/s\_mrs/sec.asp?CID=2073&DID=92005

**December 1–5 Eighth International Geostatistics Congress - GEOSTATS 2008**, Santiago, Chile. E-mail: info@geostats2008.com; website: www.geostats2008.com

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

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

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

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

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

## 2009

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

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

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

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

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

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

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

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

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

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

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

**April 2–4 Conference on Micro-Raman Spectroscopy and Luminescence Studies in the Earth and Planetary Sciences (Spectroscopy 2009)**, Mainz, Germany. Web page: www.lpi.usra.edu/meetings/spectroscopy2009

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

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

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

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

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

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

**May 24–28 AGU Joint Assembly and Geological Association of Canada/Mineralogical Association of Canada Annual Meeting**, Toronto, Canada. E-mail: meetinginfo@agu.org; web page: www.agu.org/meetings

**June 1–4 IAGS 2009 – 24<sup>th</sup> International Applied Geochemistry Symposium**, Fredericton, NB, Canada. Web page: www.unb.ca/conferences/IAGS2009

**June 2009 EURISPET: High-Pressure Metamorphism and Subduction Zones**, Granada, Spain. Details: Maria Teresa Gómez-Pugnaire; e-mail: teresa@ugr.es or eurispet@eurispet.eu; web page: www.eurispet.eu

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

**June 7–10 AAPG Annual Convention and Exhibition**, Denver, CO. Web page: www.aapg.org/meetings/misc\_mtgs.cfm

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**November 16–20** Cities on Volcanoes 6 - Tenerife 2009, Canary Islands, Spain. Details: Dr. Nemesio M. Pérez; e-mail: nperez@iter.es; web page: www.citiesonvolcanoes6.com

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

**December 7–11** 2009 AGU Fall Meeting, San Francisco, CA, USA. Web page: www.agu.org/meetings

**2010**

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

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

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

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

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

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

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

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

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

**July 22–31** American Crystallographic Association (ACA) Annual Meeting, Chicago, IL, USA. Webpage: www.AmerCrystalAssn.org

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

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

**August 22–27** 20<sup>th</sup> General Meeting of the International Mineralogical Association, Budapest, Hungary. Website: www.univie.ac.at/Mineralogie/IMA\_2010

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

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

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

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

**November** EURISPET: Experimental Petrology and Rock Deformation, Zürich, Switzerland. Details: Peter Ulmer, Swiss Federal Institute of Technology (ETH) Zürich; e-mail: peter.ulmer@erdw.ethz.ch; web page: www.eurispet.eu

**2011**

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

**June 27–July 8** XXV<sup>th</sup> IUGG General Assembly, Melbourne, Australia. Web page: www.iugg2011.com

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



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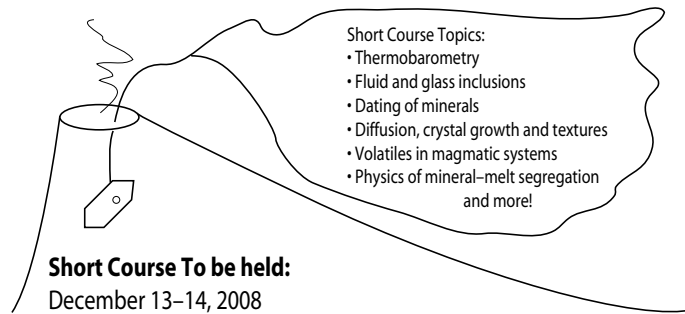
The position is available from September 1, 2009. We are looking for an internationally renowned scientist who studies minerals, rocks, melts or related substances with the aim of understanding large-scale geological processes. Fields of research may include, but are not limited to, studies of geophysically relevant phase equilibria, rock deformation, equations of state and physical properties of minerals, melts and fluids, the kinetics of phase transformations and diffusion. A strong interest in the development and application of high-pressure experimental techniques, particularly involving multi-anvil technology is expected. The successful applicant will be expected to participate in teaching, particularly in the education of graduate students, in the Master Course "Experimental Geoscience" and in basic courses for geocology students. Teaching will be mainly in English.

In addition to a Ph. D., applicants should have appropriate experience in research and teaching. Candidates must be less than 52 years old upon appointment. Women and handicapped people are especially encouraged to apply.

