

# Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology

October 2009  
Volume 5, Number 5

ISSN 1811-5209



## Gold

ROBERT HOUGH and CHARLES BUTT, Guest Editors

**Why Gold Is Valuable**

**Gold in Solution**

**Gold Deposits**

**Porphyry and Epithermal Deposits**

**Crystallography, Metallography  
and Composition**

**Biogeochemistry of Gold**

**Gold and Nanotechnology**

# Distilling Ultra-Pure Acid Just Became Ultra-Quick ▶ Ultra-Easy ▶ Ultra-Affordable

## Savillex DST-1000 Sub-Boiling Distillation System

The DST-1000 features:

- Wetted parts of molded PFA
- No cooling water required
- Controlled, gentle heating
- Elegant, compact design
- Built-in waste drain

▶ View the DST-1000 in action ◀  
online at [www.savillex.com](http://www.savillex.com).

**Savillex**  
Your Fluoropolymer Solutions Partner

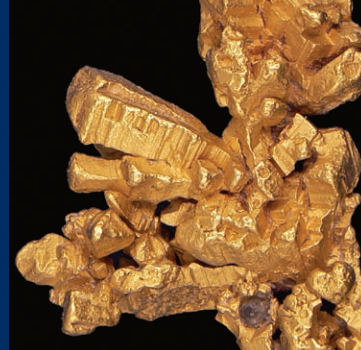


Savillex Corporation has been proudly serving the Geochemistry community for over 30 years. We are committed to providing high-quality PFA labware solutions for all your sample analysis needs.

Tel: 952-935-4100  
[www.savillex.com](http://www.savillex.com)

# Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology



*Elements* is published jointly by the Mineralogical Society of America, the Mineralogical Society of Great Britain and Ireland, the Mineralogical Association of Canada, the Geochemical Society, The Clay Minerals Society, the European Association for Geochemistry, the International Association of Geochemistry, the Société Française de Minéralogie et de Cristallographie, the Association of Applied Geochemists, the Deutsche Mineralogische Gesellschaft, the Società Italiana di Mineralogia e Petrologia, the International Association of Geoanalysts, the Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), the Sociedad Española de Mineralogía, and the Swiss Society of Mineralogy and Petrology. It is provided as a benefit to members of these societies.

*Elements* is published six times a year. Individuals are encouraged to join any one of the participating societies to receive *Elements*. Institutional subscribers to any of the following journals—*American Mineralogist*, *Clay Minerals*, *Clays and Clay Minerals*, *Mineralogical Magazine*, and *The Canadian Mineralogist*—also receive *Elements* as part of their 2009 subscription. Institutional subscriptions are available for US\$150 a year in 2009. Contact the managing editor (tremblpi@ete.inrs.ca) for information.

Copyright 2009 by the Mineralogical Society of America

All rights reserved. Reproduction in any form, including translation to other languages, or by any means—graphic, electronic or mechanical, including photocopying or information storage and retrieval systems—without written permission from the copyright holder is strictly prohibited.

Publications mail agreement no. 40037944

Return undeliverable  
Canadian addresses to:  
PO Box 503  
RPO West Beaver Creek  
Richmond Hill, ON L4B 4R6

Printed in Canada  
ISSN 1811-5209 (print)  
ISSN 1811-5217 (online)

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

Volume 5, Number 5 • October 2009

## Gold

Guest Editors: Robert M. Hough and Charles R. M. Butt



### Why Gold Is Valuable

Charles R. M. Butt and Robert M. Hough



### Gold in Solution

Anthony E. Williams-Jones, Robert J. Bowell, and Artashes A. Migdisov



### Gold Deposits: Where, When and Why

John L. Walshe and James S. Cleverley



### From Source to Sinks in Auriferous Magmatic-Hydrothermal Porphyry and Epithermal Deposits

Richard M. Tosdal, John H. Dilles, and David R. Cooke



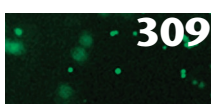
### The Crystallography, Metallography and Composition of Gold

Robert M. Hough, Charles R. M. Butt, and J. Fischer-Bühner



### The Biogeochemistry of Gold

Gordon Southam, Maggy F. Lengke, Lintern Fairbrother, and Frank Reith



### Gold and Nanotechnology

Claire M. Copley and Younan Xia

ABOUT THE COVER:  
The Liversidge nugget, in the Royal Museum, Edinburgh, was described in 1888 by Archibald Liversidge, pioneer gold geologist and geochemist and an important early protagonist for science in Australia. See page 335 of this issue. PHOTOGRAPH BY CHARLES BUTT 2009 BY PERMISSION OF THE TRUSTEES, NATIONAL MUSEUMS SCOTLAND

## Departments

<b>Editorial</b> – All That Glitters...	<b>267</b>
<b>From the Editors</b> – This Issue; 2010 Catalogue	<b>268</b>
<b>Letter to the Editors</b>	<b>268</b>
<b>Triple Point</b> – Asbestos: A View from a Different Hilltop	<b>269</b>
<b>People in the News</b> – 2009 AGU Fellows, Meibom	<b>270</b>
<b>Obituary</b> – Ernest H. Nickel	<b>272</b>
<b>Meet the Authors</b>	<b>274</b>
<b>Society News</b>	
Società Italiana di Mineralogia e Petrologia	315
Deutsche Mineralogische Gesellschaft	316
The Clay Minerals Society	318
Mineralogical Society of Great Britain and Ireland	320
Geochemical Society	314, 321
European Association for Geochemistry	322
Mineralogical Society of America	324
Mineralogical Association of Canada	326
Association of Applied Geochemists	328
Société Française de Minéralogie et de Cristallographie	329
<b>Meeting Reports</b> – 14 <sup>th</sup> ICC	<b>330</b>
<b>Book Reviews</b> – <i>Isotope Geology</i> , <i>Working with Migmatites</i>	<b>331</b>
<b>Calendar</b>	<b>333</b>
<b>Parting Shots</b> – Liversidge, Pioneer Gold Geologist	<b>335</b>
<b>Advertisers in This Issue</b>	<b>336</b>




## PRINCIPAL EDITORS

SUSAN L. S. STIPP, Københavns Universitet, Denmark (stipp@nano.ku.dk)  
 DAVID J. VAUGHAN, The University of Manchester, UK (david.vaughan@manchester.ac.uk)  
 HARRY Y. (Hap) MCSWEENEY, University of Tennessee, USA (mcsween@utk.edu)

## ADVISORY BOARD 2009

JOHN BRODHOLT, University College London  
 NORBERT CLAUER, CNRS/Uds, Université de Strasbourg, France  
 ROBERTO COMPAGNONI, Università degli Studi di Torino, Italy  
 JAMES I. DREVER, University of Wyoming, USA  
 WILL P. GATES, SmecTech Research Consulting, Australia  
 GEORGE E. HARLOW, American Museum of Natural History, USA  
 JANUSZ JANECEK, University of Silesia, Poland  
 HANS KEPPLER, Bayerisches Geoinstitut, Germany  
 DAVID R. LENTZ, University of New Brunswick, Canada  
 MAGGI LOUBSER, University of Pretoria, South Africa  
 ANHUI LU, Peking University, China  
 ROBERT W. LUTH, University of Alberta, Canada  
 DAVID W. MOGK, Montana State University, USA  
 TAKASHI MURAKAMI, University of Tokyo, Japan  
 ROBERTA OBERTI, CNR Istituto di Geoscienze e Georisorse, Pavia, Italy  
 ERIC H. OELKERS, LMTG/CNRS, France  
 TERRY PLANK, Lamont-Doherty Earth Observatory, USA  
 XAVIER QUEROL, Spanish Research Council, Spain  
 OLIVIER VIDAL, Université J. Fourier, France  
 MEENAKSHI WADHWA, Arizona State University, USA

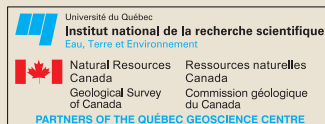
## EXECUTIVE COMMITTEE

GIUSEPPE CRUCIANI, Società Italiana di Mineralogia e Petrologia  
 BARBARA L. DUTROW, Mineralogical Society of America  
 W. CRAWFORD ELLIOTT, The Clay Minerals Society  
 RODNEY C. EWING, Chair  
 DAVID A. FOWLE, Mineralogical Association of Canada  
 CATHERINE MÉVEL, Société Française de Minéralogie et de Cristallographie  
 MAREK MICHALIK, Mineralogical Society of Poland  
 MANUEL PRIETO, Sociedad Española de Mineralogía  
 CLEMENS REIMANN, International Association of GeoChemistry  
 URS SCHALTEGGER, Swiss Society of Mineralogy and Petrology  
 CLIFFORD R. STANLEY, Association of Applied Geochemists  
 NEIL C. STURCHIO, Geochemical Society  
 PETER TRELOAR, Mineralogical Society of Great Britain and Ireland  
 FRIEDHELM VON BLANCKENBURG, Deutsche Mineralogische Gesellschaft  
 MICHAEL J. WALTER, European Association for Geochemistry  
 MICHAEL WIEDENBECK, International Association of Geoanalysts

## MANAGING EDITOR

PIERRETTE TREMBLAY, tremblpi@ete.inrs.ca

## EDITORIAL OFFICE



490, rue de la Couronne  
 Québec (Québec) G1K 9A9 Canada  
 Tel.: 418-654-2606  
 Fax: 418-653-0777

Layout: POULIOT GUAY GRAPHISTES  
 Copy editor: THOMAS CLARK  
 Proofreaders: THOMAS CLARK and DOLORES DURANT  
 Printer: SOLISCO

The opinions expressed in this magazine are those of the authors and do not necessarily reflect the views of the publishers.

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

## ALL THAT GLITTERS...



Hap McSweeney

My father had lots of wise aphorisms, including “All that glitters is not gold.” That old saying and this interesting *Elements* issue on gold prompt a timely perspective on how we conduct and archive our science. Mineralogy, petrology, and geochemistry—the main subjects of interest to the societies for which *Elements* was founded—have grown substantially in the numbers of practitioners and in their capacities to churn out huge amounts of analytical, experimental, and computational data. In fact, the volumes of data have become so large that government agencies are now exploring comprehensive, computer-based databases that can be interactively searched and utilized in research. But before these databases actually become reality, a fair question to ask is: *What are the gold standards for data, and how much data actually meet those standards?*

We all know that some laboratories produce better analyses than others. In implying that some analyses are substandard, I am not talking about fraudulent data—those cases are extremely uncommon, and our societies do a good job of policing that. Rather, I am referring to data produced by inadequately trained analysts and improperly supervised students, data from laboratories with poor sample-handling protocols and outdated instrumentation, and data with unacceptably large or even unknown uncertainties. Before we build global databases, should we not impose some screens on the quality of our analyses?

Some readers might respond by noting that science is self-correcting and might suggest that the peer review process can be counted upon to weed out substandard data. That does occur, of course, but I doubt that journal editors and reviewers always have the analytical experience and expertise to recognize substandard data. It is also unlikely that funding agencies will recognize and support the acquisition of only those data that meet the gold standard. So, if you accept that policing of data quality is appropriate, whose job should it be? I suggest that our scientific societies should take the lead. We—that is, those scientists in each discipline—should define analytical standards and provide mechanisms for investigators to check their data against those standards.

I’m not alone in worrying about this issue. A new report by the U.S. National Academies (*Ensuring the Integrity, Accessibility, and Stewardship of Research Data in the Digital Age*, National Academies Press, 2009) addressed this matter, at the behest of several scientific journals. A major conclusion from that study is that defining guidelines for data integrity for the whole community of science is impossible, because of differences among the

various disciplines. It thus falls to us, the practitioners in each field, to identify the gold standards for data in our discipline.

Consider the example of a scientific community that is already well ahead of the pack in this regard. High-precision geochronologists, who measure the isotopes of uranium, lead, and argon to define precisely the ages of rocks, have made considerable strides in setting a gold standard for themselves. They have established the EARTHTIME organization to coordinate their international efforts. The U-Pb laboratories are sharing standards, gravimetric solutions, and tracers, and the Ar isotope laboratories are exploring differences in sample pretreatments, irradiation and analytical protocols, and data reductions, all in a concerted effort to minimize interlaboratory biases and improve data quality. The importance of this effort to the geosciences is summarized by the mantra “No dates, no rates,” and the recent successes of this group are apparent in published literature. However, this kind of self-inspection is not easy and, as noted by the effort’s leader, Sam Bowring, “You have to check your ego at the door.”

Another noteworthy example is provided by one of the member organizations of *Elements*, the International Association of Geoanalysts. This organization offers a proficiency-testing program for laboratories involved in the analysis of silicate

rocks. They offer test samples for both whole-rock and microbeam techniques, as well as a compilation of reference materials. The Clay Mineral Society holds the Reynolds Cup biennially for the analysis of clay mixtures.

A related problem is how to control data quality in private laboratories that do custom work for others, when

those data are later published in scientific contributions. Many laboratories provide their analyses of standards, but these are not usually included in publications.

These examples are from the world of analytical geochemistry, but similar approaches could be applied to other areas of the geosciences, including mineralogy, hydrologic and environmental studies, and experimental petrology and geochemistry. One colleague has noted that the literature describing experimental determinations of diffusivities, partition coefficients, solubilities, and the like contains lots of questionable data, and that nonexperts understandably have trouble separating good results from bad. Even disciplines like geologic mapping probably need to impose some quality control on the information that is incorporated in these global databases. Ensuring data quality may be especially important when those data are likely to be used to support the development of public policy.

Let me add a dose of reality here. I am not advocating that all published or archived data must necessarily achieve the same high levels of accu-

Cont’d on page 268

**THIS ISSUE**

Gold! How can such a topic be covered in 36 pages of text? So many angles are possible, and so many books have been written on the various types of gold deposits, not to mention the cultural, historical, health, economic, industrial and scientific aspects of this treasured Earth material. This is the challenge every guest editor faces: how to give as broad an overview as possible while highlighting key frontier areas. Guest Editors Robert Hough and Charles Butt—our first guest editors from Australia—have risen to the challenge and orchestrated contributions from an international cast of authors. Of great interest to me was how gold nanoparticles are being investigated to aid the diagnosis and treatment of cancer.

One angle that is not covered in this issue, however, is the environmental impact of extracting a few grams of gold from a ton of rock and disposing safely of the resulting huge quantities of waste. To be fair, the topic of mine wastes would deserve a whole issue, and we hope to add this theme to our lineup in the near future. Proposals on this topic would therefore be viewed favorably by the editors.

Two of the articles in this issue make extensive reference to a 1979 Geological Survey of Canada publication by Robert W. Boyle (1920–2003), *The Geochemistry of Gold and Its Deposits*. I met Dr. Boyle and his family at the 1992 GAC-MAC meeting in Wolfville, Canada; he was a very kind and humble man, and I did not realize at the time that I was talking to a “giant,” one of Canada’s most distinguished geologists. Dr. Boyle spent his career at the Geological Survey of Canada and became a world expert on gold and silver deposits. He developed geochemical prospecting methods suited to the Canadian environment, and these became truly practical tools in mineral exploration. He published major works, notably *Gold: History and Genesis of Deposits* in 1987. The mineral boyleite was named in his honor. And his 1979 bulletin seems to have stood the test of time.

**MULTISOCIETY CATALOGUE**

Our 2010 multisociety catalogue is being mailed with this issue of *Elements*. This is the fifth catalogue we have published, and it is a truly cooperative venture involving several of the participating societies. I suggest you keep it handy during the coming year or give it to a colleague or student as an encouragement to join one of the participating societies and thereby receive *Elements*.

The idea of a multisociety catalogue was first put forward by Kevin Murphy of the Mineralogical Society of Great Britain and Ireland at the 2002 IMA meeting in Edinburgh. At the time, even though interest was expressed, the idea did not move beyond the discussion stage. It is therefore fitting that I turned to Kevin to help with assembling this catalogue, and I thank Kevin for his cheerful help.

**SPECIAL OFFER**

We are making a special offer to libraries and departments that will receive a subscription to *Elements* in 2010: for an extra \$200, they can receive all back issues, from Volume 1, Number 1 to Volume 5, Number 6. Get them while copies last (see page 20 of catalogue).

**ELEMENTS IS YOUR MAGAZINE**

Several of our features need our members’ involvement. If one of your colleagues has been recognized for his or her work or has done something extraordinary, consider submitting a short note and picture for **People in the News** or for your society pages. Have you attended a fantastic meeting? Send us some of the highlights for **Meeting Reports**. Have you done field work in, or taken a field trip to, an exotic place? Contact the managing editor about the possibility of publishing your adventures in **Travelogue**. You might want to share some outstanding images in **Parting Shots**. And finally, if your field of research is rapidly expanding and of interest to the *Elements* readership, consider the requirements for an *Elements* issue ([www.elementsmagazine.org/proposal.htm](http://www.elementsmagazine.org/proposal.htm)) and propose an issue, or at least let us know you would like to read about such a topic. We are always on the lookout for exciting topics.

**Pierrette Tremblay**  
Managing Editor

**About Minority Participation**

Sam Musaka’s Triple Point article on underrepresentation of women and minority awardees in geoscience societies (volume 5, number 2, pp 77–78) was most important and timely, and I thank the author for addressing this issue. There is indeed a long way to go toward overall diversity in the geosciences, including medals/awards. Although I am a past recipient of the Clarke Medal and not of European descent, I am amazed that after over 20 years in this field I have seen so little change with regards to cultural diversity and minority participation at meetings and on research expeditions/cruises, etc. Women, on the other hand, have done much better (other than in the awards category), and Asian and East Indian geoscientists also seem to be making strides. International diversity is great and also important, but progress in this and in gender diversity should not overshadow or be perceived to address the continued lack of presence/participation of other groups, especially U.S. minorities (e.g. Native American, African American, Hispanic, Pacific Islander) in U.S. institutions! From my experience, this has not changed much and may have even declined for some groups over the past 20 years.

**Ruth Blake**  
Department of Geology and  
Geophysics, Yale University

**BACK ISSUES  
OF ELEMENTS ARE  
NOW AVAILABLE**

**ORDER ONLINE AT  
[www.elementsmagazine.net](http://www.elementsmagazine.net)**

**EDITORIAL** *Cont’d from page 267*

racy and precision. There is an important place for data acquired by professionals in survey mode, and analyses by students are critical aspects of the learning process even though such data may not always be of high quality. I am arguing that we should not knowingly mingle those data with high-quality data in large databases. Nowadays, when X-ray diffractometers are compact enough to sit on desktops, when electron microprobes substitute for optical microscopes, when ICP mass spectrometers sprout like weeds and ion microprobes are in routine use, some gold standards for analytical data are needed. And

other disciplines such as experimental geochemistry and field studies might also benefit from judicious oversight. Our science is just too important to be compromised by glitter. I hope more of our societies take up the challenge.

**Hap McSween\***  
[mcsween@utk.edu](mailto:mcsween@utk.edu)

\* Hap McSween was the principal editor in charge of this issue.

## ASBESTOS SANS MINERALOGY? A VIEW FROM A DIFFERENT HILLTOP



Gregory Meeker

After reading Professor Mickey Gunter's June Triple Point article, I believe a view from a different hilltop might be in order. For the last ten years, most of my work and research has been on asbestos and the public issues surrounding it. My colleagues at the U.S. Geological Survey and I—professionals in the geology of asbestos; in mineralogy, geochemistry and the health effects of minerals; in microanalysis; and in remote sensing—have provided independent scientific assistance to other federal agencies on issues ranging from the Libby, Montana, asbestos Superfund site to the California “naturally occurring asbestos” (NOA) controversy.

Throughout this work, we have emphasized the importance of rigorous geoscience and encouraged the use of correct terminology and nomenclature. From this background I would like to provide additional perspective on a few of the issues Professor Gunter has raised.

*Mineralogists have not been out of the loop with regard to asbestos issues and policy.* In fact, prominent mineralogists have published in the asbestos literature for decades. Mineralogists, along with toxicologists, epidemiologists, physicians, microscopists, attorneys, lobbyists, regulators, judges, elected officials, and corporations, are all responsible for the progress, or lack thereof, in dealing with the very serious issue of asbestos-related disease. The current state of affairs is a result of give-and-take among competing interests in an arena where all voices have been heard.

Gunter takes exception to a recent legal definition of asbestos; but there is more to that story. For over 70 years, the fibrous amphibole that is a major—not trace—constituent in the Vermiculite Mountain vermiculite deposit near Libby, Montana, was called tremolite, sodium-rich tremolite, or sodic tremolite by everyone including the mineralogists and geologists who studied the deposit. During the 1970s, the names of the regulated asbestos minerals, including tremolite asbestos, were entered into the U.S. Code of Federal Regulations. As recent court proceedings have revealed, company geologists, owners, and operators of the vermiculite mine near Libby understood that the asbestiform amphiboles in the mine fell under those regulations. In 1978 and 1997, committees of the International Mineralogical Association published new recommendations for amphibole nomenclature. Based on this new system of nomenclature, most of the amphibole minerals at the Libby mine were reclassified as winchite. When public and regulatory attention returned to Libby in 1999, mineralogists working on behalf of the company that owned the mine used the changes in nomenclature to claim that the majority of the Libby amphibole had been mistakenly identified as tremolite and therefore was not regulated. A federal judge sided with the defense and, based on a 2003 USGS study of the minerals, ruled that only 6 percent of the Libby asbestos was regulated. This ruling was appealed by federal prosecutors who successfully argued that all of the Libby asbestos still fell under the American Chemical Society's Chemical Abstract Service (CAS Registry) general definition of asbestos: a “grayish, non-combustible material [that] consists primarily of impure magnesium silicates.” Contrary to Professor Gunter's assertion, mineralogists were not bystanders in this process. Reports by the Subcommittee on Amphiboles of the IMA Commission on New Minerals and Mineral Names<sup>1,2</sup> changed the classification method for amphiboles perhaps without understanding some of the legal and public health consequences. Mineralogists then struggled to explain to regulators and the public why something that had always been called tremolite was now called winchite. Finally, mineralogists helped to construct the legal arguments as to what should and should not be considered a regulated material.



Whether we appreciate it or not, the mineralogical term “asbestiform” is a fundamental part of the legal definition of “asbestos.” The Occupational Safety and Health Administration (OSHA) and the Mine Safety and Health Administration regulate only the asbestiform varieties of tremolite, actinolite, riebeckite, cummingtonite, anthophyllite, and chrysotile. However, “asbestiform” describes a crystal growth habit with unique properties such as flexibility and high tensile strength, properties that have never been directly linked to disease. Therefore, using the term “asbestiform” to differentiate a hazardous from a non-hazardous substance has no foundational basis in the medical sciences. Toxicological evidence comparing human and animal health effects of asbestiform and non-asbestiform minerals is based primarily on particle size and shape and remains controversial<sup>3</sup>. In 1992 OSHA made the decision to not regulate cleavage fragments (mineral particles broken along cleavage planes). This decision appeared to open the door for some mineralogists and others to narrow their definition of “asbestiform,” thus calling anything that did not meet this narrow definition unregulated cleavage fragments. During the Libby criminal trial, experts for the defense claimed that fibers of Libby asbestos, clearly of respirable size and with aspect ratios of more than 20:1, were not really asbestos fibers. These experts argued that, because the sides of the fibers were stepped or the cross sections of the fibers were prismatic and not round, the material could not be asbestos. Of course, the real issue lost in these arguments is not what fits someone's mineralogical or commercial definition of asbestos, but what is toxic.

Finally, consider the asbestos ban that passed in the Senate of the 110<sup>th</sup> Congress but died in the House without leaving committee. Several of my USGS colleagues and I were asked to provide technical assistance to both the House and Senate committees working on the bills. Neither bill banned all mineral particles greater than 3:1 in aspect ratio, as Gunter implies. In fact, the only change to minerals regulated in either bill was to add “amphibole asbestos” to the existing list of six asbestos minerals. Nor was the definition of “asbestiform” changed in either bill from what it has been for decades. What the Senate bill did provide was funding for extensive research to investigate the toxicity of elongate mineral particles, with the idea of improving our understanding of the roles morphology and other physical and chemical properties of minerals play in asbestos disease. All stakeholders should enthusiastically welcome such research.

The examples above demonstrate some of the complexities of how multiple, and often opposing, interests have shaped the asbestos landscape, and some of the roles played by mineralogists in the process. The simple fact that asbestos is a natural Earth material does not mean that we as mineralogists own the issues and get to drive the boat. Terminology in the asbestos community serves many purposes and needs. For example, the term “elongate mineral particle” serves to describe a wide variety of minerals that are included in the research agenda of the National Institute for Occupational Safety and Health. The term was never intended as a substitute for more specific mineralogical terminology and was not intended for regulatory language. As mineralogists and geologists, we must understand that exposure to airborne asbestos is primarily an occupational, environmental, and public health issue. The job of Earth scientists is not to decide what is toxic; our job is to assist the health community and regulators by carefully describing the physical and chemical properties of natural materials, understanding their occurrence, and providing scientifically rigorous terminology when needed. If, in this multidisciplinary process, terms appear that we would not normally use, such as “naturally occurring asbestos,” we should be somewhat tolerant and understand that we are all trying to reach the same goal: preventing unnecessary future suffering and death from asbestos-related disease.

**Gregory Meeker**  
U.S. Geological Survey

<sup>1</sup> Leake BE (1978) *Canadian Mineralogist* 16: 501-520

<sup>2</sup> Leake BE et al. (1997) *Canadian Mineralogist* 35: 219-246

<sup>3</sup> [www.cdc.gov/niosh/docket/pdfs/NIOSH-099b/099B-040109AsbestosNARReviewDoc.pdf](http://www.cdc.gov/niosh/docket/pdfs/NIOSH-099b/099B-040109AsbestosNARReviewDoc.pdf)

*Mickey Gunter's response on page 270*

2009 AGU VGP FELLOWS

Congratulations to the 2009 Fellows of the American Geophysical Union (Volcanology, Geochemistry, and Petrology Division):



**JAY D. BASS**

For his pioneering work using Brillouin spectroscopy to study the elasticity of Earth materials and applying these data to understand the internal structure of Earth



**IAN H. CAMPBELL**

For his seminal insights into mantle plumes, the dynamics of layered igneous intrusions, the genesis of platinum and related ores, and the development of continental crust



**KATHARINE V. CASHMAN**

For developing tools to quantitatively characterize volcanic rock textures and for using textural measurements to elucidate the dynamics of magma transport and eruption



**DONALD B. DINGWELL**

For research leading to a thorough and deep appreciation of the physics and chemistry of magma rheology and volcanic eruptions, thereby replacing an empirical approach to these processes



**STEVEN L. GOLDSTEIN**

For seminal studies using radiogenic isotopes in sediments and igneous rocks to trace the evolution of the Earth's crust and mantle as well as paleo-ocean circulation



**KEY HIROSE**

For his groundbreaking contributions to our understanding of the Earth's lowermost mantle and for the discovery of the post-perovskite phase transition



**JONATHAN P. PATCHETT**

For his pioneering work in the application of Hf isotope geochemistry to the geosciences and for contributions to our understanding of the origin and growth of continental crust



**FREDERICK J. RYERSON**

For his contributions to our understanding of transport processes in minerals, magmas, and crustal rocks at all scales



**RICHARD J. WALKER**

For developing the Re-Os isotope system into a useful tool and applying it to achieve fundamental discoveries in a wide range of topics in the Earth and planetary sciences

**EMU RESEARCH EXCELLENCE MEDAL TO ANDERS MEIBOM**

The European Mineralogical Union Research Excellence Medal is awarded annually to young scientists who have made significant contributions to research and are active in strengthening European scientific links. The EMU medallist committee has awarded the 2008 silver medal to Anders Meibom. Born in 1969, he obtained a PhD in physics at the University of Odense in 1997 and then held a postdoctoral position at the Institute for Geophysics and Planetology at the University of Hawai'i. Since 2005, he has been a member of the team at the Laboratoire de Minéralogie et Cosmochimie at the Muséum National d'Histoire Naturelle in Paris.



EMU's President Roberta Oberti awarding the EMU Research Excellence Medal to Anders Meibom

Ander's main interest is cosmochemistry. He is involved in a number of international projects and networks aimed at investigating the anatomy of primitive solar system materials, including early isotopic fingerprints. Anders takes part in interdisciplinary research merging biology, geochemistry, and mineralogy to better understand biomineralization and past climate change. Expeditions to recover meteorites have taken him around the world, from Greenland to Antarctica. The remarkable results from his work are related to the understanding of extraterrestrial materials and the early Earth. He is also interested in modelling thermodynamic and kinetic processes. He has published more than 70 papers in international peer-review journals and more than 100 abstracts from national and international meetings and conferences.

Anders Meibom is an excellent lecturer and a very enthusiastic and generous collaborator. He is regularly invited to give talks at international meetings and universities worldwide. He is currently an associate editor of *Geochimica et Cosmochimica Acta* and serves on the committee of the Meteoritical Society. For the relevance and international dimension of his work, Anders Meibom is a highly deserving recipient of the EMU Research Excellence Medal for 2008. His talk "NanoSIMS on Carbonates: From the Solar Nebula to the Modern Coral Reef" was given during the 2009 EGU meeting.

**ASBESTOS SANS MINERALOGY? A VIEW FROM A DIFFERENT HILLTOP – Mickey Gunter's response**

Greg Meeker's response (page 269, this issue) to my article "Asbestos Sans Mineralogy" (*Elements* 5: 141) provides much needed insight into ongoing asbestos issues (i.e. the unintended consequences of changes in mineral nomenclature). My intention in writing the article was to point out what I think should shock any mineralogist: mainly, a "new legal definition of asbestos" that did not include the word mineral, and the misuse of mineralogical nomenclature.

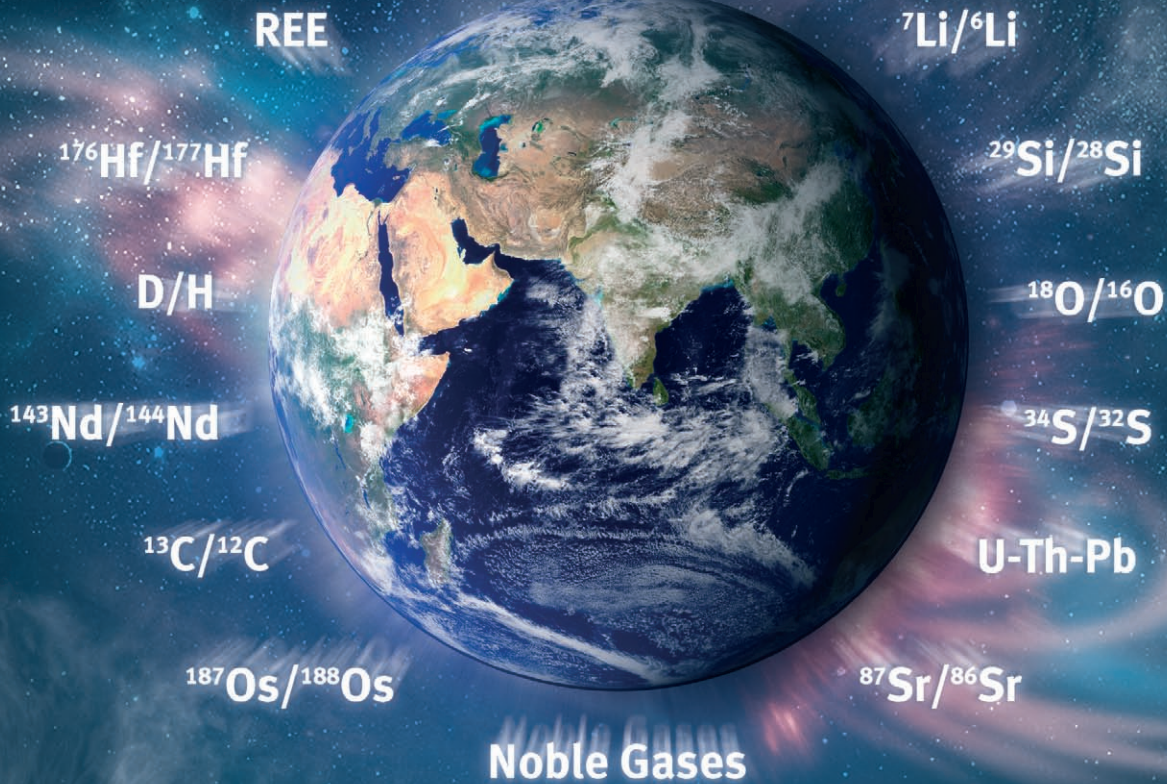
I stated that the vermiculite ore at Libby contains "trace" amounts of amphibole; Greg states that the Libby deposit contains "major" amounts of "fibrous amphiboles." Greg has defined "trace" as less than 5% and "major" as greater than 25% (Meeker et al. 2003), and he showed that samples the USGS collected at the mine all contained amphiboles as a major component; but these samples were collected in amphibole-rich areas, not in vermiculite ore. From our work (Gunter et al. 2007), we showed that the amphibole content of products produced from the ore was less than 1%, and we also showed

that only a portion of the amphiboles is asbestiform. Our unpublished results indicate that tailings contain around 5% amphiboles. We know that many amphiboles in Libby soils did not originate from the vermiculite mine (Gunter and Sanchez 2009). This case points out the need for thorough, unbiased characterization of minerals by professional mineralogists.

I stated that the Ban Asbestos bills would define asbestos as having an aspect ratio of 3:1 or greater. As might be guessed, there is more to this story. If you read these bills (House bill: [www.govtrack.us/congress/billtext.xpd?bill=h110-6903](http://www.govtrack.us/congress/billtext.xpd?bill=h110-6903); Senate bill: [www.govtrack.us/congress/billtext.xpd?bill=s110-742](http://www.govtrack.us/congress/billtext.xpd?bill=s110-742)), you will see they refer to other documents to define asbestos, and if you track through all of them you end up with the definition being chrysotile, crocidolite, amosite, and the asbestiform habit of the minerals actinolite, anthophyllite, and tremolite. From Greg's point of view, the "door was opened" to

Cont'd on page 329





## The memory of the Earth – New tools to retrieve the information.

To unravel the Earth's history and composition, high precision and high sensitivity are the keys.

The new *Plus features* of the Thermo Scientific NEPTUNE *Plus* and TRITON *Plus* represent a major step forward in MC-ICPMS and TIMS technology leading to ultimate sensitivity and precision for the smallest sample sizes.

Thermo Scientific mass spectrometers are the first choice when isotope ratio determinations or trace elemental analysis of the highest accuracy and precision is required. All Thermo Scientific instruments embody the same spirit of "no compromise" combining long experience with the latest technology.

For further information visit our geochemical resource center at [www.thermo.com/grc](http://www.thermo.com/grc)



New Thermo Scientific  
NEPTUNE *Plus* and TRITON *Plus*

## ERNEST HENRY NICKEL (1925–2009)

Ernest (Ernie) Nickel, an Honorary Fellow with CSIRO Exploration and Mining in Perth, Western Australia, died on 18 July 2009, a few weeks after being diagnosed with cancer. He was 83. Ernie was an internationally recognized mineralogist, with a unique eponymous relationship with the primary and secondary minerals he most closely studied – those associated with oxidizing nickel sulfide deposits. Latterly, his greatest passions were the classification and nomenclature of minerals. He had a significant impact on international mineralogy through his work with the International Mineralogical Association and professional mineralogical associations.

Ernst Heinrich Nickel was born in Louth, Ontario, Canada, on 31 August 1925, although it was not until he was in his twenties that he learned these were the true spellings of his forenames. During his childhood on a hard-scrabble farm in the years of the Great Depression, his interest in geology was triggered by the great variety of pebbles in the glacial debris that comprised the farm soil. But it was a school excursion to the Royal Ontario Museum in Toronto that led to his abiding interest in the wonderful world of minerals.

Ernie obtained his BSc and MSc at McMaster University in Hamilton in 1950 and 1951, respectively, and his PhD at the University of Chicago in 1953. He then began a long and productive career with the Mineragraphic Laboratory of the Mines Branch, Canadian Department of Mines and Technical Surveys (now CANMET). There, he published nearly forty papers on an eclectic range of topics, including descriptions of three new mineral species, niocalite, wodginite and cuprospinel, along with notes on mineral assemblages from Canadian localities, some papers on colour and pleochroism in minerals, and a contribution on the social responsibility of scientists.

By 1971, Ernie had attained the position of Head of the Mineralogy Section at the Department of Energy, Mines and Resources, and frequently functioned as Acting Chief of Division. However, the increasing administrative load left him very little time for working with the minerals he loved, so he started looking around for a position that would allow him more time for hands-on mineral studies. The nickel deposits in Western Australia had sparked a big exploration boom, which resulted in a shortage of geologists and mineralogists there. Ernie successfully applied for a position in CSIRO's then Division of Mineralogy in Perth.



Through CSIRO's strong research links with the mining industry, Ernie was truly in his element (forgive the pun). A series of papers on the primary and secondary mineralogy of the famous nickel sulfide deposits was published during the 1970s and 1980s, including descriptions of the new species carboydite, nickelblödite, otwayite, nullagine and kambaldaite. These are hydrated nickel sulfates and carbonates which form greenish crusts and veinlets in the oxidized zone, and they proved to be challenging minerals to characterize. In time, Ernie became a Chief Research Scientist at CSIRO, with minimal administrative duties, but he 'retired' early, in 1985, to allow his salary to be used to employ more young scientists. He once remarked that he was fortunate that his work was also his hobby. Consequently, he continued almost full-time as a CSIRO Honorary Fellow for the next 24 years, cycling daily to his office. His published bibliography includes over 120 research papers and books, including 24 new-mineral descriptions. Recently, he catalogued CSIRO's extensive collection of gold specimens and nuggets, and is pictured here with an 8 kg nugget.

Ernie's most significant and long-lasting contribution to international mineralogy was perhaps in the classification and nomenclature of minerals. In 1974, he became Australia's representative on the International Mineralogical Association's Commission on New Minerals and Mineral Names (CNMMN), now the Commission on New Minerals, Nomenclature

and Classification (CNMNC). A decade later, he took on the role of vice-chairman, teamed with noted Canadian mineralogist Joe Mandarino as chairman, and together they launched the CNMMN into a new era. Ernie extended his activities by developing several voluminous databases. He co-authored (with Monte Nicholls) the MINERAL database, which covers all IMA-approved and 'grandfathered' species, as well as minerals that have been discredited or redefined; his database is updated regularly for the CNMNC website. With Dorian Smith, Ernie also prepared a coded reference list of unnamed minerals that have been described in the mineralogical literature. His other compilations include the *Mineralogical Reference Manual* (1991) and the landmark 9<sup>th</sup> edition of the *Strunz Mineralogical Tables* (2001).


Professional organisations also benefited from Ernie's contributions. He had two life memberships in the Mineralogical Association of Canada, joining in 1954 and becoming president in 1970–1971. He had also been a member of the Mineralogical Society of America and the Mineralogical Society of Great Britain and Ireland since the 1950s. The latter society elected him an Honorary Fellow in 2008, fitting recognition of the exceptional contributions he made to mineralogy for over half a century. Ernie's nickelite – ideally  $\text{NiMn}^{4+}_3\text{O}_7 \cdot 3\text{H}_2\text{O}$  – a member of the chalcophanite group from one of the lateritic Ni–Co deposits of the Kalgoorlie region of Western Australia, was named in his honour in 1994.

During his remarkable professional career, Ernie never lost touch with the world of the knowledgeable amateur collector. He was the 'go-to' person for identification of unknown minerals found by collectors roaming the virtually unlimited deposits of Western Australia. Ernie also provided active support to the Australian mineralogical societies and to the *Australian Journal of Mineralogy*, as both editor and contributor.

Family life was always important to Ernie. He had three daughters with his first wife, Muriel, who died prematurely from cancer when she was just 50. Ernie remarried, to Eileen, after they'd met at his local bridge club, where he was president and she was secretary. Eileen survives him, as do his three daughters.

Ernie was very concerned to 'tidy up loose ends' when he was confronted by the inevitable outcome of his illness. He remained lucid and stoic to the end, keen for conversation, and this memory of him will no doubt help his family and friends come to terms with his passing.

**William D. Birch**  
Museum Victoria, Melbourne, Australia



Congratulations to the University  
of Granada, Spain, on their selection  
of the **ASI SHRIMP IIe/MC**

**SHRIMP IIe/MC - the clear SIMS choice**

- Performance** SHRIMP was the first and still is the highest performing ion microprobe, with applications to Pb/U geochronology, trace elements, stable isotopes and nuclear forensics.
- Productivity** Nothing comes close to the high reliability, comprehensive support and training, and ease of operation of the SHRIMP IIe.
- Publications** Work on SHRIMPs has produced thousands of scientific papers and citations, many more than work on similar competing instrumentation.
- Price** SHRIMP IIe has never been beaten on price, in any tender anywhere in the world.

*ASI is pleased to welcome another group  
to the vibrant worldwide SHRIMP community.*

**SHRIMP II**

**Pioneering the Technique > Perfecting the Technology**

# Meet the Authors



**Robert J. Bowell** is Principal Geochemist with SRK Consulting in Cardiff, Wales. He holds a BSc in geochemistry from the University of Manchester and a PhD from Southampton

University. He is a visiting research fellow in geochemical engineering at Cardiff University where his main fields of expertise are the geometallurgy of uranium deposits, the prediction of mine-waste geochemistry, and the recovery of precious and base metals from complex metal ores and mine wastes. He is an active micromounter specializing in gold and sulfide oxidation-product minerals.



**Charles R. M. Butt** has a BA in geology and chemistry from Keele University and a PhD in applied geochemistry from Imperial College, London. He joined CSIRO in Australia in

1971 and is currently a Chief Research Scientist. His principal research interests have been the development of geochemical exploration procedures appropriate to deeply weathered and lateritic terrains, and the genesis of secondary mineral deposits, including those of gold. He was elected a Fellow of the Australian Academy of Technological Sciences and Engineering in 2004 and appointed as a CSIRO Fellow in 2007. He has served as an associate editor of the *Journal of Geochemical Exploration* (1976–1999) and of *Geochemistry: Exploration, Environment, Analysis* (2000–present).



**James S. Cleverley** is a senior geochemist and leader of the Computational Geoscience Group at CSIRO Exploration & Mining in Perth, Western Australia. After completing his BSc at Plymouth

University, MSc at Leicester University and PhD at the University of Leeds, James moved to Australia to take up a postdoctoral position in the Economic Geology Research Unit at James Cook University. In 2006, James moved to CSIRO in Perth where he is applying hydrothermal geochemistry, simulation science and microchemical characterization to our understanding of fluids and dynamics in ore systems. Through his work on IOCG, copper, Archean gold, uranium and sediment-hosted base metal systems, he firmly believes there are ingredients common to all of them.



**Claire M. Coble** graduated with a BS in chemistry from Brown University (2006) and an MS in chemistry from the University of Washington (2007). She is pursuing her PhD in biomedical

engineering with Younan Xia at Washington University in St. Louis. Her research interests include the synthesis, analysis, and applications of metal nanostructures.



**David R. Cooke** received a PhD from Monash University and has researched the characteristics and origins of gold-rich porphyry copper and epithermal deposits throughout the Southwest

Pacific, Australia, and the Americas. He is currently the leader of the "Formation" research program at the Centre for Excellence in Ore Deposits at the University of Tasmania.



**John H. Dilles** received an MSc from Caltech and a PhD from Stanford University. He has worked for Hunt, Ware & Proffett and as an operator of small gold mines with his brother Peter. He is

currently a professor in the Department of Geosciences at Oregon State University. His research focuses on the geology of Cordilleran porphyry copper deposits, magmatic processes that generate hydrothermal fluids, structural geology, isotopic tracers, and geochronology. He is active in the Society of Economic Geologists and chairs the Minerals and Energy Section of NASULGC to advocate for federal support of universities.



**Lintern Fairbrother** holds a BSc (honours) in nanotechnology from Flinders University of South Australia, where he is currently a PhD candidate in the School of Chemistry, Physics

and Earth Sciences. He is also an affiliate at the University of Adelaide and CSIRO Land and Water. Lintern is undertaking an investigation into the formation of gold grains in the Australian regolith with a focus on the bacterial biomineralization of secondary gold. He specializes in focused ion beam scanning electron microscopy (FIBSEM) and inductively coupled plasma mass spectrometry (ICP-MS).



**Jörg Fischer-Bühner** holds a PhD in physical metallurgy and materials technology from the technical university RWTH Aachen, Germany. He is currently active in

research and development for INDUTHERM Erwärmungsanlagen GmbH (Walzbachtal, Germany) and for LEGOR Group Srl (Bressanvido, Italy). Earlier, he was head of the Division of Physical Metallurgy at FEM, Research Institute for Precious Metals and Metal Chemistry (Schwäbisch Gmünd, Germany). His work has included manufacturing support, failure analysis, training, and consultancy to manufacturing companies. His research has focused on alloy properties and manufacturing technologies, especially precious metal alloys for jewellery, dental, and electrical engineering applications.



**Robert M. Hough** is a senior research scientist with CSIRO Exploration and Mining based at the Australian Resources Research Centre in Perth; he joined CSIRO in 2002. He has a BSc in geology

from the University of London and a PhD from the Open University, UK. He now leads an area of frontier research on gold in the Minerals Down Under Flagship. He studies the metal at all scales, from nanoparticles to 8 kg nuggets. His research is aimed at understanding the controls on gold transport and deposition in both high- and low-temperature geological environments, in support of an active gold exploration industry in Australia.



**Maggie F. Lengke** is a senior geochemist at Geomega Inc. in Boulder, Colorado. She received a PhD in hydrogeology from the University of Nevada at Reno in 2001. She has worked as a

postdoctoral researcher at the University of Western Ontario, Canada. Her research interests include environmental geochemistry, biogeochemistry, and nanoscience. Her current work focuses on kinetic mineral dissolution/oxidation models, the development of mine pit-lake and waste-rock models, and the interactions between bacteria and metals or chlorinated organic compounds.



**Artashes A. Migdisov** is a research scientist at McGill University, Canada, where he runs the laboratory in experimental hydrothermal geochemistry. He received his PhD in geology and mineralogy

in 1995 from Moscow State University, Russia, and then held a postdoctoral fellowship at McGill University. His research interests are in the fields of ore-forming processes and fluid–mineral interaction, which he studies through laboratory experiments designed to produce thermodynamic data for modeling equilibria in aqueous fluids and at the surfaces of solids. He has made important contributions to our understanding of the behaviour of the REE in hydrothermal systems and the vapour transport of metals.



**Frank Reith** is a geomicrobiologist at the Centre for Tectonics, Resources and Exploration, School of Earth and Environmental Sciences, University of Adelaide. His research is aimed at understanding

the interactions of microbes and trace metals, especially gold, in the supergene environment. He uses a wide variety of techniques, such as synchrotron microanalysis, electron microscopy, transcriptome microarrays, and metagenomic approaches. After his MSc (Diplom) at the University of Bayreuth, Germany, he moved to Australia, where he received his PhD from the Australian National University in 2006. Since then he has held postdoctoral appointments at CSIRO and the University of Adelaide.



**Gordon Southam** is a professor and Canada Research Chair in geomicrobiology in the Departments of Earth Sciences and Biology at the University of Western Ontario, Canada. His

research on bacteria–mineral interactions encompasses microbiology, geochemistry, and mineralogy. It includes the examination of life in extreme environments, such as the deep subsurface of South Africa (4 km below land surface in the gold mines of the Witwatersrand Basin); the control of greenhouse gas emissions via bacterial carbonation reactions; the bioremediation of inorganic and organic pollutants; and the role of bacteria in the formation of ore deposits, in particular, the biogeochemistry of gold.



**Richard M. Tosdal** received an MSc from Queen's University (Kingston) and a PhD from the University of California, Santa Barbara. He worked for the U.S. Geological Survey and

most recently was the director of the Mineral Deposit Research Unit at the University of British Columbia. He currently is an independent consultant to the minerals industry and holds an adjunct appointment at the University of British Columbia. His research focuses on the geologic and metallogenic evolution of plate margins and on the structural controls of ore deposition.