Applications, accompanied by a curriculum vitae, publication list, copies of university certificates, a statement on teaching experience and an outline of proposed research should be sent before October 10, 2008 to the Dekan der Fakultät für Biologie, Chemie und Geowissenschaften der Universität Bayreuth, 95440 Bayreuth, Germany.

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## THE "GLASS FLOWERS" AT THE HARVARD MUSEUM OF NATURAL HISTORY

No visit to New England is complete without exploring the remarkable collection of "glass flowers" at the Harvard Museum of Natural History in Cambridge, Massachusetts, USA (see Triple Point, this issue). The Ware Collection of Glass Models of plants represents 847 plant species painstakingly and accurately crafted in glass by Leopold and Rudolph Blaschka. The father and son glassmakers in Hosterwitz, near Dresden, Germany, were last in a line of family jewelers and glassmakers going back to 15<sup>th</sup>-century Venice. Originally charged with the creation of just a few models, the Blaschkas later signed an exclusive contract with Harvard to make a collection of over 3000 glass models, a task accomplished over five decades from 1886 through 1936. In addition to being highly skilled craftsmen, the Blaschkas had a remarkable understanding of botany and were able to create specimens that were scientifically accurate.

The unique chemical and physical properties of glass lent themselves particularly well to making models of botanical specimens. Glass was the perfect medium with which to visually capture the translucence of a petal or the brittle strength of a cactus spine. The parts were shaped after the glass was softened by heat. Some models were blown. Colored glass was used for many; others were painted with a thin wash of colored ground glass or metal oxide(s) and heated until the material fused to the model. The Blaschkas continually experimented with new techniques to perfect colors and to incorporate other materials into the models, such as internal wire supports, glue, and enamels. They used many different minerals to make colored glass: lapis lazuli for blue, iron oxides for reds, manganese dioxide for purple, malachite for green, cinnabar for another red vermilion, and others.

Adapted from text provided by  
the Harvard Museum



Some of the "glass flowers" on display at the Harvard Museum of Natural History; [www.hmn.harvard.edu](http://www.hmn.harvard.edu)  
PHOTO CREDIT: HILLEL BURGER© PRESIDENT AND FELLOWS OF HARVARD COLLEGE



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**Sedimentary Geology**  
**Two Faculty Positions**

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

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

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

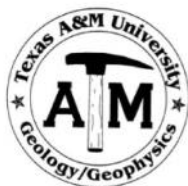
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UNIVERSITY OF WYOMING

*Isotope Geology*

The Department of Geology and Geophysics at the University of Wyoming invites applications for a tenure-track faculty position in the broad field of isotope geology. This appointment will most likely be made at the Assistant Professor level beginning in August 2009.

We encourage applications from promising scientists that apply radiogenic and/or stable isotopes to problems in the fields of geologic or environmental processes, including but not restricted to topics as diverse as aqueous/environmental geochemistry, climate change, crustal and mantle petrogenesis, mineral deposits, paleoaltimetry, sedimentary provenance, and structural geology. The successful candidate will be expected to develop a research program in their field, and contribute to the graduate and undergraduate teaching missions of the Department of Geology and Geophysics.

The Department has strength in radiogenic isotopes and thermochronology, including laboratories with TIMS instrumentation and fission-track dating facilities. Furthermore, the Department supports a full range of aqueous analytical instrumentation, an electron microprobe, and SEM. Additional information on the Department Geology and Geophysics can be obtained at <http://home.gg.uwyo.edu/>. There is a well-equipped University stable isotope facility with multiple IRMS linked to TC/EA, EA, GasBench, and other peripheral devices (<http://uwacadweb.uwyo.edu/sif/>).

Applications should include a statement of research and teaching interests, curriculum vitae, and the names and contact information for at least three individuals who can provide letters of evaluation. Review of completed applications will begin September 24, 2008. Send an electronic copy of your application to: Ms. Carol Pribyl at [cpribyl@uwyo.edu](mailto:cpribyl@uwyo.edu); if you have additional application materials to send, please direct them to the Isotope Geology Search Committee, Department of Geology and Geophysics, University of Wyoming, 1000 East University Avenue, Dept. 3006, Laramie, WY 82071-2000.