**John L. Walshe** is Chief Research Scientist, CSIRO Exploration and Mining, and is based at the Australian Resources Research Centre (ARRC) at Kensington, Perth, Western Australia. Since

joining CSIRO in 1996, he has contributed to developing mineral systems concepts and their application to mineral exploration in the Eastern Goldfields, Western Australia, through the AGCRC (Australian Geodynamics) and pmd\*CRG (Predictive Mineral Deposits) Cooperative Research Centres. His is particularly interested in Earth-scale geochemical systems, their links to mineral systems and the processes of formation of the Earth's giant resources. Prior to joining CSIRO, he lectured in economic geology at the Australian National University, Canberra. He is a graduate of the University of Tasmania.




**Anthony E. (Willy) Williams-Jones** is a professor in economic geology and geochemistry at McGill University, Canada. He received his early education in South Africa, completing BSc

and MSc degrees at the University of Natal. He then immigrated to Canada where he earned a PhD at Queen's University (Kingston) and worked for several years as an exploration geologist. His research, which combines field-based and experimental approaches, focuses on the behaviour of metals in crustal fluids in the context of ore genesis and has been published in over 130 peer-reviewed journal articles. He is an associate editor of several journals and a fellow of the Royal Society of Canada.




**Younan Xia** received a BS in chemical physics from the University of Science and Technology of China in 1987, an MS in chemistry from the University of Pennsylvania in 1993, and a PhD in

physical chemistry from Harvard University in 1996. He was appointed an assistant professor of chemistry at the University of Washington in Seattle in 1997 and was promoted to professor in 2004. He moved to Washington University in St. Louis in the fall of 2007 and is now the James M. McKelvey Professor of Biomedical Engineering. His research interests include nanostructured materials, nanomedicine, biomaterials, self-assembly, photonic crystals, colloidal science, surface modification, and electrospinning.



### Journals

GSW's online service, the *GSW Millennium Collection*, includes peer-reviewed articles and other materials with linked reference lists from over 30 high-impact journals in a broad range of geoscience areas. The digital collection is updated continuously with the most current journal issues. All journals have a minimum of one back year, and most in the database start with the year 2000. A Literature Archive of pre-2000 articles enhances the *Millennium Collection*.



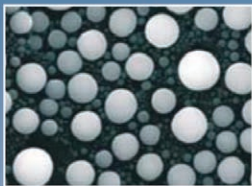
**30-day free trials available**  
**Check it out at:**  
[www.geoscienceworld.org](http://www.geoscienceworld.org)

### GeoRef

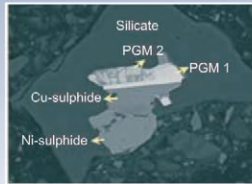
A primary strength of GSW is the ability to search full text in a linked collection, but GSW is also integrated with GeoRef, the premier abstracting and indexing database in our field. GSW's fully-searchable version of GeoRef is updated weekly, making it the most current version of GeoRef available anywhere.



MLA



MLA 600F (above)  
MLA 600 (below)



SEM Micrograph



**Actlabs has added a Mineral Liberation Analyser (MLA600F) to its array of services. The MLA can quickly perform high-resolution automated searches in large numbers of particles to identify rare phases such as Au, Ag or PGMs.**

**Actlabs is an ISO 17025 (Lab 266) and NELAP (lab E87979) accredited lab for specific registered tests.**

[www.actlabs.com](http://www.actlabs.com)

**CANADA • AUSTRALIA • PERU  
VENEZUELA • MEXICO • GUYANA  
CHILE • GREENLAND • MONGOLIA**

### RARE MINERALS FOR RESEARCHERS

Our stock of over 200,000 mineral specimens encompasses more than 3100 different species from worldwide localities. If you require reliably identified samples for your research or reference collection, let us supply your needs. We and our predecessor companies have been the suppliers of choice since 1950. E-mail inquiries are invited to: [info@excaliburmineral.com](mailto:info@excaliburmineral.com)

### DIAMOND CRYSTALS

Diamond crystals from numerous worldwide deposits are in stock, from tiny micros to large, multi-carat single crystals. Select from one of the world's largest, locality-specific inventories available! See our diamond website for details! [www.diamondcrystals.net](http://www.diamondcrystals.net)

### FRANKLIN & STERLING HILL: The World's Most Magnificent Mineral Deposits

By Dr. Pete J. Dunn – Smithsonian Institution

The revised HARDCOVER edition is available exclusively from us, in two handsome volumes of royal blue buckram, oversewn, with acid-free endpapers and gold-stamping on spines and covers. Over 750 pages, 900 b/w illustrations and photographs fill this important, definitive work. Every scientific library, serious collector and bibliophile should own this set, only \$195.00 plus \$15.00 s/h in the U.S.; foreign inquiries are invited!

### **Excalibur Mineral Corporation**

1000 N. Division Street – Peekskill, NY 10566 - USA

[www.excaliburmineral.com](http://www.excaliburmineral.com)

Tel: 914-739-1134

Fax: 914-739-1257

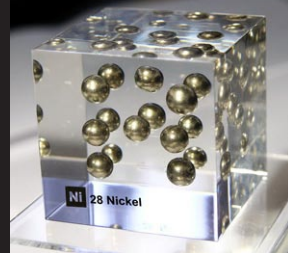
## smart-elements.com

Element displays for collection & science complete periodic table displays

*Living science - touch it, grasp it...*

### Sensational ! Acrylic Element Cubes **NEW!**

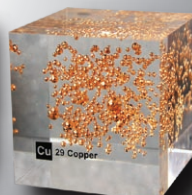
A novelty ! Stunning periodic element samples in generous amounts encapsulated in high-quality clear acrylic glass cubes 50x50x50mm. Labeled with element symbol, atomic number and element name. Highly polished and absolutely UV-proof! The "building blocks of the universe" are thus protected and may be viewed and stored without hazard. Handmade in Germany ! Each acrylic block is an individual original and a fascinating eyecatcher ! Ideally suited for display, collections, exhibitions and teaching purposes !



The worldwide first and only complete set of all naturally occurring elements is available in our shop:

[www.smart-elements.com](http://www.smart-elements.com)

Come and visit us right now to get your favorite sample! We ship worldwide!



<http://www.smart-elements.com> - Tel. +43-650/4798888 - Fax +43-1/4798809 - Email: [jbauer@smart-elements.com](mailto:jbauer@smart-elements.com)



# Why Gold is Valuable

Charles R. M. Butt and Robert M. Hough\*

1811-5209/09/0005-0277\$2.50 DOI: 10.2113/gselements.5.5.277

**Gold has fascinated people of most cultures since earliest times because of its colour, seeming immutability and ease of fabrication into exquisite objects. Due to gold's rarity, its principal functions have been as currency and a store of wealth. Most of the gold ever mined has been hoarded, and rich discoveries over the past 160 years have increased the notional global amount per capita two to five fold. This rate of inflation is minor in comparison to that of currency, so gold still performs its historical financial role. Research is directed at discovering new deposits to support this role, and at finding practical applications commensurate with its monetary cost.**

**KEYWORDS:** historical production, gold properties, gold use, wealth

## HISTORY

For the past 5000 years of human history, gold has been regarded as a valuable commodity, to be acquired and treasured, and to be traded and warred over. It was probably the first metal known to humans. Initially, it would have been regarded with little more than curiosity, based on its colour, malleability and density. In comparison with other materials, it had no obvious use. Some peoples, such as the Australian Aborigines, seem not to have considered gold as either useful or attractive, even in those areas where nuggets were comparatively abundant and no doubt known to them. However, in the Aegean region and China, from about 3200 BC, following the discovery and use of metallic copper and bronze, gold became prized, probably because of its rarity, lustre, resistance to corrosion and comparative ease of working. Many gold artefacts, such as jewellery and decorative and religious objects, are known from this time.

Early gold mining was mainly from placers, and these are still a source today. Gold-bearing quartz veins were exploited by the Egyptians in ancient Nubia (now Sudan) and by the Greeks and Romans across Europe. As demand grew in wealthy civilizations, gold was traded over great distances across Arabia, Europe, southern Asia and, especially, Africa. Trade assisted in establishing relatively peaceful interactions between peoples, but throughout history, gold has also been a prize looted after conquest, and the quest for gold has driven many invasions and much exploration.

The importance of gold as a unit of exchange and store of wealth drove technological and scientific developments. By about 1200 BC, the Egyptians had learned to alloy gold with other metals, but the need to obtain pure gold and ensure its quality came with the development of gold currency. The first known coins were produced in the seventh century BC in the ancient kingdom of Lydia, part

of modern Turkey (Davies 2002). They were made from natural electrum to a strict weight standard, but they had irregular sizes, shapes and composition. The need for consistent quality soon led to procedures for separating and refining gold by amalgamation, cupellation and cementation (Moorey 1994). Cupellation, the basis of fire assay, could not be used for testing the purity of gold in coins and artefacts. However, the observation that the colour of gold varied according to the type and proportion

of alloyed metal was used for analysis by touchstone: a simple, accurate and almost non-destructive procedure.

Over the centuries since, metallurgists developed procedures for extracting gold efficiently and economically from different styles of deposit, including gold hosted in tellurides, and from increasingly lower-grade ores. Minters, goldsmiths and jewellers devised gold alloys with a range of colours, hardnesses and other properties, using different alloying metals and treatments such as deformation and annealing, and learned to manipulate gold to form exquisite objects (Fig. 1). From the earliest times, different cultures enhanced the appearance of artefacts by depletion gilding – that is, leaching the alloyed metal (usually silver or copper) from the outer surface, leaving a thin outer coating of pure gold (Grimwade 1999). This procedure is still employed in the decorative arts, and has recently been used to produce porous films of pure gold as a catalytic substrate (Cobley and Xia 2009 this issue). Similarly, the depletion rims and veinlets observed in natural gold grains and nuggets form in the same way (Hough et al. 2009 this issue). The dramatic results of the mysteries of smelting and refining of gold and other metals, and of processes such as depletion gilding, driven by avarice, gave rise to alchemy, the quest to form gold from base metals.

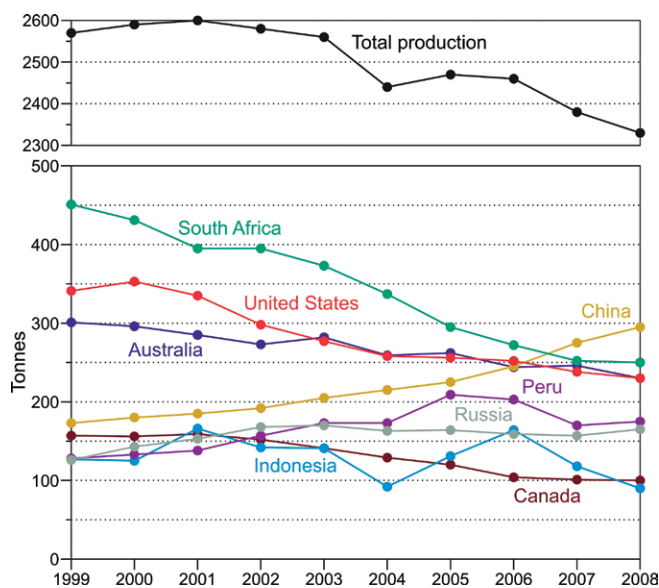
## SUPPLY AND DEMAND

The total amount of gold that has ever been mined is estimated at about 164,000 tonnes (end of 2008). More than 85% of this is still fairly readily available, whether in industrial use (12%) or hoarded, either as jewellery and decorative artefacts (51%) or as bullion and coins (34%). In comparison, platinum, which has a similar crustal abundance and higher price, is not hoarded to nearly the same extent and much is consumed irrecoverably by industry. Over 75% of the total gold stock has been mined since 1900, with a mean annual production of 2466 tonnes during the period 2003–2007. The annual demand for gold over the same period was 3674 tonnes, and the deficit in mine supply was filled by recycling (data: WGC 2009; USGS 2009).

\* CSIRO Exploration and Mining  
Minerals Down Under Flagship  
PO Box 1130, Bentley, WA 6102, Australia  
E-mail: Charles.Butt@csiro.au; Robert.Hough@csiro.au



**FIGURE 1** Gold artefacts: (A) English Celtic gold ring money, ca 1100–700 BC, 38 mm diameter. (B) Scythian gold nose-ring money, ca 4<sup>th</sup>–5<sup>th</sup> century BC, 19 mm diameter. (C) Roman gold aureus coin, Emperor Caracalla, 211–217 AD, 20 mm diameter. (D) Eldorado raft, Muisca culture, Colombia, 1200–1500 AD, 19.5 cm long, 10.2 cm high, Museo de Oro, Bogota, Colombia. (E) Golden Buddha, Wat Traimit, Bangkok, Thailand, approximately 3 metres high and weighing 10 tons. (F) Heraldic figure of a 13<sup>th</sup>-century knight illuminated using gold leaf, England, drawn in 1718. A, B, C PUBLISHED COURTESY OF ARCHAEO GALLERY (WWW.ARCHAEOGALLERY.COM)



**FIGURE 2** Gold mine production trends, 1999–2008. Other regions with collective production exceeding 100 tonnes per annum include the West African Shield (Ghana, Mali, Guinea), the Andes (Chile, Colombia, Argentina; additional to Peru) and central Asia (Uzbekistan, Kazakhstan, Kyrgyzstan). DATA: USGS (2009)

Gold mine production has declined steadily from a peak of 2600 tonnes in 2001, and during that period, dominance in production has moved from South Africa to China (FIG. 2). Innovations in exploration, mining and processing have been driven by the need to maintain the supply of ‘new’ gold. Exploration targets are based on detailed geological models, supported by a range of deep-probing geophysical techniques, including ground and airborne gravity and electromagnetic surveys. Rather than panning for visible particles of detrital gold, geochemical exploration relies on sophisticated analyses to detect less than 1 part per billion (micrograms per kilogram) in soil and rock, and less than 1 part per trillion in water. Similarly, mining and extraction technologies have improved such that, whereas a century ago mine grades were mostly 15–25 grams per tonne (g/t), it is now profitable to mine deposits having ore grades as low as 1–4 g/t by open cut methods, or 4–10 g/t underground. Such deposits need substantial infrastructure to support bulk mining and require processing methods capable of recovering a high percentage of the gold. The mean cost of production varies from mine to mine, but in 2005 was estimated to exceed US\$420/troy ounce (oz = 31.1034 g) (WGC 2009).

Gold is a unique commodity with some remarkable properties (TABLE 1). However, despite this, only about 12% (425 tonnes) of the annual gold demand has an industrial use. Electrical components account for over half of this, taking advantage of pure gold’s resistance to corrosion and its high electrical and heat conductivity. Dentistry has used gold for over 3000 years and currently consumes about 60 tonnes annually. Usually alloyed with silver or other metals, gold is commonly favoured over ceramic or resin

**TABLE 1** SOME PROPERTIES OF GOLD

<b>Symbol</b>	Au (Latin <i>aurum</i> )
<b>Colour</b>	Gold
<b>Atomic number</b>	79
<b>Atomic mass</b>	196.96655 amu
<b>No. neutrons</b>	118
<b>Electrons per shell</b>	2, 8, 18, 32, 18, 1
<b>Abundance</b>	Earth’s crust: ~1.3 ppb Iron meteorites: 1 ppm Seawater: 0.005–0.01 ppb
<b>Isotopes</b>	<b>amu</b> <b>half-life</b> 194    1.6 days 195    186.1 days 195m    30.5 seconds 196    6.2 days 197    stable 198    2.7 days 199    3.14 days
<b>Crystal system</b>	Face-centred cubic, close packed
<b>Unit cell</b>	0.40783 nm
<b>Melting point</b>	1064.43°C
<b>Boiling point</b>	2807.0°C
<b>Density at 293 K</b>	19.32 g/cm <sup>3</sup>
<b>Liquid density</b>	17.31 g/cm <sup>3</sup>
<b>Hardness</b>	Mohs: 2 Vickers HV: 25
<b>Thermal conductivity</b>	317 W m <sup>-1</sup> K <sup>-1</sup>
<b>Electrical resistivity at 20°C</b>	0.022 micro-ohm m
<b>Young’s modulus</b>	79
<b>Poisson’s ratio</b>	0.42
<b>0.2% proof stress</b>	30 MPa
<b>Tensile stress</b>	124 MPa
<b>Malleability</b>	Foil thickness: 0.1–0.125 μm
<b>Ductility</b>	Wire thickness: <25 μm

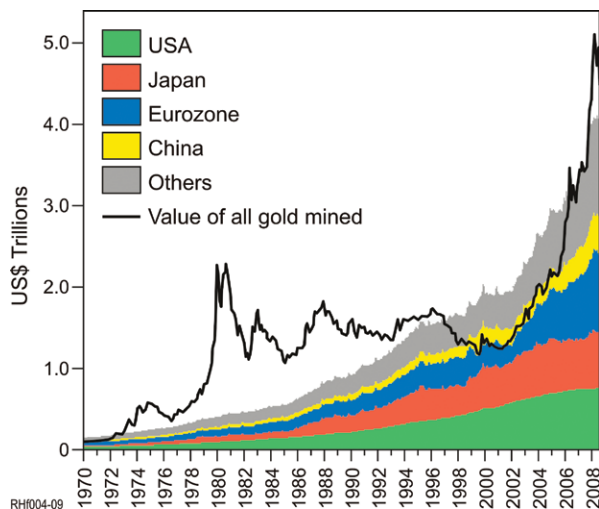


for dental crowns and caps because of its chemical and physical durability and biocompatibility. Other uses include a variety of applications in medicine, engineering, aerospace and catalysis – but none of these can sustain the high costs of acquisition, which thus restricts their further potential.

The principal use of gold is less tangible than industrial application. Hand in hand with human perceptions of its attractiveness and intrinsic value came its adoption as a medium of exchange (i.e. money) and as a means for storing and measuring wealth. Jewellery (68%) and investment as coins and bullion (19%) accounted for the bulk of the demand for gold during the period 2003–2007.

### SO WHY IS GOLD VALUABLE?

Until recently, there has been a direct correlation between gold and currency. Limited gold reserves led to the relaxation of a strict ‘gold standard’ in 1913, allowing the creation of additional paper currency reserves. Its abandonment in 1931 arguably exacerbated, if not precipitated, the Great Depression of the 1930s (Greenspan 1966). Nevertheless, the nexus remained: in 1933, gold was valued at US\$20.67/oz and a US\$20 coin contained 0.9675 oz of gold. This was much the same as in 1717, when Sir Isaac Newton valued gold at £4 4s. 11½d. per oz (equivalent to US\$20 in 1800). In 1934, when the United States overvalued gold at \$35/oz, there was a net influx of gold to the USA in exchange for dollars. The Bretton Woods agreement of 1944 in effect re-established a gold standard, reaffirming the price at US\$35/oz and linking other currencies to the US dollar. In the 1950s and 1960s, however, gold came to be considered undervalued, resulting in a net outflow from the USA. By 1971, artificial pricing had become unsustainable and the price was allowed to float. The price rose sharply between 1971 and 1982 and also after 2001, reaching US\$950–1000/oz in 2009. The value of all gold mined (i.e. existing gold plus new production) over this period, in dollars of the day, increased from about US\$100 billion in 1970 to over US\$4.5 trillion in early 2009. During the same period, the M0 money supply (i.e. all currency in circulation) also increased, albeit more steadily, to over US\$4 trillion (Fig. 3) and is set to advance further as the world tries to overcome the present recession. At ~\$1000/oz (September 2009), compared to \$20/oz until 80 years ago, gold appears to be maintaining its traditional role as a store of wealth and a hedge against currency inflation, however archaic that might seem.

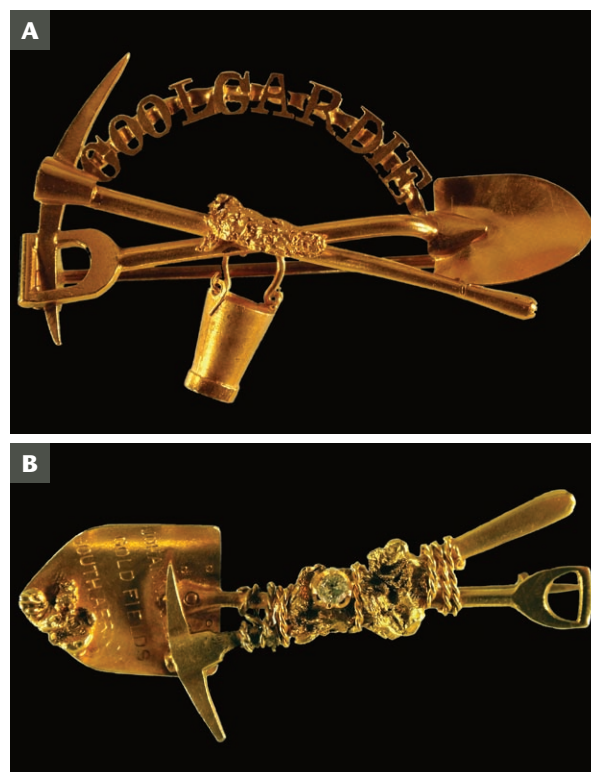


**FIGURE 3** Global money supply (M0: total currency in circulation) compared to the value of all mined gold (i.e. gold price multiplied by total all-time production at that date). AFTER HEWITT AND PETROV (2009), REDRAFTED WITH PERMISSION

The total amount of gold mined by 1850 is variously estimated at between 5400 and 17,500 tonnes. With the then world population of about 1.262 billion, this amounted to about 4–14 g per person, rare at an individual level. Nevertheless, gold was affordable as gold leaf for religious purposes, even to some of the poorest. Increased production, especially due to huge discoveries in the United States, Australia and South Africa (Fig. 4), led to some inflation in gold, and by 1970, the total amount of gold mined had risen to about 24 g per person, which is its present level (based on the current world population of about 6.769 billion). By 2040, when the world population is predicted to be 8.8 billion, some 49,200 tonnes (1590 tonnes per annum) will have to be mined to maintain this per capita demand. Current annual mine production is about 2340 tonnes. Gold’s value lies in its financial role – but in the end, it is valuable because we, the human race, continue to believe it is so, for whatever reason!

### GOLD RESEARCH

Current research is directed at the discovery, extraction and uses of gold. For geologists, the continuing demand for gold provides a huge challenge. New gold deposits must contribute much of the 2200–2500 tonnes per annum needed to satisfy present demand trends, or at least the 1600 tonnes required to maintain the per capita amount over the next 30 years and beyond. Fewer and fewer of these deposits will outcrop, or even have any chemical or mineralogical expression at the Earth’s surface. Accordingly, research is targeted at a fundamental understanding of how deposits form and occur where they do, in an attempt to predict the locations of future resources. This issue of *Elements* concentrates on aspects of this frontier research, together with examples of innovative uses of gold. Walshe and Cleverley (2009) outline the mineral systems approach



**FIGURE 4** Gold miners’ brooches typifying the wealth derived from the vast new discoveries made in the late nineteenth century. (A) Coolgardie, Western Australia; (B) Johannesburg, South Africa, also set with a diamond; 55 mm wide. PHOTOGRAPHS: I.D.M. ROBERTSON, FROM PRIVATE COLLECTIONS

to the genesis of gold deposits, highlighting research priorities. Tosdal et al. (2009) and Williams-Jones et al. (2009) describe details of the geological settings and the chemical processes involved in the solution, transport and deposition of gold, particularly with respect to porphyry and epithermal deposits. Because of its rarity and small size, metallic gold is rarely included in such studies, but it has the potential to provide direct evidence of the conditions of formation or of subsequent events. The time-honoured procedures of systematic panning of stream sediments and soils can be enhanced by detailed study of the gold (Hough et al. 2009) to provide evidence of source and process. Near-surface exploration nevertheless remains important. Gold exposed to surface conditions may be mobilized both physically and chemically, providing a larger target for exploration. Ever-improving analytical procedures now permit knowledge of the low-temperature aqueous geochemistry of gold

(Williams-Jones et al. 2009) to be exploited through hydro-geochemical surveys, with the intriguing possibility that some reactions are bacterially mediated (Southam et al. 2009). Research outside the fields of geology and metallurgy has increased in importance in recent years, and the use of nanoparticulate gold in medicine and catalysis is eloquently described by Cobley and Xia (2009).

## ACKNOWLEDGMENTS

We would like to thank Hap McSween and Pierrette Tremblay for their assistance and support in the publication of this issue of *Elements* and the authors who have devoted time and effort to produce their articles. Financial support was provided by the CSIRO Minerals Down Under National Research Flagship. ■

## REFERENCES

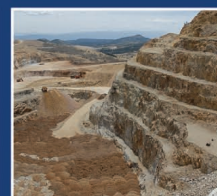
- Cobley CM, Xia Y (2009) Gold and nanotechnology. *Elements* 5: 309-313
- Davies G (2002) *A History of Money from Ancient Times to the Present Day*. University of Wales Press, Cardiff, 716 pp
- Greenspan A (1966) Gold and economic freedom. In: Rand A (ed) *Capitalism: The Unknown Ideal*. Signet, Penguin, New York, pp 101-107
- Grimwade M (1999) The surface enrichment of carat gold alloys – depletion gilding. *Gold Technology* 26: 16-23
- Hewitt M, Petrov K (2009) Global currency and gold. [www.dollardaze.org/blog/?post\\_id=00555](http://www.dollardaze.org/blog/?post_id=00555) (accessed April 1, 2009)
- Hough RM, Butt CRM, Fischer-Bühner J (2009) The crystallography, metallography and composition of gold. *Elements* 5: 297-302
- Moorey PRS (1994) *Ancient Mesopotamian Materials and Industries, the Archaeological Evidence*. Clarendon Press, Oxford 1994, 414 pp
- Southam G, Lengke MF, Fairbrother L, Reith F (2009) The biogeochemistry of gold. *Elements* 5: 303-307
- Tosdal RM, Dilles JH, Cooke DR (2009) From source to sinks in auriferous magmatic-hydrothermal porphyry and epithermal deposits. *Elements* 5: 289-295
- USGS (2009) United States Geological Survey Minerals Information publications <http://minerals.usgs.gov/minerals/pubs/commodity/gold> (accessed September 2, 2009)
- Walshe JL, Cleverley JS (2009) Gold deposits: Where, when and why. *Elements* 5: 288
- WGC (2009) World Gold Council [www.gold.org](http://www.gold.org) (accessed September 1, 2009)
- Williams-Jones AE, Bowell RJ, Migdisov AA (2009) Gold in solution. *Elements* 5: 281-287 ■



## SEG 2010 CONFERENCE

October 2-5  
Keystone, Colorado  
USA

[www.seg2010.org](http://www.seg2010.org)



**THE CHALLENGE OF FINDING NEW MINERAL RESOURCES:**  
**GLOBAL METALLOGENY INNOVATIVE EXPLORATION AND NEW DISCOVERIES**

The geology and metallogeny of the world's major domains will be covered, highlighting those that are emerging and gaining focus.

Technical Program ~ Student Conference ~ Workshops  
Field Trips ~ Sponsorship Opportunities ~ Exhibits

First Announcement & Exhibitor Prospectus at [www.seg2010.org](http://www.seg2010.org)  
For general inquiries and exhibits, contact QBS at +1.303.914.9647 or [Darline@QBSoffice.com](mailto:Darline@QBSoffice.com)



# Gold in Solution

Anthony E. Williams-Jones<sup>1</sup>, Robert J. Bowell<sup>2</sup> and Artashes A. Migdisov<sup>1</sup>

1811-5209/09/0005-0281\$2.50 DOI: 10.2113/gselements.5.5.281

**Although gold is a noble metal and is effectively insoluble even in strong acids, we have known for nearly 500 years that it can be concentrated to mineable levels by being transported as dissolved species in crustal fluids (indeed, most economic gold deposits owe their origin to this mode of transport). From alchemy and later experimental chemistry and geochemistry, we have developed an understanding of the solubility and speciation of gold in aqueous liquids and other crustal fluids. This knowledge informs us about the processes that promote the transport of gold in the Earth's crust, result in exploitable gold deposits and lead to the remobilization of gold in the surficial environment.**

**KEYWORDS:** gold, solubility, hydrothermal fluids, petroleum, supergene

## INTRODUCTION

Gold is the most noble of all metals. No other metal is less reactive at its surface when in contact with liquids or gases (this helps explain why in nature gold occurs dominantly in its native form), and no other metal is more valued for its resistance to corrosion. Indeed, gold was accorded the status of noble metal because, unlike other metals, it was not known to tarnish or dissolve in strong acids and was therefore deemed incorruptible. However, as early as the 8<sup>th</sup> century CE, Jabir ibn Hayyan (721–815), an Arab alchemist, discovered that gold dissolves in a mixture of three parts hydrochloric acid and one part nitric acid, a liquid that later became known as *aqua regia* (royal water) because of its capacity to dissolve gold (Russell 1686). This capacity, which even today is used in the analysis of gold, results from the fact that nitric acid, an extremely strong oxidant, is able to convert the gold to Au<sup>3+</sup>, thereby making it available for complexation with Cl<sup>-</sup> ions to form aqueous species such as AuCl<sub>4</sub><sup>-</sup>.

During the 17<sup>th</sup> century, the German chemist Georg Stahl (1660–1734), in a quest to explain how Moses was able to turn the golden calf into “bitter water”, found that gold dissolves in aqueous solutions prepared by heating a mixture of *sal mirabilis* (Na<sub>2</sub>SO<sub>4</sub>) and charcoal. He had discovered that gold is soluble in aqueous solutions of NaHS and, as we now know, this occurs because of the complexation of gold to form the species AuHS<sup>0</sup> and Au(HS)<sub>2</sub><sup>-</sup>. However, an equally plausible “bitter water” that Stahl could have considered is colloidal gold, which had been used in

Roman times to make dichroic glass (Fig. 1) and was later promoted by Paracelsus (1493–1541), under the name *aurum potable*, as an elixir of life; the colloidal nature of this deep red fluid was eventually deduced by Michael Faraday (1791–1867).

From an industrial perspective, arguably the most important discovery about the solubility of gold came in the 18<sup>th</sup> century when the Swedish chemist Carl Scheele (1742–1786) found that gold is highly soluble in hydrocyanic acid. This finding eventually led to the patenting of the cyanidation process for refining gold by MacArthur and the Forrest brothers in 1887; the process involves dissolving the gold as Au(CN)<sub>2</sub><sup>-</sup> and reducing it to the native metal with zinc powder. By the early 20<sup>th</sup> century, cyanidation had become the method of choice for the beneficiation of gold ores and remains so to this day.

The idea that gold could be transported in crustal fluids and concentrated as ore can be traced back to the 16<sup>th</sup>-century writings of Agricola (1546) in *De Ortu et Causis Subterraneorum*. This work describes vapours of heated groundwaters mixing with “earth” to form “juices” that rise into fractures, where they deposit metals including gold. Interestingly, however, Jabir ibn Hayyan had noticed some 800 years earlier that waters flowing from copper mines carried scales of copper, which after drying in the desert “contained amongst them the purest gold”. He concluded that the gold was the product of “long washing in water and digestion by

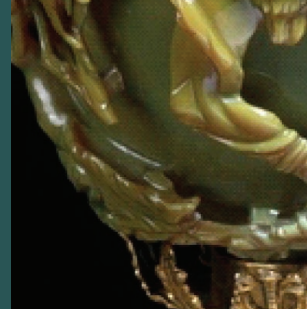
the heat of the sun” (Russell 1686), an idea that foreshadows modern thinking about the supergene origin of some of the gold in placer- and regolith-hosted deposits. In the late 17<sup>th</sup> century, the roots of modern hydrothermalism started to take hold, with the proposal by Webster (1671), in his *Metallographia*, that the ore metal is in *principis solutis*, that is, it dissolves in water or steam. This proposal was further developed in the 19<sup>th</sup> century with the observation that dissolution of metals requires “mineralizers” such as B, F, PO<sub>4</sub> and Cl (Daubr e 1841). By the late 19<sup>th</sup> century, hydrothermalism was well established, although opinion continued to be divided well into the 20<sup>th</sup> century over whether the ore-forming fluid is invariably liquid (Graton 1940), or whether, in magmatic-hydrothermal systems, vapour can also play this role (Ingerson and Morey 1940). The issue was finally thought to have been settled when Krauskopf (1957) concluded that the

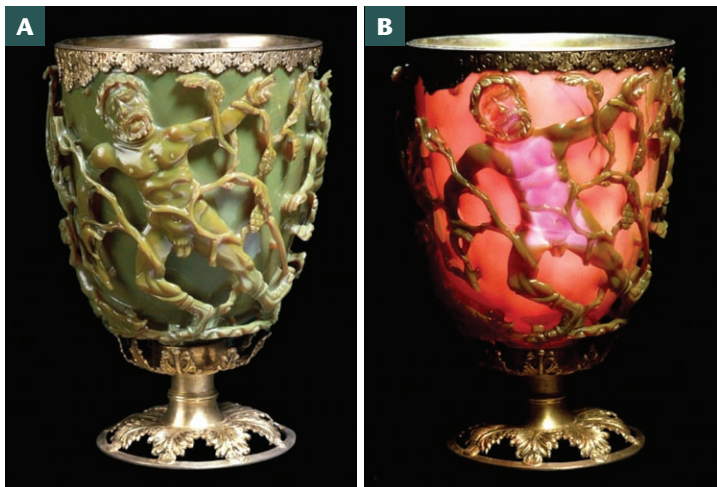
“Now I will discuss that kind of minerals for which it is not necessary to dig, because the forces of water carries them out of the veins”

– Agricola 1556

1 Department of Earth and Planetary Sciences, McGill University  
3450 University Street, Montreal, Quebec, H3A 2A7, Canada  
Corresponding author: Anthony.Williams-Jones@mcgill.ca

2 SRK Consulting, Churchill House, Churchill Way  
Cardiff CF10 2HH, Wales, UK





**FIGURE 1** The Lycurgus cup in (A) reflected light and (B) transmitted light. The cup, which depicts the legend of King Lycurgus from Homer's *Iliad*, was made from cut glass for the Roman Emperor Hadrian during the 4<sup>th</sup> century CE. The dichroic quality (green and red colours) is produced by the light-scattering effects of colloidal gold within the glass. COURTESY OF THE BRITISH MUSEUM

volatilities of important ore metals, including gold, are so low at temperatures below 600°C that “simple vapor transport cannot account for the origin of ore deposits”.

Concurrent with the establishment of hydrothermalism in the 19<sup>th</sup> century, it was observed that the fineness (purity) of placer gold increases down drainage and that hexagonal flakes and “fungoid growths” of gold can form at ambient temperature (Liversidge 1893). These observations raised questions about the possible mobilization of gold by surface waters and introduced the idea that supergene processes may play an important role in the dispersal and concentration of gold in the surficial environment.

The first quantitative experiments to investigate the solubility of gold in hydrothermal fluids were by Ogryzlo (1935). Because of the debate over whether metals could be transported in the vapour phase, some of these experiments were conducted with gas mixtures, that is, steam and chlorine gas (used in refining gold ores) and steam and HCl gas. Not unexpectedly, the chlorine–steam mixtures dissolved high (percentage) levels of gold. However, gold was not observed to dissolve in the HCl gas mixtures. The experiments in aqueous liquids were conducted with a variety of solutes, but only solutions containing Cl<sup>-</sup> or HS<sup>-</sup> dissolved significant gold. In both cases, gold concentrations exceeded 1000 ppm at 300°C. This work laid the foundations for modern experimental studies by identifying HS<sup>-</sup> and Cl<sup>-</sup> as important ligands for the aqueous transport of gold.

## AQUEOUS GEOCHEMISTRY OF GOLD

Pearson (1963) subdivided metals and their ligands (the electron donors with which the metals bond and permit their aqueous dissolution) into two groups: (1) small and strongly charged ions, which he termed “hard”, and (2) large, weakly charged, and highly polarizable ions, which he termed “soft”. Furthermore, he proposed that, where there is competition among ions, hard ions will bond preferentially with hard ligands, and vice versa. In the case of compound ions, however, this classification also considers the valence state of the electron donor or acceptor. Thus, for example, in SO<sub>3</sub><sup>2-</sup>, the electron donor, sulphur, has a valence of +4 and the ion is classified as borderline between hard and soft, whereas in HS<sup>-</sup>, sulphur has a valence of -2

and the anion is classified as soft. According to the hard–soft classification, gold, which occurs in nature dominantly as Au<sup>+</sup> or Au(I) and is highly polarizable due to a filled *d* shell, is considered to be a soft metal and will tend to bond preferentially with soft ligands. Gold also occurs as Au(III) but, as discussed below, this harder form is important only under very oxidizing conditions at ambient temperature. An additional characteristic of gold, which relates to its “softness”, is that the outer electron cloud is readily delocalized, allowing for electron transfer and weak bonding between gold atoms. This leads to the formation of clusters with charged surfaces (mainly negative) that repel each other and, in turn, form colloids.

At near-ambient temperature, the most important soft ligands are HS<sup>-</sup>, S<sub>2</sub>O<sub>3</sub><sup>2-</sup>, CN<sup>-</sup> and SCN<sup>-</sup>, the last two being the products of the breakdown of plant matter and algae. Given the importance of CN<sup>-</sup> in the beneficiation of gold, it is not surprising that Au(I) forms its strongest complexes with this ligand [e.g. Au(CN)<sub>2</sub><sup>-</sup>]. Next in importance are S<sub>2</sub>O<sub>3</sub><sup>2-</sup> [e.g. Au(S<sub>2</sub>O<sub>3</sub>)<sub>2</sub><sup>3-</sup>], where conditions are oxidizing, and HS<sup>-</sup> [e.g. Au(HS)<sub>2</sub><sup>-</sup>], where conditions are reducing and pH is near to neutral (Vlassopoulos and Wood 1990). Thiocyanate (SCN<sup>-</sup>) also forms stable complexes with Au(I) but, in environments where it is concentrated, cyanate complexes are likely to predominate. At low concentrations of the above ligands, gold will dissolve predominantly as the hydrolysed species AuOH·(H<sub>2</sub>O)<sup>o</sup> (Vlassopoulos and Wood 1990). Finally, under very oxidizing conditions, such as those of highly saline, acidic groundwaters, gold may be present as Au(III) and therefore form stable species with the borderline ligand Cl<sup>-</sup> (e.g. AuCl<sub>4</sub><sup>-</sup>). If, however, the conditions are somewhat less oxidizing and acidic, AuCl<sub>2</sub><sup>-</sup> will become the dominant gold chloride species, although AuOH·(H<sub>2</sub>O)<sup>o</sup> will predominate (Gammons et al. 1997).

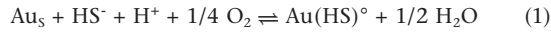
Several studies have documented the dissolution of appreciable quantities of gold in humic and fulvic acids and proposed that organic complexation may also be important in the transport of gold in the surficial environment. However, to date, the only study that has investigated the organic complexation of gold quantitatively is that of Vlassopoulos et al. (1990). These authors employed a variety of organic ligands to act as simple analogues of organic moieties and concluded that the stability of gold organic complexes is greatest with sulphur as the electron donor, very much weaker with nitrogen and even weaker with oxygen.

At elevated temperatures, such as those responsible for the formation of hydrothermal deposits, the speciation of gold is simpler (Figs. 2, 3). The most important ligand at temperatures up to 350°C is HS<sup>-</sup> (Seward 1973), with AuHS<sup>o</sup> predominating at lower pH and Au(HS)<sub>2</sub><sup>-</sup> at higher pH (Stefánsson and Seward 2004). The stability constants for these species reach maxima at 350 and 250°C, respectively, due to increased association of H<sup>+</sup> and HS<sup>-</sup> as H<sub>2</sub>S. This limits their capacity to transport gold at very high temperature. Moreover, the dielectric constant of water decreases with increasing temperature, which favours electrostatic interactions, thereby promoting “hard” behaviour and allowing a soft metallic ion like Au<sup>+</sup> to form stable bonds with harder anions like Cl<sup>-</sup> and OH<sup>-</sup>. Thus, whereas at 25°C the species Au(HS)<sub>2</sub><sup>-</sup> is about 14 orders of magnitude more stable than the corresponding chloride species (AuCl<sub>2</sub><sup>-</sup>), at ~400°C the two species have similar stability constants (Stefánsson and Seward 2004). Consequently, at the higher temperatures of magmatic-hydrothermal systems, AuCl<sub>2</sub><sup>-</sup> will predominate; the stability of AuCl<sup>-</sup> is too low for this species to be significant. In general, AuCl<sub>2</sub><sup>-</sup> will tend to dominate under acidic (and oxidizing) conditions, Au(HS)<sup>o</sup> at acidic to intermediate pH and Au(HS)<sub>2</sub><sup>-</sup> at higher pH (Stefánsson and Seward 2004). In very dilute solutions, Au(OH)<sup>o</sup> may

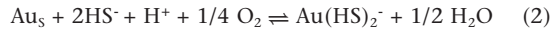
control gold transport at intermediate to alkaline pH, but only at relatively high temperature. This species is, however, less stable than the bisulphide ( $\text{HS}^-$ ) and chloride species and will therefore be subordinate to them, even at relatively low concentrations of  $\text{HS}^-$  and  $\text{Cl}^-$ .

## HYDROTHERMAL TRANSPORT AND DEPOSITION

The dissolution and deposition of gold at temperatures up to about 350°C is controlled by the reactions:



and



Applying Le Châtelier's principle, we can therefore predict that deposition of gold will be promoted by a decrease in the activity of  $\text{HS}^-$  and  $f\text{O}_2$  and an increase in pH.

### Boiling

A decrease in  $\text{HS}^-$  activity could be accomplished by boiling, which would fractionate  $\text{H}_2\text{S}$  strongly into the vapour and lower the activity of  $\text{HS}^-$  via the reaction:



Indeed, this is the favoured mechanism for the precipitation of gold in low-sulphidation (sulphur in a low oxidation state) epithermal systems. Furthermore, boiling increases pH by fractionating acidic components into the vapour, and this also promotes deposition of gold. An additional effect of boiling is the decrease in temperature that accompanies adiabatic expansion of the liquid. However, in some cases (e.g. constant total S), decreasing temperature may actually increase solubility rather than lower it (Fig. 2A). The effect of boiling on  $f\text{O}_2$  contrasts with that on  $\text{HS}^-$  activity and pH. Because hydrogen partitions strongly into the vapour,  $f\text{O}_2$  increases, promoting dissolution of gold.

### Sulphidation

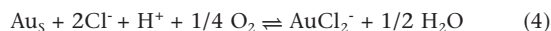
Sulphidation of iron-bearing minerals in the wall rocks to form pyrite is another effective means of reducing  $\text{HS}^-$  concentration. Indeed, this is a frequently proposed explanation for the genesis of mesothermal (orogenic) gold deposits, where hydrothermal alteration commonly involves pyritization and where commonly there is a close spatial association between gold and pyrite.

### Oxidation

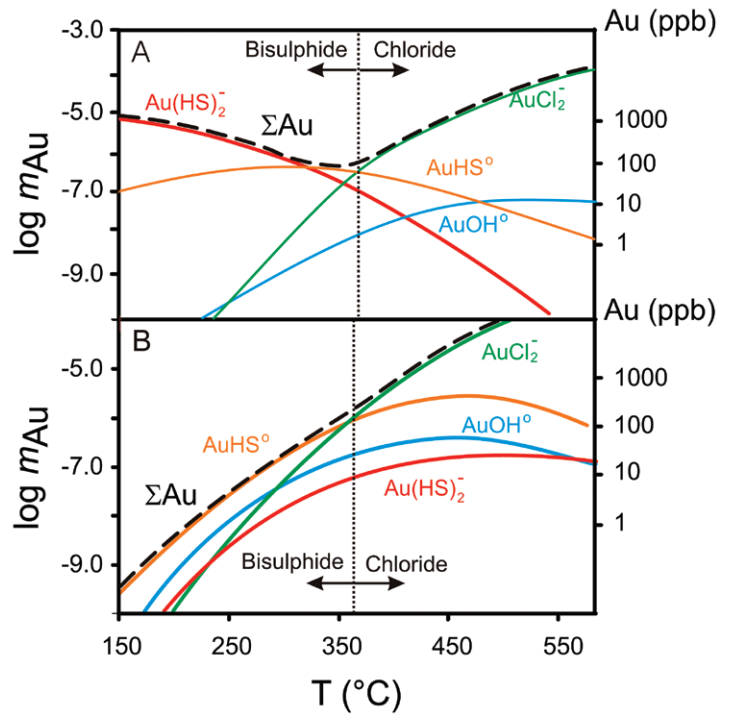
An important feature of the solubility of gold as the species  $\text{Au}(\text{HS})_2^-$  is that its concentration reaches a maximum at  $f\text{O}_2$ -pH conditions close to equi-predominance of the species  $\text{H}_2\text{S}$ ,  $\text{HS}^-$  and  $\text{SO}_4^{2-}$  (Fig. 3). Moreover, a relatively small increase in  $f\text{O}_2$  leads to a precipitous drop in  $\text{HS}^-$  concentration and consequently in gold solubility. As a result, deposition of gold at these conditions is strongly favoured by oxidation and could occur through interaction of the ore-bearing fluid with a hematite-bearing host rock or mixing with oxygenated meteoric waters.

### Cooling

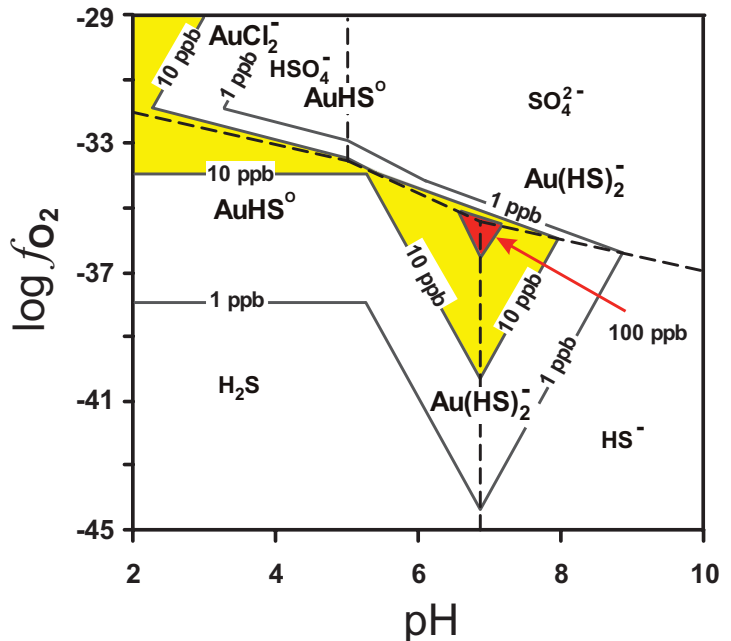
At temperatures above 350°C,  $\text{AuCl}_2^-$  is likely to be the main control on the solubility of gold in chloride-rich systems, such as those forming porphyry copper-gold deposits (Fig. 2). This solubility will be governed by the reaction:



As is the case for reactions 1 and 2, gold deposition is promoted by a decrease in ligand activity and  $f\text{O}_2$ , and by an increase in pH. However, whereas cooling may be rela-



**FIGURE 2** Gold solubility (in terms of molality,  $m$ , and parts per billion) and speciation at 1 kbar as a function of temperature for an aqueous solution containing 1.5 molal ( $m$ ) NaCl and 0.5  $m$  KCl, with pH buffered by the assemblage K-feldspar–muscovite–quartz. (A)  $\Sigma\text{S}$  (total S) = 0.01  $m$  and  $f\text{O}_2$  (oxygen fugacity) is buffered by the assemblage hematite–magnetite. (B)  $\Sigma\text{S}$  and  $f\text{O}_2$  are buffered by the assemblage pyrite–pyrrhotite–magnetite; the maximum value of  $\Sigma\text{S}$  is 0.1  $m$ . The black dashed line ( $\Sigma\text{Au}$ ) indicates the total solubility of gold. The stability constants for gold species are from Stefánsson and Seward (2004), and thermodynamic data for other species are from the SUPCRT92 database (Johnson et al. 1992).