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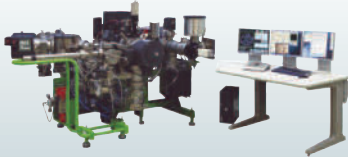
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Texas A&M University	288
University of Wyoming	288

See also [www.elementsmagazine.org/jobpostings](http://www.elementsmagazine.org/jobpostings)

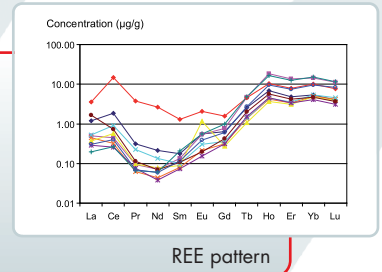
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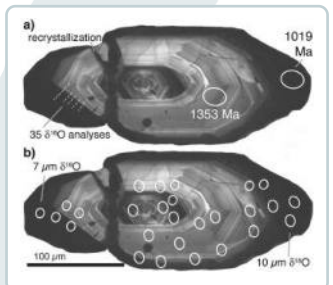
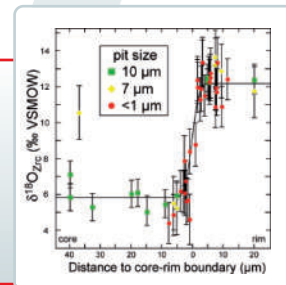
- Sub-permil reproducibility on stable isotopes from 15-40µm spots
- REE and trace element mapping down to micron scale resolution



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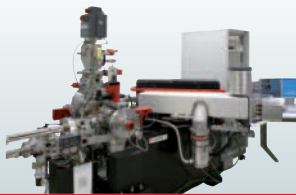


- Tenth of permil reproducibility on stable isotopes from 5-10µm spots
- U-Pb zircon dating from 10-20µm spots



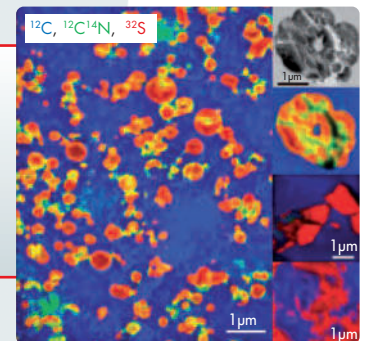
Gradient of oxygen 18/16 ratio over 2 microns in zircon. Z. Page et al., 2007, U. Wisconsin

## NanoSIMS 50



- Sub-permil reproducibility on stable isotopes from 5-10µm spots
- Trace element mapping down to 50nm lateral resolution

Red regions represent relatively pure Sulphur (as ZnS), Orange & Yellow: increased levels of Nitrogen in presence of ZnS. Light blue: presence of both C and N, with little to no S (no ZnS).

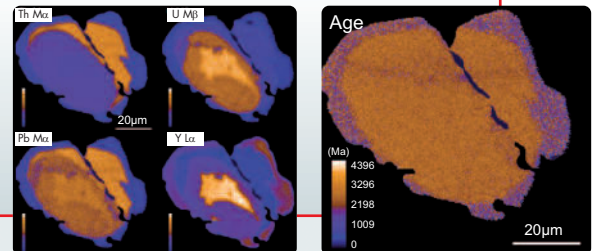


Extracellular proteins limit the dispersal of biogenic nanoparticles, John W. Moreau et al., SCIENCE, vol 316 (2007)

## SX 100



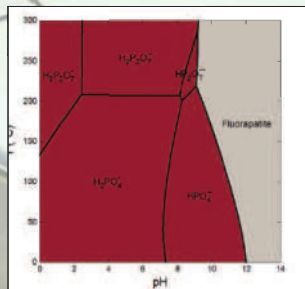
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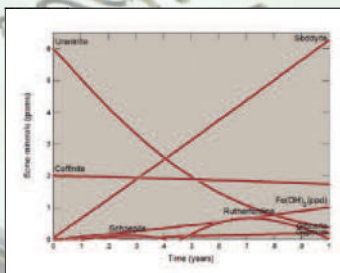
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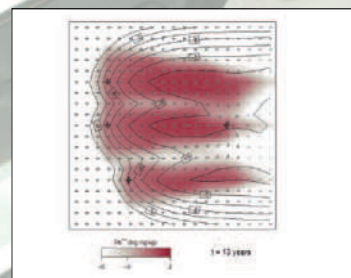


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