**FIGURE 3** Gold solubility (in parts per billion; solid lines) and speciation at 500 bar and 250°C as a function of  $\log f\text{O}_2$  and pH in a solution containing 1  $m$  NaCl with  $\Sigma\text{S} = 0.01 \text{ m}$ . The dashed lines separate regions of predominance of  $\text{H}_2\text{S}$ ,  $\text{HS}^-$ ,  $\text{SO}_4^{2-}$  and  $\text{HSO}_4^-$ . Regions of high solubility are highlighted. The stability constants for gold species are from Stefánsson and Seward (2004), and thermodynamic data for other species are from the SUPCRT92 database (Johnson et al. 1992).

tively ineffective in causing large-scale deposition of gold transported as a bisulphide complex, the opposite is true for gold transported as a chloride complex. For example, based on the values of the stability constant of  $\text{AuCl}_2^-$  at 500 bars, a 50°C drop in temperature within the interval 500 to 300°C will result in deposition of over 95% of the gold in solution. Such a drop in temperature is relatively modest for porphyry copper–gold ore-forming systems, where decreases of several hundred degrees are commonplace during the magmatic phase of hydrothermal activity. However, as shown by FIGURE 2, unless the total concentration of sulphur is buffered to much lower values with decreasing temperature (commonly the case; FIG. 2B), after an initial decrease, solubility may actually increase due to the increased stability of bisulphide species, allowing remobilization of the gold into the epithermal environment (FIG. 2A; see also Gammons and Williams-Jones 1997).

## COLLOIDAL PROCESSES

If gold-bearing solutions become supersaturated due, for example, to a sharp drop in temperature, instead of precipitating the gold, they may nucleate negatively charged colloidal particles that repel each other, allowing the gold to remain indefinitely in suspension (a natural *aurum potabile*) and be available for further transport. Commonly, this is accompanied by supersaturation and polymerization of silica, thus forming a suspension of negatively charged colloidal silica particles among which the negatively charged gold particles are dispersed (Saunders 1990). Deposition of gold (e.g. as dendrites in amorphous silica) occurs as a result of flocculation due to changes in the fluid chemistry, such as an increase in salinity or pH, both of which may occur as a result of boiling or fluid mixing. However, colloidal gold may also be adsorbed onto minerals with positive surface charge (p-type conductors), such as arsenian pyrite, a hypothesis that may explain the “invisible” gold in some deposits.

## VAPOUR TRANSPORT

As discussed in the introduction, the idea that vapours may play a role in the hydrothermal transport of metals was thought to have been put to rest by the theoretical study of Krauskopf (1957). However, the discovery of percentage levels of copper in vapour inclusions from the Mole granite (Australia) (Heinrich et al. 1992) and similar concentrations of copper and parts-per-million levels of gold in vapour inclusions from the Bajo de la Alumbrera (Argentina) and Grasberg (Indonesia) porphyry copper–gold deposits (Ulrich et al. 1999) has reopened the debate, particularly as, in all three settings, the concentration of these metals in the vapour exceeded those in the coexisting brine. This has led to proposals that the vapour rather than the liquid may be the main agent of metal transport for copper and gold in porphyry systems.

Since the discoveries mentioned above, several experimental studies have been conducted to investigate the behaviour of metals in water vapour. Their results demonstrate that theoretical estimates based on volatility data grossly underestimate the capacity of this phase to transport metals under hydrothermal conditions, because of a failure to consider the effect of hydration. In the case of gold, Archibald et al. (2001) showed that  $\text{HCl-H}_2\text{O}$  gas mixtures are capable of dissolving up to 10 ppb Au at temperatures similar to those of high-sulphidation (sulphur in a high oxidation state) epithermal systems, due to the formation of  $\text{AuCl}\cdot(\text{H}_2\text{O})_{3-5}$ . This is sufficient to form a deposit containing several tens of metric tons of gold, assuming fluxes and lifetimes of typical hydrothermal systems. More recently, Zevin et al. (2007, 2008) showed

that similar concentrations of gold dissolve in  $\text{H}_2\text{S-H}_2\text{O}$  gas mixtures as  $\text{AuS}\cdot(\text{H}_2\text{S})_2$  and  $\text{AuS}\cdot(\text{H}_2\text{O})_3$ . These concentrations are substantially lower than the parts-per-million concentrations of gold reported in vapour inclusions. However, these inclusions were trapped at temperatures in the range 500 to 600°C and pressures between 500 and 1000 bar, conditions that would have promoted much higher gold solubility than would have been possible at the experimental conditions.

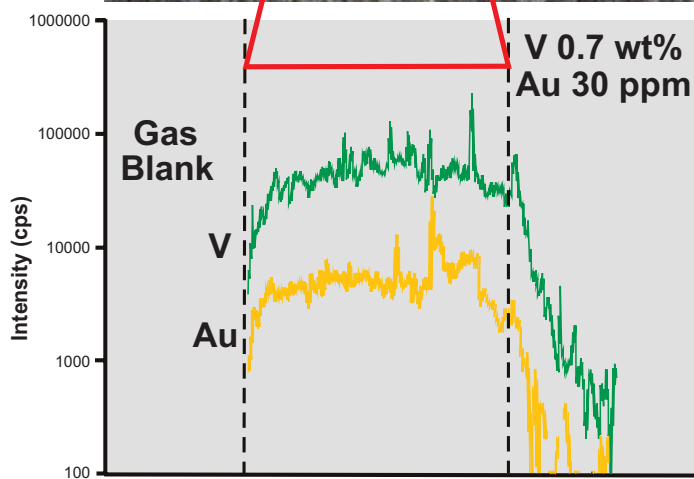
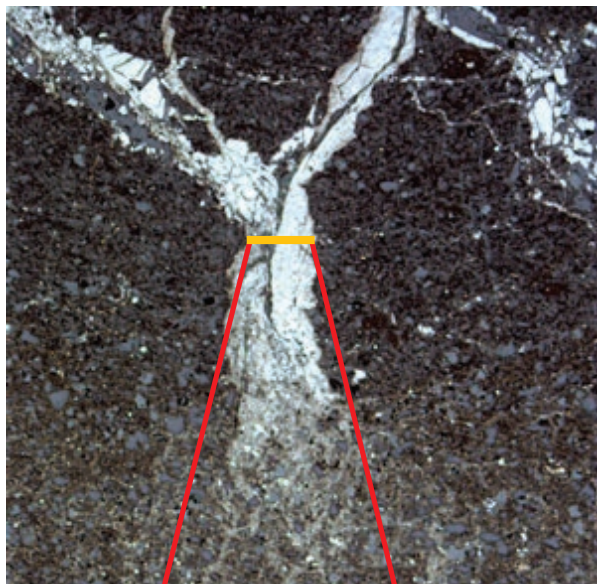
According to the vapour-transport model, which has been applied to both porphyry and epithermal environments, vapour initially condenses some hypersaline liquid at deeper levels where it forms porphyry gold deposits. At subvolcanic levels, the remaining vapour may mix with circulating groundwaters, which subsequently boil to form low-sulphidation gold deposits or condense to an acidic liquid from which high-sulphidation deposits form directly; where the mineralization is late, the high-sulphidation deposits may form from a vapour that contracts to liquid without condensation (Williams-Jones and Heinrich 2005).

## HYDROCARBONS AS A MEDIUM OF TRANSPORT

A crustal fluid that has received little consideration as a possible agent of metal transport is liquid petroleum, despite the fact that it has long been known to commonly contain appreciable concentrations of metals, notably nickel and vanadium, which are used routinely to determine the source of the petroleum. In fact, concentrations of these metals are generally on the order of tens of parts per million and may reach 100 ppm and 1500 ppm, respectively. This metal enrichment and a close spatial and, in some cases, temporal association between gold and hydrocarbons in several deposit types are arguments that liquid petroleum merits consideration as a possible ore fluid.

In the Carlin District (Nevada), hydrocarbons are commonly associated with gold mineralization and, in some deposits, notably along Alligator Ridge, were introduced contemporaneously with the gold, as shown by the presence of oil-bearing fluid inclusions in ore samples (Hulen and Collister 1999). Moreover, Howell et al. (1999) reported amorphous carbon from the Getchell mine containing 915 ppm Au, and Emsbo and Koenig (2007) described veins of pyrobitumen in the El Rodeo deposit containing up to 100 ppm Au. The El Rodeo veins are of particular interest because the gold is homogeneously distributed and the veins have coalesced from underlying microveinlets, suggesting that they record liquid hydrocarbon migration and, in turn, gold mobilization (FIG. 4).

Another mining district where gold is intimately associated with hydrocarbons is the Witwatersrand (South Africa), where 40% of the gold is in reefs with carbon seams, many containing in excess of 1000 ppm Au (Halbauer 1986). On the basis of their organic geochemistry (e.g. Spangenberg and Frimmel 2001) and the occurrence of liquid hydrocarbons preserved as fluid inclusions in overgrowths on detrital quartz grains (England et al. 2002), these seams are now generally considered to represent residues from the migration of liquid hydrocarbons. Proponents of both the modified palaeoplacer and hydrothermal models for the genesis of the Witwatersrand gold deposits have therefore suggested that the hydrocarbons may have promoted deposition of hydrothermally mobilized gold, by reducing  $f\text{O}_2$  and destabilizing  $\text{Au}(\text{HS})_2^-$ . However, the possibility that the hydrocarbons transported gold has been ignored.



**FIGURE 4** Pyrobitumen vein containing 30 ppm gold from the El Rodeo deposit, Carlin Trend, Nevada. The uniform nature of the laser ablation ICP-MS gold profile across the vein and its parallelism with the vanadium (V) profile show that both metals are homogeneously distributed and suggest that they are chemically bound in the pyrobitumen. PHOTOGRAPH AND LA-ICP-MS PROFILES SUPPLIED BY P. EMSBO

In order to test the hypothesis that liquid hydrocarbons may play a role in gold transport, Williams-Jones and Migdisov (2007) determined gold's solubility in crude oils at temperatures from 100 to 250°C. Although the upper temperature limit is well above the oil window (the temperature above which liquid petroleum is normally converted to natural gas; 160°C), there is good reason to believe, from pyrolysis experiments and the occurrence of liquid hydrocarbon inclusions preserved in black chimneys, that oil in petroleum reservoirs heated by intrusions or hydrothermal fluids will remain stable for considerable periods of time at temperatures up to 300°C. Thus, if the capacity to dissolve metals is sufficient, liquid petroleum could be a viable ore fluid for gold. The results of the solubility experiments show that crude oil dissolves 2 to 3 ppb Au at 100°C and approximately 50 ppb Au at 250°C. At this stage, we have little understanding of how gold dissolves in hydrocarbons. However, the most plausible explanation is that it bonds to functional groups in asphaltene molecules containing sulphur, nitrogen or oxygen. Similarly, we do not know how the gold may be concentrated, although, given its occurrence in pyrobitumen, distillation is an obvious possibility.

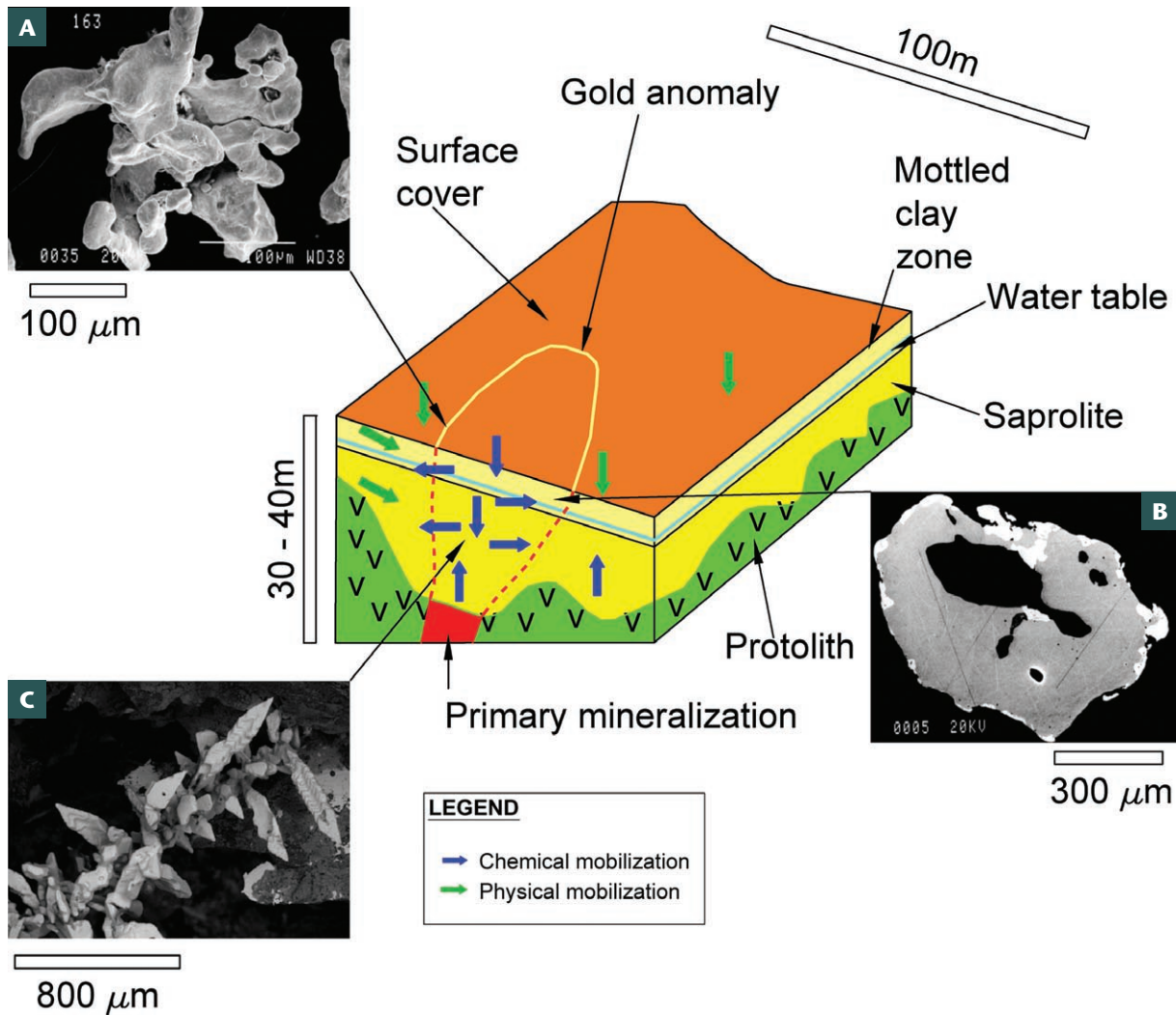
## SUPERGENE CONCENTRATION

The dissolution of gold and its reprecipitation under surface conditions depends on environmental factors and the characteristics of the primary mineralization. Early experimental studies showed the potential for gold remobilization under surface conditions (Machairas 1967) and were supported by mineralogical assessments of placer- and soil-derived gold (Desborough 1970). Regional case studies in Australia, Brazil and Africa provided further evidence of gold mobilization based on particle morphology and chemistry (Fig. 5), as well as on geochemical enrichment patterns and mass balance predictions (summarized in Gray et al. 1992). The determining environmental factors for gold mobilization are geomorphology, climatic conditions, weathering rate, and the physical-chemical characteristics of runoff and groundwater. These are complemented by factors intrinsic to primary gold deposits that are related to the behaviour of the mineralized structures and organic/mineral gangue during weathering. Among them are the permeability of the gangue, its mineralogical composition and the chemical characteristics of the solutions.

The formation of aqueous complexes of gold is strictly dependent on the climatic conditions and the groundwater chemistry generated by mineral-water reactions. Proximal to primary gold deposits, oxidation of sulphides leads to the formation of  $S_2O_3^{2-}$  and the remobilization of gold as the species  $Au(S_2O_3)_2^{3-}$ , provided that pH conditions are neutral to weakly alkaline and the environment is not too oxidizing;  $Au(HS)_2^-$  may be important if conditions are unusually reducing. However, this transport is commonly limited due to subsequent oxidation of the thiosulphate ( $S_2O_3^{2-}$ ) to sulphate (Freyssinet et al. 2005). Beyond the immediate vicinity of the primary deposits, other complexes become more important in controlling gold mobility. For example, in semi-arid to arid environments, such as the gold districts of the southern Yilgarn Craton, Australia, where the groundwater is hypersaline, acidic and oxidizing, gold is transported as halide complexes, predominantly  $AuCl_4^-$ , or possibly as  $AuOH \cdot (H_2O)$  where conditions are slightly less oxidizing and acidic (Gammons et al. 1997; Freyssinet et al. 2005). By contrast, in tropical and equatorial climates, where the soils have high contents of organic matter, gold concentrations in their pore waters correlate well with concentrations of cyanide, ammonia and dissolved organic species (Bowell et al. 1993). Based on their relative stabilities,  $Au(CN)_2^-$  and  $AuOH \cdot (H_2O)$  are interpreted to be the dominant species. However, organic acids may also play an important role in gold transport.

The first studies linking gold genetically to organic matter were based on observations of high gold concentrations in the organic-rich parts of eluvial and palaeoplacer deposits; supported by experiments, Freise (1931) attributed this association to complexing of the gold by organic acids. Other studies, however, have concluded that humic substances merely reduce aqueous gold species, forming colloidal gold, which can then be transported in suspension (Machesky et al. 1992). The critical factor in determining whether organic matter plays a role in gold mobilization is the presence of suitable functional groups on the organic acids to facilitate reduction and/or dissolution. On the basis of experimental data and characterization of soil organic acids, Bowell et al. (1993) argued that both reduction and dissolution take place, and that their net effect depends on the magnitudes of the reactions and the rates at which they occur.

Another potentially important means of gold mobilization is via colloidal processes. From the morphology of gold grains collected in Quaternary palaeochannels in the Ampalit and Cempaga-Busang drainage basins in Central Kalimantan,



**FIGURE 5** Gold morphology in relation to chemical and physical mechanisms of gold mobilization in a typical tropical regolith, based on *Bowell et al. (1996)*. Physical transport of gold can occur due to profile reduction (erosion) and creep of fine-grained material, whereas chemical mobilization is the product of dissolution and reprecipitation of the gold by groundwater and near-surface soil water. Groundwater in a tropical regolith can flow laterally, downwards and, through evapotranspiration, upwards as well. The gold grains imaged in this figure show morphologies typically observed in the regolith, including (A) “fungoid”-type in the organic-rich soils of the near-surface (reflecting the actions of micro-organisms or dissolution and reprecipitation of the gold by organic acids), (B) rounded grains, commonly with silver-depleted rims, in the clay zone and laterite; and (C) pristine crystals in the matrix of the saprolite.

Indonesia, *Seeley and Senden (1994)* concluded that the gold grains had formed in situ, that is, the gold had been transported as humic acid-stabilized colloids and not as physical grains. More specifically, they proposed that the colloids were carried in groundwater that percolated through the terrace sands and gravels, and when this pregnant groundwater migrated toward the depositional channel, it encountered a “steep chemical gradient” causing the colloids to aggregate near clay zones within the palaeo-channel sands and gravels.

## CONCLUDING REMARKS

During the past 50 years, detailed descriptions of gold deposits, coupled with theoretical and experimental studies, have provided us with a relatively good understanding of how natural waters transport gold and of the mechanisms that may cause its deposition in hypogene and supergene environments. However, recent evidence for gold transport by aqueous vapours in magmatic-hydrothermal systems and proposals that liquid petroleum could transport gold in some environments suggest that not all deposits currently considered to be products of hydrothermal liquids may have formed as envisaged. The challenge for future research dealing with gold in solution will be to expand the current focus on aqueous liquids to include the other fluids known to be present in appreciable volumes in the Earth’s crust. By meeting this broader challenge of embracing all significant crustal fluids in our enquiry, we can expect not only to improve our models of how gold deposits form but also to contribute fundamental scientific knowledge to other fields of geoscience that require an understanding of metal transport.

## ACKNOWLEDGMENTS

We wish to thank *Christoph Heinrich* for his critical review of the manuscript and the editors for their insightful comments. The research was supported by an NSERC discovery grant to *AEW-J*. ■



## REFERENCES

- Agricola G (1556) De Re Metallica. Hoover HC, Hoover LC (translators, 1912). Mining Magazine, London, 637 pp
- Archibald SM, Migdisov AA, Williams-Jones AE (2001) The stability of Au-chloride complexes in water vapor at elevated temperatures and pressures. *Geochimica et Cosmochimica Acta* 65: 4413-4423
- Bowell RJ, Foster RP, Gize AP (1993) The mobility of gold in tropical rain forest soils. *Economic Geology* 88: 999-1016
- Bowell RJ, Laffoley NA, d'Ahreth EO, Hanssen E, Abe S, Yao RK, Pohl D (1996) Gold and base metal distribution and exploration in tropical soils: Four contrasting case studies from West Africa. In: Foster RP (ed) *Exploration and Mining in Africa: Towards 2000*. Transactions of the Institute of Mining and Metallurgy 105: B12-33
- Bowell RJ, Baumann M, Gingrich M, Tretbar D, Perkins WF, Fisher PC (1999) The occurrence of gold at the Getchell mine, Nevada. *Journal of Geochemical Exploration* 67: 127-143
- Daubr e A (1841) M moire sur le gisement, la constitution et l'origine des amas de minerai d'tain. *Annales des Mines, 3<sup>e</sup> s rie, tome XX*: 65-112
- Desborough GA (1970) Silver depletion indicated by microanalysis of gold from placer occurrences, western United States. *Economic Geology* 65: 304-311
- Emsbo P, Koenig AE (2007) Transport of Au in petroleum: evidence from the northern Carlin trend, Nevada. In: Andrew CJ et al. (eds) *Proceedings of the 9th Biennial SGA Meeting*, Dublin. Millpress, pp 695-698
- England GL, Rasmussen B, Krapez B, Groves DI (2002) Archean oil migration in the Witwatersrand Basin of South Africa. *Journal of the Geological Society* 159: 189-201
- Freise FW (1931) The transportation of gold by organic underground solutions. *Economic Geology* 26: 421-431
- Freyssinet P, Butt CRM, Morris RC, Piantone P (2005) Ore-forming processes related to lateritic weathering. In: Hedenquist JW, Thompson JFH, Goldfarb RJ, Richards JP (eds) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, pp 681-722
- Gammons CH, Williams-Jones AE (1997) Chemical mobility of gold in the porphyry-epithermal environment. *Economic Geology* 92: 45-59
- Gammons CH, Yu Y, Williams-Jones AE (1997) The disproportionation of gold chloride complexes at 25 to 200°C. *Geochimica et Cosmochimica Acta* 61: 1971-1983
- Graton LC (1940) Nature of the ore-forming fluid. *Economic Geology* 35: 197-358
- Gray DJ, Butt CRM, Lawrance LM (1992) The geochemistry of gold in lateritic terrains. In: Butt CRM and Zeegers H (eds), *Regolith Exploration Geochemistry in Tropical and Subtropical Terrains*. Handbook of Exploration Geochemistry, Volume 4. Elsevier, Amsterdam, pp 461-482
- Halbauer DK (1986) The mineralogy and geochemistry of Witwatersrand pyrite, gold, uranium and carbonaceous matter. In: Anhaeusser CR, Maske S (eds) *Mineral Deposits of Southern Africa*. Geological Society of South Africa, Johannesburg, pp 731-752
- Heinrich CA, Ryan CG, Mernagh, TP, Eadington PJ (1992) Segregation of ore metals between magmatic brine and vapor; a fluid inclusion study using PIXE microanalysis. *Economic Geology* 87: 1566-1583
- Hulen JB, Collister JW (1999) The oil-bearing, carlin-type gold deposits of Yankee Basin, Alligator Ridge District, Nevada. *Economic Geology* 94: 1029-1049
- Ingerson E, Morey GW (1940) Nature of the ore-forming fluid: A discussion. *Economic Geology* 35: 772-785
- Johnson JW, Oelkers EH, Helgeson HC (1992) SUPCRT92: A software package for calculating the standard molal thermodynamic properties of minerals, gases, aqueous species, and reactions from 1 to 5000 bar and 0 to 1000°C. *Computers & Geosciences* 18: 899-947
- Krauskopf KB (1957) The heavy metal content of magmatic vapor at 600 degrees C. *Economic Geology* 52: 786-807
- Liversidge A (1893) On the origin of gold nuggets. *Journal of the Royal Society of New South Wales* 27: 303-343
- Machairas G (1967) Dissolution et recristallisation de l'or primaire pendant l'oxydo-r duction des sulfures aurif res. *Bureau de recherches g ologiques et mini res bulletin* 5: 111-121
- Machesky ML, Andrade WO, Rose AW (1992) Interactions of gold (III) chloride and elemental gold with peat-derived humic substances. *Chemical Geology* 102: 53-71
- Ogryzlo SP (1935) Hydrothermal experiments with gold. *Economic Geology* 30: 400-424
- Pearson RG (1963) Hard and soft acids and bases. *Journal of the American Chemical Society* 85: 3533-3539
- Russell R (1686) *The Works of Geber* (Translation, edited by EJ Holmyard 1928). Kessinger Publishing, 1997, 306 pp
- Saunders JA (1990) Colloidal transport of gold and silica in epithermal precious-metal systems: Evidence from the Sleeper deposit, Nevada. *Geology* 18: 757-760
- Seeley JB, Senden TJ (1994) Alluvial gold in Kalimantan, Indonesia: A colloidal origin. *Journal of Geochemical Exploration* 50: 457-478
- Seward TM (1973) Thio complexes of gold and the transport of gold in hydrothermal ore solutions. *Geochimica et Cosmochimica Acta* 37: 379-399
- Spangenberg JE, Frimmel HE (2001) Basin-internal derivation of hydrocarbons in the Witwatersrand Basin, South Africa: evidence from bulk and molecular  $\delta^{13}C$  data. *Chemical Geology* 173: 339-355
- Stef nsson A, Seward TM (2004) Gold(I) complexing in aqueous sulphide solutions to 500°C at 500 bar. *Geochimica et Cosmochimica Acta* 68: 4121-4143
- Ulrich T, G nther D, Heinrich CA (1999) Gold concentrations of magmatic brines and the metal budget of porphyry copper deposits: *Nature* 399: 676-679
- Vlassopoulos D, Wood SA (1990) Gold speciation in natural waters: I. Solubility and hydrolysis of gold in aqueous solution. *Geochimica et Cosmochimica Acta* 54: 3-12
- Vlassopoulos D, Wood SA, Mucci A (1990) Gold speciation in natural waters: II. The importance of organic complexing—Experiments with simple model ligands. *Geochimica et Cosmochimica Acta* 54: 1575-1586
- Webster J (1671) *Metallographia: or An History of Metals*. Walter Kettilby, London, 389 pp
- Williams-Jones AE, Heinrich CA (2005) Vapor transport of metals and the formation of magmatic-hydrothermal ore deposits. *Economic Geology* 100: 1287-1312
- Williams-Jones AE, Migdisov AA (2007) The solubility of gold in crude oil: implications for ore genesis. In: Andrew CJ et al. (eds) *Proceedings of the 9th Biennial SGA Meeting*, Dublin. Millpress, pp 765-768
- Zezin DYu, Migdisov AA, Williams-Jones AE (2007) The solubility of gold in hydrogen sulfide gas: An experimental study. *Geochimica et Cosmochimica Acta* 71: 3070-3081
- Zezin DYu, Migdisov AA, Williams-Jones AE (2008) The solubility of gold in H<sub>2</sub>O-H<sub>2</sub>S vapour. *Geochimica et Cosmochimica Acta* 72 (Supplement 1): A1076



# Gold Deposits: Where, When and Why

John L. Walshe and James S. Cleverley\*

1811-5209/09/0005-0288\$2.50 DOI: 10.2113/gselements.5.5.288

## DEPOSIT CLASSIFICATION AND GENESIS

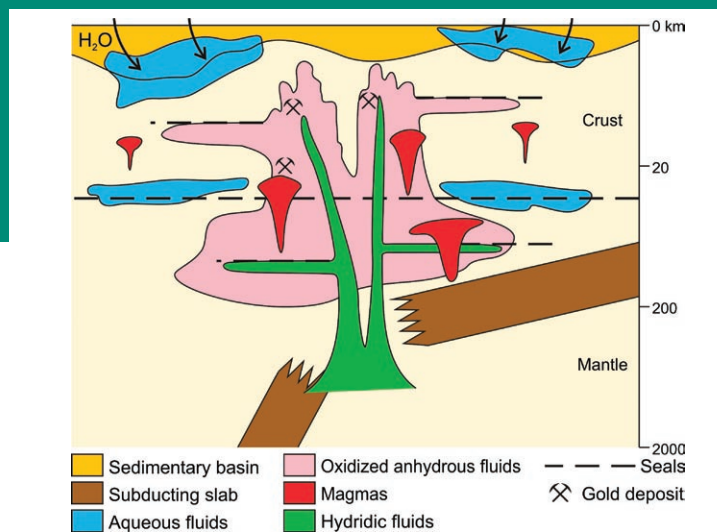
Gold concentrations in mineable deposits range from ~1 to 100 parts per million (ppm), or higher in bonanza deposits, in comparison to an average crustal abundance of ~1.3 ppb. A diverse range of elements may be associated with Au (La, Ce, U, V, Cr, Mo, W, Fe, Co, Ni, Pd, Pt, Cu, Ag, Zn, Hg, B, Tl, C, Si, Pb, As, Sb, Bi, S, Se, Te). A common mineralogical association is gold and quartz, but gold accumulations are also found with carbonates, carbon, feldspars, Fe sulfides and oxides, base metal sulfides,  $\text{Fe} \pm \text{Co} \pm \text{Ni}$  arsenides, and  $\text{Fe} \pm \text{Mg} \pm \text{Ca} \pm \text{V} \pm \text{Cr}$  silicates.

Deposits classified as epithermal gold–silver deposits, copper–gold porphyry deposits, gold skarn deposits, iron oxide–copper–gold deposits and intrusion-related Au deposits show some spatial  $\pm$  temporal affinity with intrusive magmatic activity, commonly in shallow crustal settings at active plate margins. Such deposits are inferred or assumed to be genetically linked to magmatic-hydrothermal activity. Gold-rich volcanic-hosted massive sulfides are related to sub-seafloor volcanic–hydrothermal processes, whereas gold-rich sedimentary-exhalative deposits are associated with the expulsion of basinal brines onto the seafloor in intra-cratonic and epi-cratonic rift systems. Syn-deformational, mostly gold-only deposits in metamorphic terrains and greenstone belts are commonly classified as orogenic lode Au deposits. The economically significant Carlin-type Au deposits, characterized by “invisible gold” in pyrite, take their name from a geographically restricted area of northern Nevada, which is the type and major locality of these deposits. Similarly, conglomerate-hosted Au–U deposits are defined by the deposits of the Late Archean Witwatersrand Basin of South Africa and account for a staggering 45% of total gold production.

Many of the characteristics used to classify deposits may not be particularly significant in terms of the processes that formed them. Very different element and mineralogical associations may arise in quite different geological settings from similar underlying processes. Observations across a range of scales suggest that a limited number of processes, some not fully understood, have controlled the distribution of gold in the Earth’s crust.

## A MINERAL SYSTEMS PERSPECTIVE

A mineral systems approach (Barnicoat 2008) can be used to help understand where, when and why gold deposits form. This approach asks five questions relating to the (1) geodynamic history, (2) architecture, (3) fluid sources and reservoirs, (4) fluid pathways and driving forces, and (5) metal transport and depositional mechanisms of a mineral system. In order to establish the salient characteristics of gold systems, it is necessary to consider the five answers in the broadest possible context over different time and length scales of the system. Some periods of Earth history produced more gold deposits than others. Most important are the Late Archean (~2.7 to 2.6 Ga: greenstone-hosted deposits), Paleoproterozoic (~2.0 to 1.6 Ga: iron oxide–copper–gold and lode gold deposits) and, after a billion-year gap, the Phanerozoic (~0.6 Ga to the present: porphyry and epithermal deposits). These periods of gold production broadly correspond with phases of new crustal growth although, paradoxically, the deposits do not necessarily occur in the most juvenile crust. Rather, gold deposits and provinces are commonly spatially associated with cratonic margins, cross-arc structures, tears in slabs and trans-crustal structures. These architectural constraints, together with geodynamic links to plate reorientation, slab rollback and slab foundering, suggest gold metallogenesis is in



**FIGURE 1** A crust–mantle perspective on gold mineralizing systems. Geodynamics and architecture constrain the release of mantle fluids into the crust and gold mobility. Significant deposits have developed where thermo-chemical gradients (redox, pH, water activity) were sustained by focused flux of anhydrous, oxidized ( $\text{CO}_2 \pm \text{SO}_2$ ) and hydridic ( $\text{H}_2$ ,  $\text{CH}_4$ ,  $\text{HCl}$ ) mantle/crustal volatiles, triggered by plate-scale deformation events.

some way related to fluid fluxes from the mantle. If there is a common unifying theme to the genesis of gold deposits, it could lie in the nature of the fluid reservoirs in the mantle and the forces that drive fluid release. Storage of anhydrous volatile-rich fluids in the mantle and their subsequent release are conceivable without significant magma production. The abundance of  $\text{SO}_2$  in volcanic gases implies that anhydrous fluids in the outer few hundred kilometres of the mantle are highly oxidized ( $\text{CO}_2 \pm \text{SO}_2$  fluids). However, thermodynamic studies and the mineralogy of inclusions in diamondiferous kimberlites suggest hydridic ( $\text{H}_2$ -rich) fluids may dominate at depths greater than 300–400 km.

Fluxes of reduced and oxidized volatiles, of either mantle or crustal derivation, could sustain thermo-chemical gradients (e.g. redox and acidity), promote metal transport and drive terrain-scale metasomatism. Gold mineral systems may be viewed as thermo-chemical engines with their roots deep in the mantle (Fig. 1). Such a model links metallogenesis to secular changes in architecture and geochemistry of the planet over its 4.5-billion-year history.

## GOLD DEPOSITION MECHANISMS

At the smallest scale, we need to understand the processes that drive metal transport and deposition. Specific element, mineral and isotope associations, particularly with bonanza gold deposits, imply deposition has occurred in chemical environments dominated by fluids far from equilibrium with local host rocks and ambient fluids. In situ Sr isotope analysis of apatite associated with gold in laminated quartz veins point to an oxidized,  $\text{CO}_2$ -rich (water-poor) fluid with a strong mantle affinity at the time of gold deposition. An understanding of the nature and extent of gold complexing in anhydrous fluids has not yet been achieved. It is possible that very rapid growth of deposits may have occurred, in tens of years, from relatively small volumes of fluid, assuming the presence of gold (and other metals) at concentrations of  $10^3$ – $10^4$  ppm. This mineral systems approach addresses fundamental mantle–crust interactions and suggests the following research priorities:

- properties of non-aqueous fluids and the capacity of such fluids to dissolve and transport metals;
- links between mantle degassing and fluid-driven processes in the Earth’s outer ~10 km;
- mapping of fluid flow paths to resolve their sources and sinks and enhance mineral exploration. ■

## REFERENCE

Barnicoat AC (2008) The pmd\*CRCs Mineral Systems approach. In: Korsch RJ, Barnicoat AC (eds) *New Perspective: The Foundations and Future of Australian Exploration*. Abstracts for the June 2008 pmd\*CRCs Conference, Perth, Geoscience Australia, 2008/09, pp 7-16 ■

\* CSIRO Exploration & Mining, PO Box 1130 Bentley, Western Australia 6102, Australia  
E-mail: John.Walshe@csiro.au; James.Cleverley@csiro.au

# From Source to Sinks in Auriferous Magmatic-Hydrothermal Porphyry and Epithermal Deposits



Richard M. Tosdal<sup>1</sup>, John H. Dilles<sup>2</sup> and David R. Cooke<sup>3</sup>

1811-5209/09/0005-0289\$2.50 DOI: 10.2113/gselements.5.5.289

**A**uriferous porphyry Cu deposits are restricted to convergent plate settings, whereas epithermal precious metal deposits form at extending convergent plate settings and in rifts. Both deposit types are linked to magma carrying metals and ligands that rises to form an upper-crustal magma chamber. Magma convection and fractionation lead to volatile exsolution and collection in the apical parts of the chamber, from which exsolved hydrothermal fluid ascends to form either a porphyry Cu–Au deposit associated with stocks and dykes generally at 2–5 km depth, or an epithermal deposit associated with coeval volcanic rocks at depths of <1 km.

**KEYWORDS:** magma, hydrothermal evolution, porphyry Cu, epithermal precious metal

## INTRODUCTION

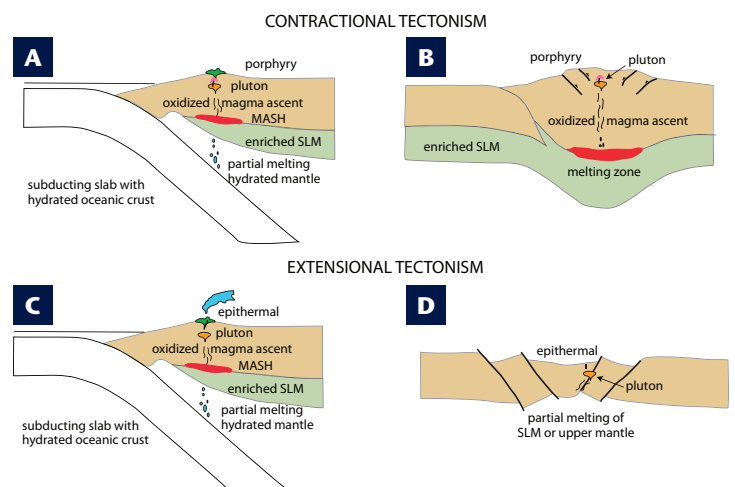
Gold deposits come in many different sizes and shapes and are found in a range of environments. Each Au-bearing deposit type is the end result of a series of geological events that together lead to an anomalous concentration in the Earth's crust. Of the many types of gold deposits, porphyry- and epithermal-type deposits associated with upper-crustal intrusions account for significant Au production on an annual basis. We review the salient features of these magmatic-hydrothermal deposits, considering first the ultimate source of the magmatic components, then the hydrothermal system and metal transport, and, finally, metal deposition.

## MAGMA GENESIS

Most Au-bearing porphyry Cu and epithermal deposits are associated with the emplacement of upper-crustal magma chambers. The magma chambers are largely the product of subduction of an oceanic plate beneath an overriding oceanic or continental plate, although a distinct subset of mineralized porphyry-related magmatic complexes form in collisional orogens long after subduction of an oceanic plate has ceased (FIG. 1) (Seedorff et al. 2005; Richards 2009). Magma generation begins in the mantle, most probably through dehydration of the subducting slab at a depth of ~100 km or through depression of the lower crust and upper mantle into a zone of melting during collisional orogenesis. Above subducting slabs, rising aqueous fluids carry incompatible elements (volatiles, large-ion lithophile elements, silicon) into the overlying mantle wedge, thereby metasomatizing and enriching it. Melting the modified subcrustal mantle yields basaltic melts that collect at the base of the crust (FIG. 1A, C). There, the mantle-derived melts undergo

extensive interchange with the mafic-rich lower crust (Hildreth and Moorbath 1988), forming magma of intermediate composition. This magma rises to higher crustal levels, where it assimilates crustal material and fractionates to more felsic compositions. Dioritic magma is common in mafic-dominated crust, whereas magma of granodioritic composition is more common in felsic-dominated crust. Magma composition influences the metal budget of an associated porphyry deposit (Seedorff et al. 2005).

Magma ascending into the upper crust accumulates in a chamber (FIG. 2) that commonly measures 10–15 km across and a few kilometres in vertical extent at depths of 2 to 12 km (Hamilton and Myers 1967; Dilles et al. 2000). Critical to the chamber construction is a high and sustained rate of magma generation and ascent, as individual magma chambers can solidify in a very short time, measured in tens of thousands of years, unless continually replenished. There is considerable uncertainty as to the duration of an upper-crustal magma chamber as many factors are involved. Nonetheless, it is clear that continual magma intrusion from depth is required to form in a remarkably short time and then sustain a convecting upper-crustal chamber (FIG. 2).

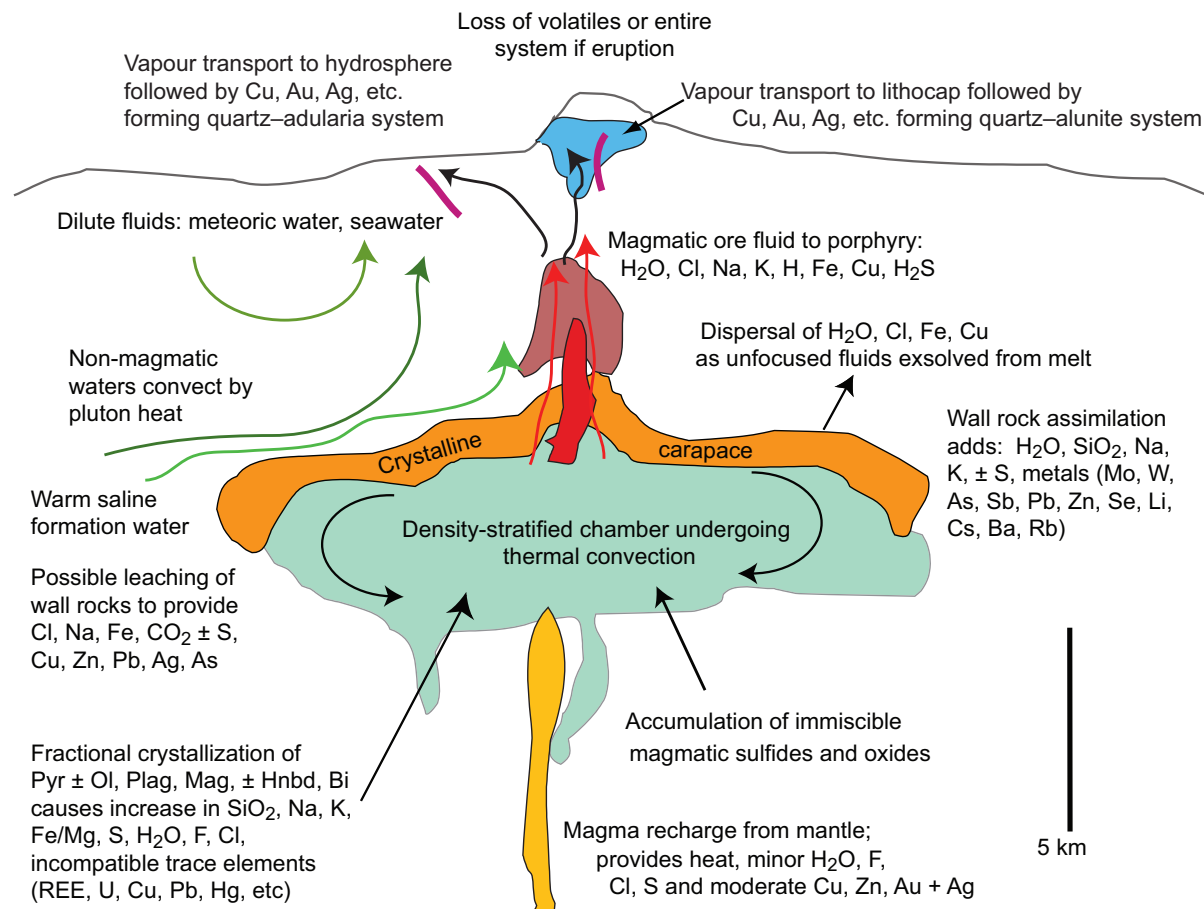


**FIGURE 1** Tectonic setting of porphyry Cu and epithermal deposits. Porphyry Cu–Au deposits form at the end of magmatic episodes during contraction, dominantly in a convergent plate margin undergoing collision (**A**) or soon after collision (**B**). In contrast, epithermal deposits are associated with extension at the convergent plate margin (**C**) or (**D**) in a rift zone. MASH: zone of crustal melting and assimilation, magma storage, and homogenization. SLM: sublithospheric mantle

1 Mineral Deposit Research Unit, University of British Columbia Vancouver, BC, V6T 1Z4, Canada E-mail: rtosdal@gmail.com

2 Department of Geosciences, Oregon State University OR 97370, USA

3 Australian Research Council Centre of Excellence University of Tasmania, Hobart, Tasmania, Australia



A critical component of magma-related porphyry and epithermal deposits is an oxidized magma. An average dioritic or granodioritic magma has sufficient metals to generate porphyry deposits, but the magma must be oxidized and sulfur rich such that sulfur is retained in the magma as sulfate and not in the reduced form, which will crystallize to form sulfide minerals that sink to the bottom of the magma chamber (Chambefort et al. 2008). Thus, magma must ascend through tens of kilometres of crust of variable composition (FIG. 1A, B) without significantly changing its oxidation state. Upon volatile saturation, the sulfur may partition into the magmatic volatile phase and be transported to the site of deposition (Candela and Piccoli 2005).

Porphyry and epithermal deposits are inherently related to arc magmatism. Overall, there is a common theme of short- to long-lived magmatism (~1 to 10 million years), evolving from early volcanism to main-stage plutonism as the magmatic arc wanes (Sillitoe 2000). Porphyry intrusions directly associated with mineralization do not erupt and commonly form relatively late during the magmatic episode. Where a case can be made for approximately synchronous volcanism, it is low-volume domes that appear to be largely present. Volcanic activity results in the loss of key volatiles in the eruption column, which can short-circuit the porphyry-forming process and yield “negative” porphyry systems (Pasteris 1996). In contrast, volcanic activity is intimately associated with epithermal deposits (Simmons et al. 2005), as it may enhance the ability of hydrothermal fluids to rise into the shallow crust.

Emplacement of hot magma into shallow crust typically drives hydrothermal convection cells in the wall rocks (FIGS. 2 AND 3) that operate over radii of many kilometres (Dilles et al. 2000). These ground waters range from dilute meteoric waters – which may produce propylitic alteration

**FIGURE 2** Construction of a convecting upper-crustal magma chamber at depths of 6–12 km beneath the surface through the input of mafic magma from depth. Exsolved hydrothermal fluid collects in the apical parts of the chamber and escapes vertically into the porphyry and epithermal environment. Mineral abbreviations: Bi, biotite; Hnbd, hornblende; Mag, magnetite; Ol, olivine; Pl, plagioclase; Pyr, pyroxene.

dominated by hydration, carbonation and oxidation reactions, forming albite, chlorite, epidote and carbonate minerals – to saline fluids and brines capable of strong alkali metasomatism producing higher-temperature sodic-calcic alteration (Na-plagioclase, actinolite, epidote) at depth and associated propylitic alteration at shallower crustal levels (FIG. 4). Brines involved in such large-scale alteration can dissolve and transport large quantities of Fe, K, Cu, Au and other elements, and where precipitation occurs may form iron oxide–copper–gold deposits (Dilles et al. 2000).

## TECTONIC SETTING OF PORPHYRY AND EPITHERMAL DEPOSITS

Plate tectonic setting plays a critical role in determining what type of ore deposit forms in a particular location at a particular time. The relationship of porphyry Cu deposits to convergent plate margins and, as recognized more recently, to collisional orogens (FIG. 1A-B) is a long-held tenet in the deposit model. Within these orogens, porphyry deposits form during narrow time intervals in a particular segment of an arc. Generally, porphyry deposits form near the end of a magmatic episode or during a change of deformation styles when the arc is undergoing limited contraction (Sillitoe 2000). The ultimate tectonic trigger for these events is uncertain, with proposed scenarios including changing subduction geometry, collision and subduction of irregularities in the down-going plate.

In contrast, the geological setting of epithermal deposits is more variable, including volcanic dome fields, peripheral areas of volcanoes and rift zones. Most deposits form in extending arcs or rifts (FIG. 1c, d), contemporaneous with shallow-level magmatism and thermally driven hydrothermal circulation (Sillitoe and Hedenquist 2003). Few epithermal deposits form during contraction, and those known formed in localized extensional settings (Cooke and Simmons 2000).

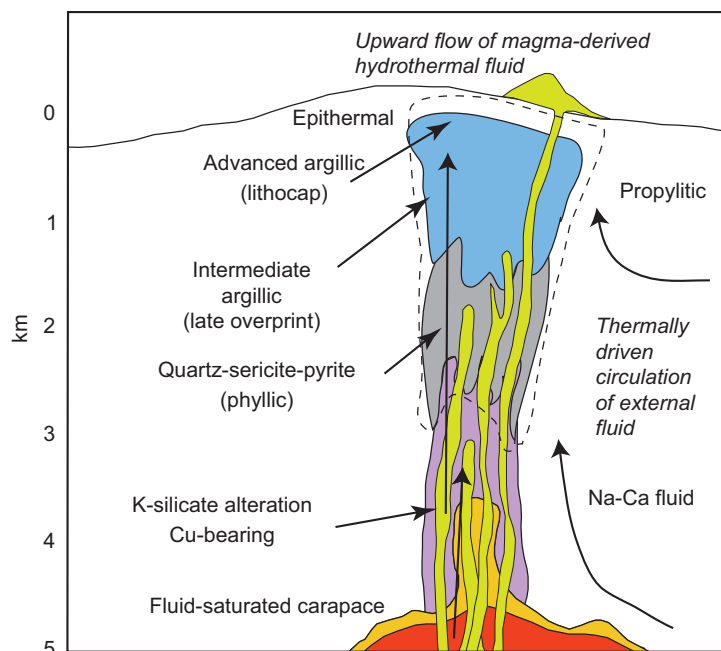
### GOLD-BEARING PORPHYRY Cu DEPOSITS

Porphyry Cu deposits with average Au contents of >0.4 gram (g)/metric ton (t) are defined as gold rich (Sillitoe 2000). In general, Au contents are <1 g/t although in some deposits, such as Grasberg (Indonesia) and Ridgeway (Australia), they are higher. What makes porphyry deposits major sources of Au is their sheer size, with deposits containing from 50 Mt to 4500 Mt of ore. (There are very few Au-only porphyry deposits. Most deposits become mines based on their Cu content, which pays for the development; Au is recovered as a by-product). The deposits are associated with low-K calc-alkaline diorite to tonalite, high-K calc-alkaline quartz monzonite, and alkaline monzonite and syenite, some of which are silica undersaturated and compose a class of alkalic porphyry systems (Jensen and Barton 2000; Sillitoe 2000).

Porphyry-type systems are spatially and genetically associated with porphyritic intrusions. The stocks are of calc-alkaline to alkaline composition and oxidized. The stocks are characterized by hydrous phenocryst phases, such as amphibole and biotite, whose stability requires at least 4 wt% H<sub>2</sub>O in the melt (Burnham 1979). Convecting magma reaches saturation in the lower-pressure parts of the magma chamber, so that the apical parts of the magma chamber become water saturated, forming a bubble-rich froth (FIGS. 2 AND 3). Ascent of such fluids hydrofractures the overlying rock, allowing magma to ascend as narrow dykes and plugs. Magma ascent is accompanied by a pressure drop, vapour loss and pressure-quenching, thus forming the characteristic aplitic groundmass of the porphyry intrusions. Massive hydrofracturing of wall rocks and stocks forms the pathways for ascent of magmatic fluids from the cupola.

The exsolved, water-rich volatile phase concentrated at the top of the magma chamber contains a range of water-soluble volatile components, such as Cl and S species. Magmatic-hydrothermal fluid commonly separates from the magma as a single-phase fluid (>1.4 kb or 5 km depth) of relatively low density, with ~5 wt% dissolved solids, dominated by salts. The ascending and depressurizing parent fluid intersects the broad field of fluid immiscibility between 750°C and the critical point of a dilute salty fluid water at 374°C, leading to the separation of a small quantity of high-density brine from a larger volume of low-density vapour (Williams-Jones and Heinrich 2005).

Gold, being dominantly transported as a chloride complex at high temperature (Williams-Jones et al. 2009 this issue), is precipitated along with Cu-Fe sulfides in the porphyry environment at around 400°C as a result of decreasing solubility, during cooling, of metal chloride complexes in the presence of H<sub>2</sub>S (Hemley and Hunt 1992). Precipitation of Au and other metals is enhanced by fluid-rock reaction, changes in pH and fluid speciation, brine-vapour unmixing (so-called boiling) and, in a few cases, potentially by local fluid mixing (Beane and Titley 1981; Seedorff et al. 2005). With cooling to ~400°C, most SO<sub>2</sub> in the hydrothermal fluid disproportionates via reaction with water in the rising fluid to form H<sub>2</sub>SO<sub>4</sub> and H<sub>2</sub>S, which promotes sulfide precipi-



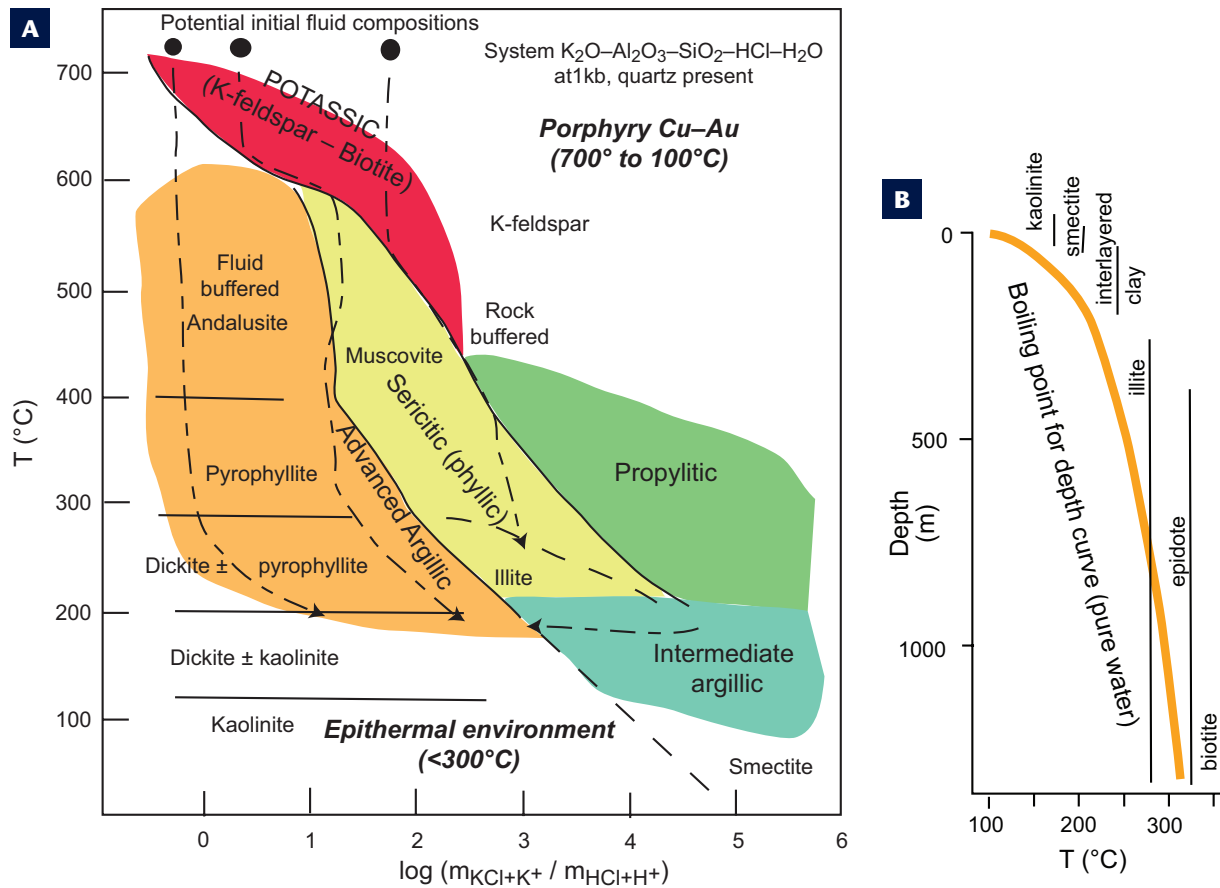
**FIGURE 3** Distribution of alteration assemblages in a simplified porphyry Cu-Au deposit. Volatiles collect in the apical carapace of the magma chamber and follow the porphyry intrusion to shallow depths. Alteration assemblages reflecting the gradual cooling of the exsolved magmatic-hydrothermal plume are stacked vertically; mineral assemblages also depend on physicochemical changes in the fluid during the buoyant rise to shallow depths. Circulating ground waters driven by thermal energy from the underlying pluton form the propylitic alteration assemblage.

itation. Brine and vapour, due to their large density contrast, may physically separate, with chloride and chloride-complexed species (for example, Cu, Pb, Zn, K, and some Au) concentrated in the brine and H<sub>2</sub>S and bisulfide-complexed species (potentially Au, Cu and As) concentrated in the vapour.

In the porphyry environment, the high-temperature fluid alters the rock to mineral assemblages consisting of quartz, K-feldspar, biotite, anhydrite and magnetite – the potassic alteration assemblage (FIGS. 4A AND 5A, B) (Gustafson and Hunt 1975). In alkalic porphyry systems, the Ca-bearing minerals garnet, diopside and actinolite are reported in equilibrium with the typical potassic alteration assemblage in the high-temperature core of the system (Lang et al. 1995). In other porphyry deposits, Na-Ca alteration minerals in the core represent the influx of external non-magmatic fluids into the magma-derived hydrothermal systems (Dilles et al. 1995).

Gold-bearing sulfide minerals are deposited with the potassic alteration assemblages in association with chalcopyrite and bornite as disseminations in wavy or ductilely deformed, straight-walled, quartz-rich or sulfide-only veins. Much of the Au is originally deposited as trace components in solid solution within Cu-Fe sulfides, which upon cooling undergo exsolution to form native Au grains within the sulfide host (Kesler et al. 2002). The Cu-Fe sulfide and Au veins are cut, and accompanied, by successively younger intra-mineral to post-mineral intrusions (FIG. 5c), with less and less Cu and Au being precipitated with each successive intrusion (Garwin 2002).

Superposed on the high-temperature alteration assemblages in the upper parts of the porphyry system are alteration assemblages that reflect progressive cooling and changing physicochemical conditions (FIGS. 3 AND 4A). One assemblage, less common in Au-rich porphyry Cu deposits, is



dominated by quartz, sericite (fine-grained white mica: either muscovite, phengite or, in rare cases, paragonite) and pyrite, and is known as phyllic or sericitic alteration (FIGS. 3 AND 4A). Where the rocks are Mg and Fe rich, chlorite will form part of the assemblage. The quartz-sericite ± chlorite assemblage forms through cooling of the fluid as it rises buoyantly. As previously mentioned, sulfur originally dissolved as  $SO_2$  reacts with water and disproportionates to form  $H_2S$  and sulfuric acid, which extensively alters the host rocks to acid-stable minerals (Burnham 1979). The phyllic alteration may be accompanied by the partial to almost complete destruction of rock texture and by some Cu-Fe sulfide precipitation or be associated with the loss or redistribution of Cu and Au (Sillitoe 2000; Seedorff et al. 2005). Associated veins (Gustafson and Hunt 1975) are coarse grained and sharply defined, with strong alteration haloes; they consist of sulfide minerals (abundant pyrite, variable but generally lesser proportions of Cu-Fe sulfide minerals, sulfosalt minerals, sphalerite and galena), anhydrite and minor quartz. In most porphyry Cu deposits, pervasive clays represent a low-temperature (<250°C) intermediate argillic alteration assemblage formed during the cooling and collapse of the hydrothermal system (FIGS. 3 AND 4A).

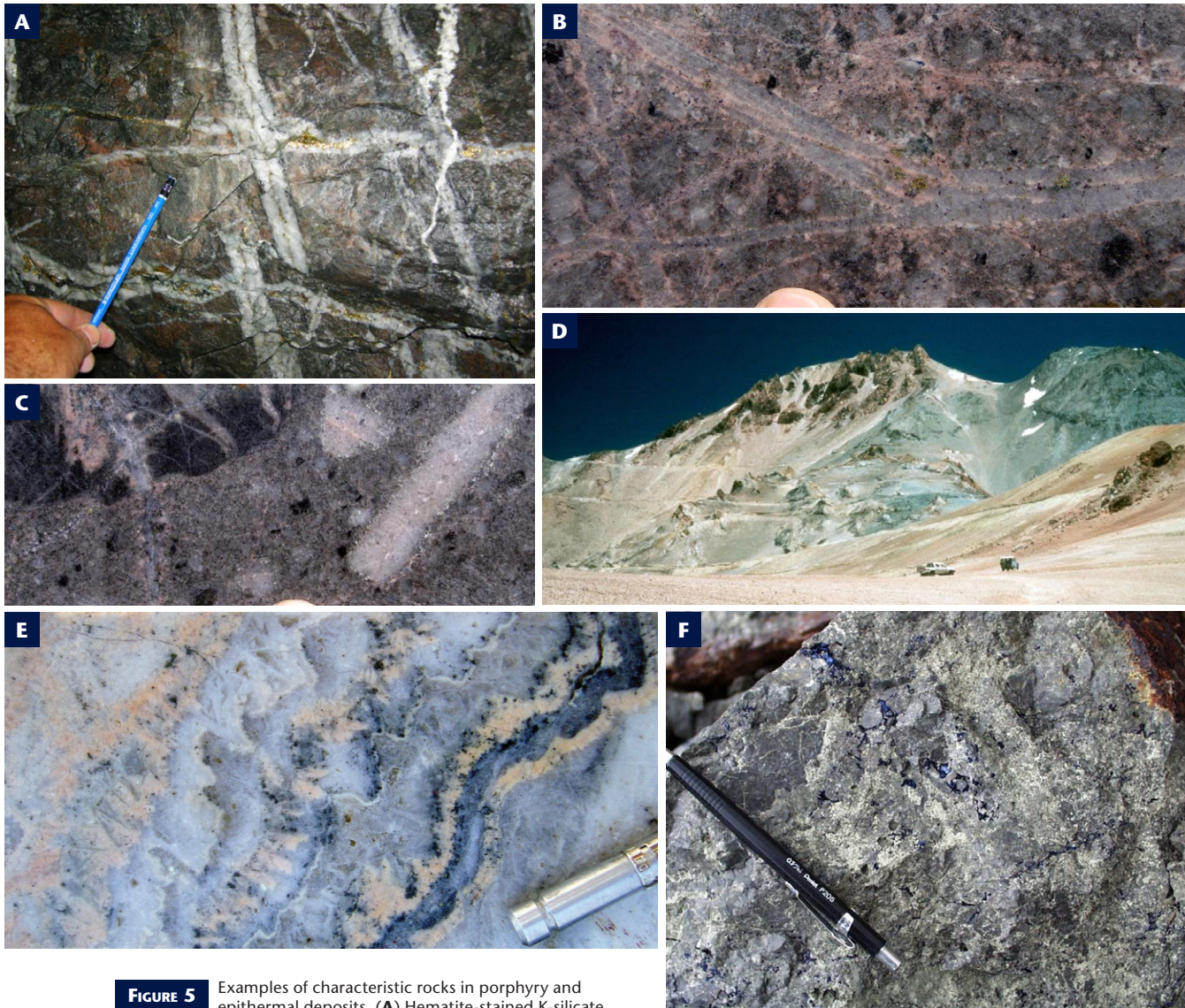
Separation of the fluid phase into brine and vapour leads to the formation of a low-density vapour plume rich in acidic volatiles such as  $SO_2$ , HF,  $H_2S$  and  $CO_2$ . If the vapour separates from the brine, it may rise buoyantly into the epithermal environment. As it cools and condenses during interaction with ground water at shallow depths, it causes intense acid leaching, thus forming the advanced argillic alteration (Williams-Jones and Heinrich 2005); this alteration may or may not be associated with an epithermal deposit (FIGS. 3 AND 4A). Advanced argillic alteration is characterized by the total destruction of primary minerals, leaving an insoluble residue of quartz, clays (kaolinite or pyrophyllite), aluminium hydroxides (diaspore) and

**FIGURE 4** (A) Phase diagram for the system  $K_2O-Al_2O_3-SiO_2-H_2O-KCl-HCl$  at  $P_{H_2O} = 1$  kbar, showing possible paths of fluid evolution (dashed lines) depending upon starting fluid composition. The diagram is shown in terms of temperature and the molal (m) composition of the fluid. The path at left represents a fluid-dominant alteration sequence, whereas the other two illustrate rock-buffered alterations. Different paths demonstrate the importance of the starting fluid composition on the sequence of alteration, which is in part due to different magma compositions. Late influx of external fluid into the porphyry environment forms the widespread rock-buffered intermediate argillic alteration. MODIFIED FROM SEEDORFF ET AL. (2005) (B) Boiling point for depth curve for epithermal deposits showing the vertical distribution of minerals in a boiling upflow zone. REDRAFTED FROM SIMMONS ET AL. (2005)

alunite. This assemblage is referred to as the leached cap (FIG. 5D). Such porous and permeable alteration zones are rarely exposed in porphyry systems due to erosion, so whether they overlie all porphyry deposits is unknown.

### Breccias

Hydrothermal breccias are common in Au-rich porphyry Cu deposits (Sillitoe 2000). Brecciation occurs as a result of the large mechanical energy available from ascending, depressurizing, water-rich magmatic-hydrothermal fluids, which form initially under lithostatic pressure and move to hydrostatic pressure conditions. Accompanying massive hydrofracturing destroys and displaces downward the brittle-ductile transition zone separating the deeper lithostatic from the overlying hydrostatic environment (Burnham 1985). The result is a breccia that expands upwards, generally forming a cone of fragmented rock whose geometry will depend upon the host rock and the extant structural fabric. Depending upon the timing, early breccia can host significant metal grade, whereas late



**FIGURE 5** Examples of characteristic rocks in porphyry and epithermal deposits. **(A)** Hematite-stained K-silicate alteration and quartz-Cu-Fe sulfide veins at the Ridgeway alkalic porphyry Au-Cu deposit (New South Wales, Australia). **(B)** Intense multi-generational quartz vein mesh in early porphyry at the Reko Diq porphyry Cu-Au deposit (Pakistan). The pink halo on the quartz veins is K-feldspar. **(C)** Intra-mineral, hornblende-biotite diorite porphyry containing xenoliths of biotite hornfels cut by a quartz vein mesh and of older, sugary high-temperature quartz veins at the Reko Diq porphyry Cu-Au deposit (Pakistan). **(D)** Advanced argillic-altered lithocap (bold outcrops with white, quartz-rich talus on slope) located above the Cerro Casale porphyry Cu-Au deposit (Chile). **(E)** Banded quartz-adularia-illite vein containing dark bands of pyrargarite from the Maria vein, Manantial Espejo Mine (southern Argentina). **(F)** Unoxidized and brecciated, grey quartz  $\pm$  alunite-altered volcanic rock with infill covellite (blue mineral) and Au precipitated in breccia voids, at Yanacocha (Peru).

breccia forming at the end of the hydrothermal system may be weakly mineralized or essentially remove and dilute significant portions of an orebody.

## EPITHERMAL DEPOSITS

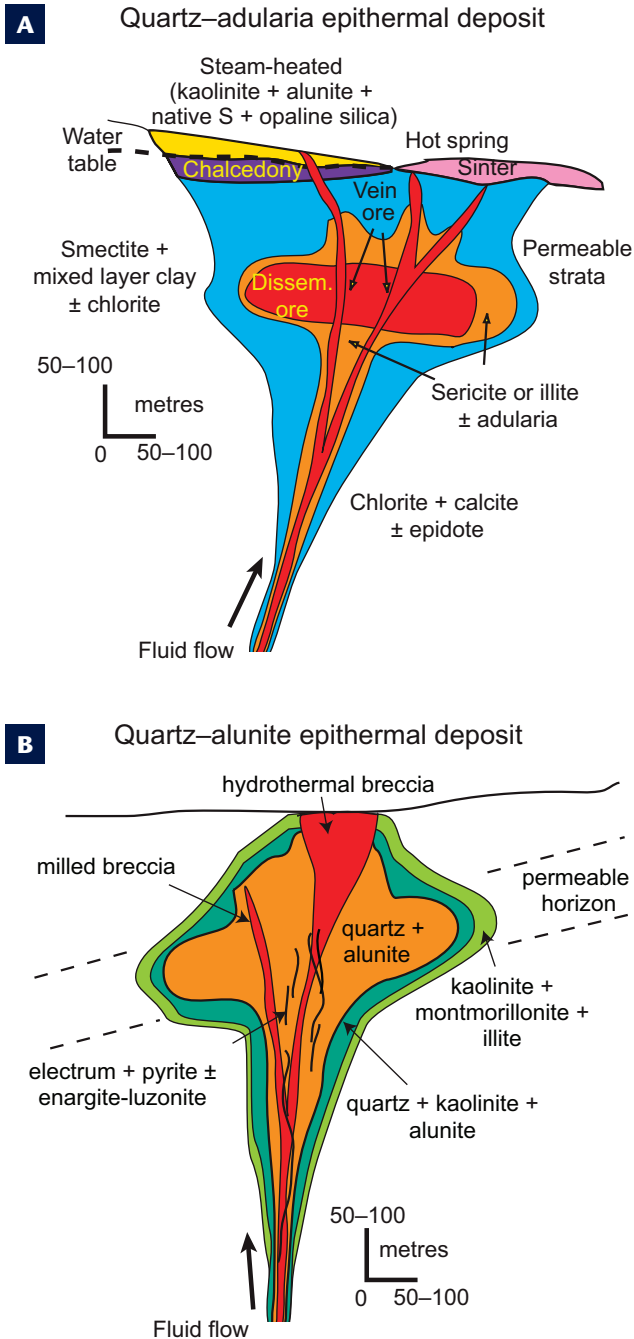
Epithermal deposits form in the uppermost crust at depths ranging from ~50 m to as much as 1500 m below the water table. They form primarily from subaerial hydrothermal systems driven by magmatic heat and, less commonly, by deeply circulating ground water rising along basin-bounding faults (Lindgren 1933; Simmons et al. 2005). The deposits are principally linked to magmatism, either close to and above the intrusion or at some distance from it,

where the magmatic input is entrained in and diluted by a structurally controlled or topographically driven large-scale geothermal system (Fig. 2). Unlike the high- to low-temperature fluid history of a porphyry Cu-Au deposit, epithermal deposits form at temperatures ranging from 150 to 300°C, and metal content is controlled by the composition of the hydrothermal solution, reflecting differing origins and geological environments (Simmons et al. 2005).

Although numerous classifications of epithermal systems have been proposed, they essentially can be defined by two end member types based on the characteristic hypogene mineral assemblages: (1) quartz  $\pm$  calcite  $\pm$  adularia  $\pm$  illite (Figs. 4B and 6A) and (2) quartz + alunite  $\pm$  pyrophyllite  $\pm$  dickite  $\pm$  kaolinite (Fig. 6B) (Simmons et al. 2005). The first mineral assemblage forms in neutral pH environments and encompasses the low-sulfidation and intermediate-sulfidation deposits (Sillitoe and Hedenquist 2003), whereas the second forms in acidic environments and is equivalent to high-sulfidation deposits (White and Hedenquist 1995).

### Quartz $\pm$ Calcite $\pm$ Adularia $\pm$ Illite Assemblage

Epithermal deposits composed of this assemblage form in geothermal systems in volcanic arcs and rifts and result from the deep circulation of meteoric water driven principally by a shallow intrusion. At depth, the chloride-dominated waters are near neutral and contain reduced S species



**FIGURE 6** (A) Idealized cross section of a quartz–adularia epithermal deposit showing distribution of alteration assemblages. (B) Idealized cross section of a quartz–alunite epithermal deposit. MODIFIED FROM WHITE AND HEDENQUIST (1995) AND HEDENQUIST ET AL. (2000)

and dissolved  $\text{CO}_2$ . The  $\text{H}_2\text{S}$  provides an important ligand for the transport of Au as a bisulfide complex (Seward and Barnes 1997; Williams-Jones et al. 2009 this issue). These waters contain small amounts of magmatic fluid, which is considered to be the source of metal precipitated in the epithermal deposits. The fluid is generally in equilibrium with the host rocks and is thus rock buffered. Boiling in the central upflowing fluid, the primary mechanism for sulfide deposition, is controlled by the ambient near-hydrostatic pressure and temperature conditions, and quartz,

adularia and platy calcite are deposited (FIGS. 4B, 5E, AND 6A). The chloride-dominated fluid may rise to the surface and discharge, depositing sinter, or be dispersed laterally through an outflow zone, producing extensive zones of alteration and replacement. During boiling of the ascending fluid, dissolved  $\text{CO}_2$  and  $\text{H}_2\text{S}$  are partitioned into the vapour, which rises to the surface and condenses into the local cool ground water, forming  $\text{CO}_2$ -rich or  $\text{H}_2\text{S}$ -rich steam-heated water. The  $\text{CO}_2$ -rich ground water is concentrated along the shallow margins of the upflow zones, where a carbonate mineral-rich assemblage forms. The  $\text{H}_2\text{S}$ -rich ground water enters the vadose (unsaturated) zone, and  $\text{H}_2\text{S}$  reacts with the atmosphere and is oxidized to  $\text{H}_2\text{SO}_4$ . This results in steam-heated zones of alteration, in which a low-pH (<2) fluid high in dissolved sulfate alters the rocks to an advanced argillic mineral assemblage consisting of opal (cristobalite), alunite, kaolinite and pyrite as the fluid becomes neutralized near the water table.

### Quartz + Alunite ± Pyrophyllite ± Dickite ± Kaolinite Assemblage

Epithermal deposits of this type are associated with near-surface magmatic-hydrothermal systems that are acidic (FIG. 6B) and have the potential to transport large quantities of precious and base metals (Williams-Jones and Heinrich 2005). The upflow zones are dominated by magmatic vapours containing HCl,  $\text{SO}_2$  and HF, which condense into shallow ground water and form the extremely acidic environments seen in some modern systems, such as crater lakes in degassing volcanoes. Fluid–rock reactions leach cations, neutralize the acidic fluid and lead to the precipitation of alunite, pyrophyllite, dickite, quartz, anhydrite, diaspore, topaz, kaolinite and illite, which is an assemblage characteristic of fluid-dominated conditions and advanced argillic alteration (FIG. 4A). Steam-heated acid-sulfate waters also form in the vadose zone, but silica sinters do not, because the acid conditions inhibit deposition of amorphous silica (Fournier 1985). In many magmatic-hydrothermal systems, metal-bearing fluids may not ascend to the shallow epithermal environment, leading to a barren leached zone characterized by advanced argillic mineral assemblages; these lithocaps are exposed in a few shallow porphyry Cu deposits, where they represent the uppermost part of the porphyry Cu magma-derived hydrothermal plume (FIG. 5D). Where metal-bearing fluid reaches the epithermal environment, it generally post-dates intense leaching of wall rocks (FIG. 5F). The metalliferous oxidized fluid may cause minimal wall rock interaction and, upon cooling, precipitate high-sulfidation-state minerals or, with greater water–rock interaction, more intermediate-sulfidation-state minerals (Einaudi et al. 2003).

### HOW LONG DOES IT TAKE TO FORM A DEPOSIT?

Available geochronological and geological data suggest that a porphyry or epithermal deposit can form in what is a geological instant, on the order of a few thousand to a few hundred thousand years (Arribas et al. 1995; Garwin 2002). In fact, the process of metal introduction and deposition may be so efficient that, for example, the 42 million ounces of Au in the Ladolam epithermal deposit in Papua New Guinea could have been precipitated in as little as 55,000 years (Simmons and Brown 2006). However, it is also important to recognize that a magmatic-hydrothermal system, particularly a porphyry deposit, is an integral part



of a long-lived and evolving magmatic complex. Such a complex includes a deep magma chamber, numerous intrusive events and overlapping hydrothermal systems, which may have formed, cooled and been overprinted or moved to a different location by a younger hydrothermal system (Gustafson and Hunt 1975; Garwin 2002). In the epithermal environment, because of the rapid cooling inherent in shallow crust, geochronology commonly distinguishes the multiple events. In contrast, the long-term perturbation of the thermal profile by multiple porphyry intrusions and their related hydrothermal systems, as well as by the underlying cooling batholith, may blur temporal distinctions between discrete spatially related porphyry systems, potentially detectable using modern geochronology tools. The result is an apparently long-lived and continuously operating porphyry hydrothermal system, rather than one characterized by superposed systems that may have acted episodically over a protracted period of time.

## CONCLUSIONS

Porphyry and epithermal deposits have contributed significantly to the global and historical production of gold. Their formation involves the entire lithospheric column, starting in metasomatized upper mantle, then in the upper crust where a hydrothermal fluid exsolves from an oxidized magma, and finally higher in the upper crust where changing physico-chemical conditions coupled with external geological controls contribute to precipitation and the formation of ore deposits.

## ACKNOWLEDGMENTS

This overview has benefited from decades of research by the geological community, much of which could not be directly cited herein. The authors thank the many scientists who have contributed their knowledge to the subject. Suggestions to improve the manuscript by Anthony Williams-Jones and Robert Hough are greatly appreciated. This is MDRU contribution no. 236. ■

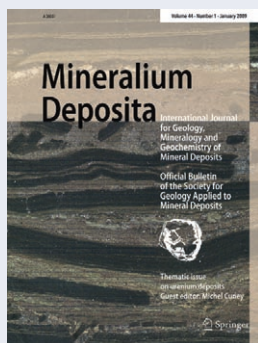
## REFERENCES

- Arribas AA Jr, Hedenquist JW, Itaya T, Okada T, Concepción RA, Garcia JS Jr (1995) Contemporaneous formation of adjacent porphyry and epithermal Cu-Au deposits over 300 ka in northern Luzon, Philippines. *Geology* 23: 337-340
- Beane RE, Tittle SR (1981) Porphyry copper deposits. Part II. Hydrothermal alteration and mineralization. *Economic Geology* 75<sup>th</sup> Anniversary Volume, pp 235-263
- Burnham CW (1979) Magmas and hydrothermal fluids. In: Barnes HL (ed) *Geochemistry of Hydrothermal Ore Deposits*, 2<sup>nd</sup> edition. John Wiley and Sons, New York, pp 71-136
- Burnham CW (1985) Energy release in subvolcanic environments: Implications for breccia formation. *Economic Geology* 80: 1515-1522
- Candela PA, Piccoli PM (2005) Magmatic processes in the development of porphyry-type ore systems. *Economic Geology* 100<sup>th</sup> Anniversary Volume, pp 25-37
- Chambefort I, Dilles JH, Kent AJR (2008) Anhydrite-bearing andesite and dacite as a source for sulfur in magmatic-hydrothermal mineral deposits. *Geology* 36: 719-722
- Cooke DR, Simmons SF (2000) Characteristics and genesis of epithermal gold deposits. *Reviews in Economic Geology* 13: 221-244
- Dilles JH, Farmer GL, Field CW (1995) Sodium-calcium alteration by non-magmatic saline fluids in porphyry copper deposits: Results from Yerington, Nevada. *Mineralogical Association of Canada Short Course Volume* 23: 309-338
- Dilles JH, Einaudi MT, Proffett JM, Barton MD (2000) Overview of the Yerington porphyry copper district: Magmatic to non magmatic sources of hydrothermal fluids: Their flow paths and alteration effects on rocks and Cu-Mo-Fe-Au ores. *Society of Economic Geologists Guidebook* 32: 55-66
- Einaudi MT, Hedenquist JW, Inan EE (2003) Sulfidation state of fluids in active and extinct hydrothermal systems: Transitions from porphyry to epithermal environments. *Society of Economic Geologists Special Publication* 10: 285-313
- Fournier RO (1985) The behaviour of silica in hydrothermal solutions. *Reviews in Economic Geology* 2: 45-72
- Garwin S (2002) The geological setting of intrusion-related hydrothermal systems near the Batu Hijau porphyry copper-gold deposit, Sumbawa, Indonesia. *Society of Economic Geologists Special Publication* 9: 333-366
- Gustafson LB, Hunt JP (1975) The porphyry copper deposit at El Salvador, Chile. *Economic Geology* 70: 857-912
- Hamilton WB, Myers WB (1967) The Nature of Batholiths. *U.S. Geological Survey Professional Paper* 554-C, 30 pp
- Hedenquist JW, Arribas A, Gonzalez-Urien E (2000) Exploration for epithermal gold deposits. *Reviews in Economic Geology* 23: 245-278
- Hemley JJ, Hunt JP (1992) Hydrothermal ore-forming processes in the light of studies in rock-buffered systems: II. Some general geologic applications. *Economic Geology* 87: 23-43
- Hildreth W, Moorbath S (1988) Crustal contributions to arc magmatism in the Andes of central Chile. *Contributions to Mineralogy and Petrology* 98: 455-489
- Jensen EP, Barton MD (2000) Gold deposits related to alkaline magmatism. *Reviews in Economic Geology* 13: 279-314
- Kesler SE, Chryssoulis SL, Simon G (2002) Gold in porphyry copper deposits: its abundance and fate. *Ore Geology Reviews* 21: 103-124
- Lang JR, Stanley CR, Thompson JFH, Dunne KPE (1995) Na-K-Ca magmatic-hydrothermal alteration in alkalic porphyry Cu-Au deposits, British Columbia. *Mineralogical Association of Canada Short Course Volume* 23: 339-366
- Lindgren W (1933) *Mineral Deposits*, 4<sup>th</sup> edition. McGraw-Hill, New York, 883 pp
- Pasteris JD (1996) Mount Pinatubo volcano and "negative" porphyry copper deposits. *Geology* 24: 1075-1078
- Richards JP (2009) Postsubduction porphyry Cu-Au and epithermal Au deposits: Products of remelting of subduction-modified lithosphere. *Geology* 37: 247-250
- Seedorff E, Dilles JH, Proffett JM, Einaudi MT, Zurcher L, Stavast WJA, Barton MD, Johnson DA (2005) Porphyry-related deposits: Characteristics and origin of hypogene features. *Economic Geology* 100<sup>th</sup> Anniversary Volume, pp 251-298
- Seward TM, Barnes HL (1997) Metal transport by hydrothermal ore fluids. In: Barnes HL (ed) *Geochemistry of Hydrothermal Ore Deposits*, 3<sup>rd</sup> edition. John Wiley & Sons, New York, pp 435-486
- Sillitoe RH (2000) Gold-rich porphyry deposits: Descriptive and genetic models and their role in exploration and discovery. *Reviews in Economic Geology* 13: 315-345
- Sillitoe RH, Hedenquist JW (2003) Linkages between volcanotectonic settings, ore-fluid compositions, and epithermal precious metal deposits. *Society of Economic Geologists Special Publication* 10: 315-343
- Simmons SF, Brown KL (2006) Gold in magmatic hydrothermal solutions and the rapid formation of a giant ore deposit. *Science* 314: 288-291
- Simmons SF, White NC, John DA (2005) Geologic characteristics of epithermal precious and base metal deposits. *Economic Geology* 100<sup>th</sup> Anniversary Volume, pp 485-522
- White NC, Hedenquist JW (1995) Epithermal gold deposits: Styles, characteristics and exploration. *Society of Economic Geologists Newsletter* 23: 1-13
- Williams-Jones AE, Heinrich CA (2005) Vapor transport of metals and the formation of magmatic-hydrothermal ore deposits. *Economic Geology* 100: 1287-1312
- Williams-Jones AE, Bowtell RJ, Migdisov AA (2009) Gold in solution. *Elements* 5: 281-287 ■



# Economic Geology

*Telfer gold mine, Western Australia (M 10 Reef). Image from Roger Taylor's "Ore Textures".*



**Impact Factor:**  
**2.037**

## Mineralium Deposita

International Journal for Geology, Mineralogy and Geochemistry of Mineral Deposits

Mineralium Deposita introduces new observations, principles, and interpretations from the field of economic geology, including nonmetallic mineral deposits, experimental and applied geochemistry, with emphasis on mineral deposits.

Official journal of The Society for Geology Applied to Mineral Deposits (SGA)

---

[Submit at Springer.com](http://springer.com)

---



**Specifically designed  
for the field geologist**

## Ore Textures

Recognition and Interpretation

Taylor, Roger

Covers the basic building blocks of textural recognition including: infill, alteration and the textures associated with tectonic and intrusive breccias.

2009, 288 p. 348 illus., 174 in color. With CD-ROM, Hardcover ISBN 978-3-642-01782-7

---

[Order from Springer.com](http://springer.com)

---

# The Crystallography, Metallography and Composition of Gold

Robert M. Hough<sup>1</sup>, Charles R. M. Butt<sup>1</sup> and Jörg Fischer-Bühner<sup>2</sup>

1811-5209/09/0005-0297\$2.50 DOI: 10.2113/gselements.5.5.297

**Gold is an element, a metal and a mineral. In nature, gold most commonly occurs as an alloy with silver and, more rarely, with palladium, mercury and copper, and ranges in size from nanoparticles to nuggets weighing 70 kg. Crystallography, metallography and composition control the colour of the alloy, how it will deform, how it will behave at high temperature and how it reacts. These properties offer insights into how gold deposits have formed and been altered, whether under hydrothermal or Earth-surface conditions.**

KEYWORDS: gold grains, electrum, alloy, annealing, gold nuggets

## INTRODUCTION

Elemental gold is relatively rare (~1 ppb) in the Earth's mantle and continental crust and is a trace constituent (~1 ppm) in some meteorites (Palme and O'Neill 2003). As a metal, gold has a high melting point, is soft, dense, highly malleable and ductile, and is an excellent conductor. As a mineral, gold is an isometric (face-centred cubic) phase with a close-packed atomic structure. It takes many crystal habits, including cubes, octahedra, dodecahedra, triangles and hexagons. Native gold is found dominantly as small (micrometre- to millimetre-sized), finely disseminated, mostly polycrystalline particles and grains and, more rarely, as single crystals. It also occurs as polycrystalline dendrites, wires, plates, sheets and nuggets (Fig. 1). Many of these are exquisite forms and are a result of twinning controlled by the {111} 60° twin law; for example, wires (Fig. 1b) are formed by repeated twins. Gold also occurs as a component in other minerals, including tellurides (calaverite, petzite), selenides and sulfides, and as a trace component in, for example, pyrite, arsenian pyrite and arsenopyrite. The extensive studies of arsenian pyrite from Carlin-type deposits revealed that incorporation of Au into the pyrite structure is facilitated by As. In this case, Au can be "invisible" and in solid solution, with a maximum Au/As molar ratio of 0.02 (Reich et al. 2005); above this ratio, though, gold can be imaged directly by high-resolution transmission electron microscopy as nanoparticles of metallic Au (Palenik et al. 2004). Such nanoparticles in arsenian pyrite have been shown (experimentally) to become unstable above 370°C; however, if they coarsen during heating, the particles are stable up to 650°C (Reich et al. 2006). These observations set an upper limit on the temperature at which the nanoparticles (<4 nm in size) are likely to exist in such refractory ores. Gold nanoparticles are clearly an important component of hydrothermal gold systems, which we are only beginning to understand.

1 CSIRO Exploration and Mining, 26 Dick Perry Avenue Kensington, Perth, WA 6151, Australia  
Corresponding author: Robert.Hough@csiro.au

2 Indutherm Erwärmungsanlagen GmbH, Walzbachtal-Wössingen Germany, and Legor Group Srl, Bressanvido (VI), Italy

Native gold nearly always occurs as an alloy with Ag; natural alloys with Cu, platinoids, Hg, Pb, Sn, Sb and Bi are much rarer. Gold and Ag have the same atomic radius and so can form a continuous alloy series; when the Ag content exceeds 20 wt%, the alloy is termed **electrum**. The variation in the Au/Ag ratio of native gold has led to the composition being described in terms of "fineness", which is represented by the formula  $1000 \times \text{wt\% Au} / (\text{wt\% Au} + \text{wt\% Ag})$ .

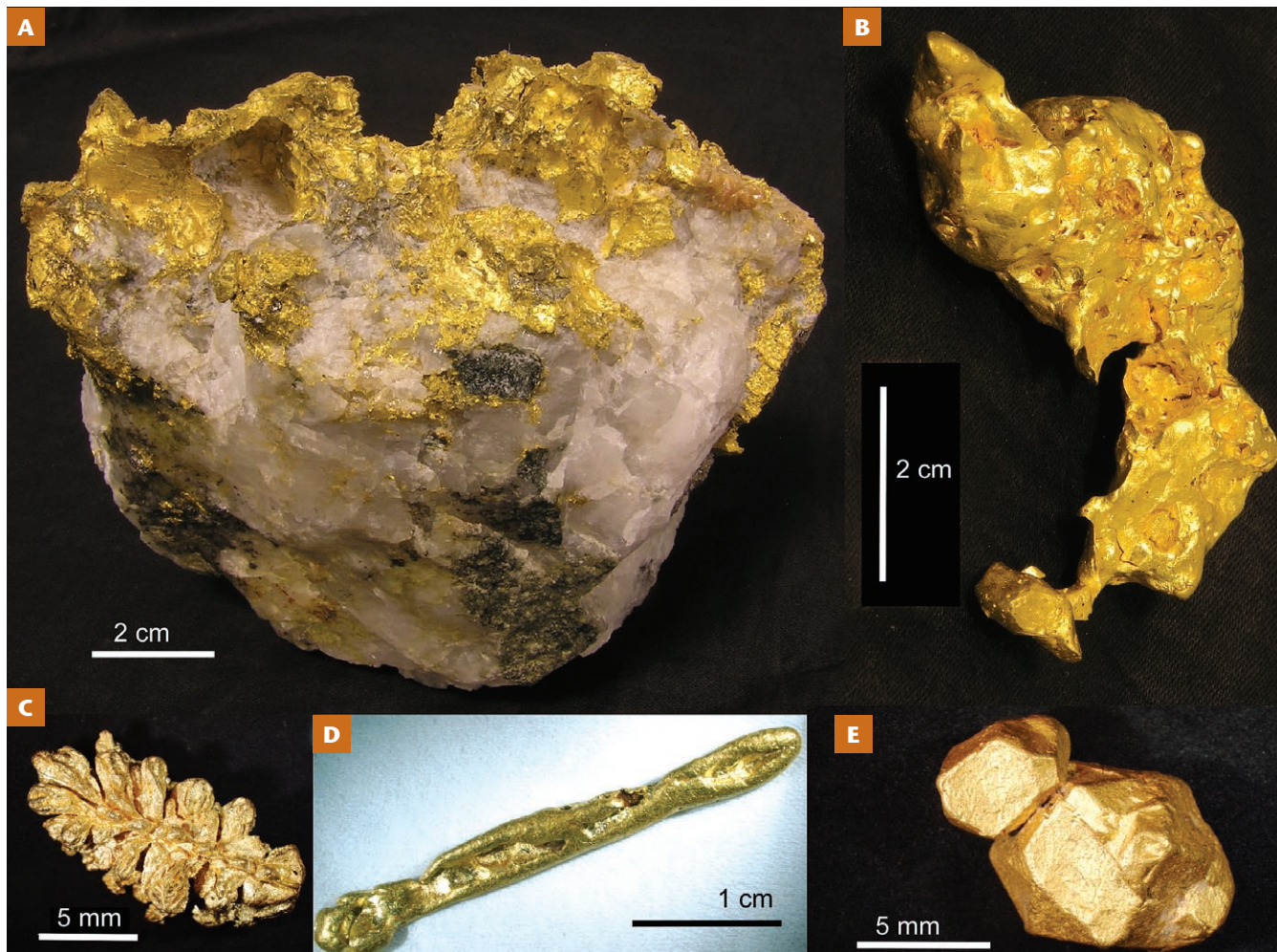
In effect, this describes the gold content of the alloy in parts per thousand and is a key parameter used to characterize gold in hypogene, alluvial and supergene environments. From a few weight percent up to 50–60 wt% Ag, the alloy retains its malleability and ductility, but properties such as colour, microstructure, hardness, work-hardening during deformation and response to heating are altered.

Much of the literature on gold deposits ignores the gold itself, other than giving a chemical analysis. Gold composition is discussed in some contexts, but gold's crystallography and metallography are less commonly considered. This paper highlights the significance of these properties to studies of gold ore systems.

## Au/Ag RATIOS AND PRIMARY GOLD

**Primary (hypogene) gold** is gold that has been deposited/precipitated from high-temperature hydrothermal fluids. These either originated deep in the Earth's crust or were circulating meteoric waters heated at shallower levels. Ore bodies formed from these systems, or the placers derived from them, are the most commonly mined deposits. Most primary gold is an alloy of Au and Ag, with the Au/Ag ratio >1. The gold typically contains 5–20% Ag, but in some deposits, it is essentially pure whereas, in others, the Ag content may exceed 50%. In general, the Au/Ag ratio of primary gold has been little studied. Most reported Au/Ag ratios are <1 (e.g. Boyle 1979) because they derived from the ore or from mine bullion, and thus include contributions from other Ag-bearing minerals. Variable proportions of the Ag are recovered from different ore minerals during processing; therefore, the Au/Ag ratio differs among ore, bullion and primary gold from the same deposit. Nevertheless, in the absence of direct analyses of gold, these ratios have been used as indicators of evolving fluid chemistry and temperature of deposition, with the more soluble and volatile Ag becoming enriched in the alloy higher in the crust and more distally from the centre of the deposit. An increase in Ag content laterally and towards the surface has been noted in several porphyry deposits, including Tonopah (Nevada, USA) and Bingham (Utah, USA) (Boyle 1979). At Cerro Casale in Chile, variation in





**FIGURE 1** Hypogene gold: (A) gold with arsenopyrite in quartz, Bayleys Reward, Coolgardie, Western Australia; (B) gold nugget, Mount Pleasant, Western Australia; (C) polycrystalline, multiply twinned, fern-shaped gold crystal, Victoria, Australia; (D) wire gold, Victoria, Australia; (E) two joined single gold crystals, Victoria, Australia

the Ag and Cu concentration in gold was related to hydrothermal alteration and to specific lithologies (Townley et al. 2003). Potassic alteration led to higher Ag and lower Cu contents, and provided the link to show that the gold associated with this alteration was sourced from a particular granodiorite intrusion.

The Au/Ag ratio can also indicate temperature. At the Challenger gold deposit in South Australia, metamorphism to 800°C is believed to have melted gold (melting point 1064°C) and remobilized it as a result of a lowered eutectic due to the presence of bismuth (melting point 271°C) and other components in the gold melt. The low Ag content (2%) in gold at Challenger could be a result of the decoupling of Au and Ag due to their different melting points (Tomkins and Mavrogenes 2002).

## GOLD METALLOGRAPHY

### Colour Variation

Gold and copper are the only metals that are not white or grey in their pure form. A deep drop in the reflectivity curve of pure gold occurs within the higher-energy (green and blue) part of the visible-light spectrum, resulting in gold's yellow colour (Saeger and Rodies 1977). With the addition of Cu, the drop in reflectivity is shifted further towards the low-energy end of the visible-light spectrum,

producing deeper yellow colours and a pink to reddish hue at high Cu content. In contrast, if Ag is present, the drop in the reflectivity curve is shifted towards the high-energy end of the visible-light spectrum, giving pale yellow, greenish yellow, greyish or whitish colours, depending on the Ag content. Colour variations in the ternary Au–Ag–Cu system are illustrated in FIGURE 2.

### Constitution, Microstructure and Hardness

Deformation of Au, like any metal, takes place by the sliding of crystal planes over each other through the movement of lattice defects, called dislocations. This is particularly easy for pure gold, which is characterized by a low hardness of 20–30 HV (Vickers hardness number) and a high deformability of over 90% in an as-solidified or annealed state. Any distortion of the crystal lattice or any obstacle in the lattice increases the force required to move the dislocations through the lattice, resulting in an increase in hardness. Alloying elements and impurities can lead in many different ways to such distortions or obstacles to deformation.

Silver is completely soluble in liquid and solid Au in all proportions. The melting temperature decreases gradually and continuously from 1064 to 962°C, as Ag content increases from 0 to 100%. This behaviour is directly related to the close similarity in the atomic radius of Au and Ag, so that Ag atoms easily replace Au atoms (and vice versa) in the face-centred cubic crystal lattice. As a consequence, the microstructure of Au–Ag alloys is single-phased, and very little hardening of Au is observed with increasing Ag content. On the other hand, Cu is ~12% smaller in atomic radius than Au, resulting in larger distortions when it replaces

Au in the crystal lattice. Hence, even small additions of Cu lead to significant solid solution hardening of Au. Minor additions (well below 0.5 wt%) of rare earth, alkali, alkaline or light metals can harden gold up to ~60 HV in the as-solidified or annealed state (Corti 1999).

### Recovery, Recrystallization and Grain Growth at Elevated Temperature

During deformation, the microstructure of any metal becomes strongly distorted and the material is 'work-hardened'. If it is subsequently exposed to elevated temperature (say, between 150 and 500°C), the metal softens again: the microstructure first recovers by the annihilation of some lattice defects and the nucleation and growth of new, undeformed crystals of regular shape. The size of the resulting crystals depends critically on the degree of deformation and the temperature; this is shown for pure gold by the recrystallization diagram in FIGURE 3. This process is referred to as **annealing**.

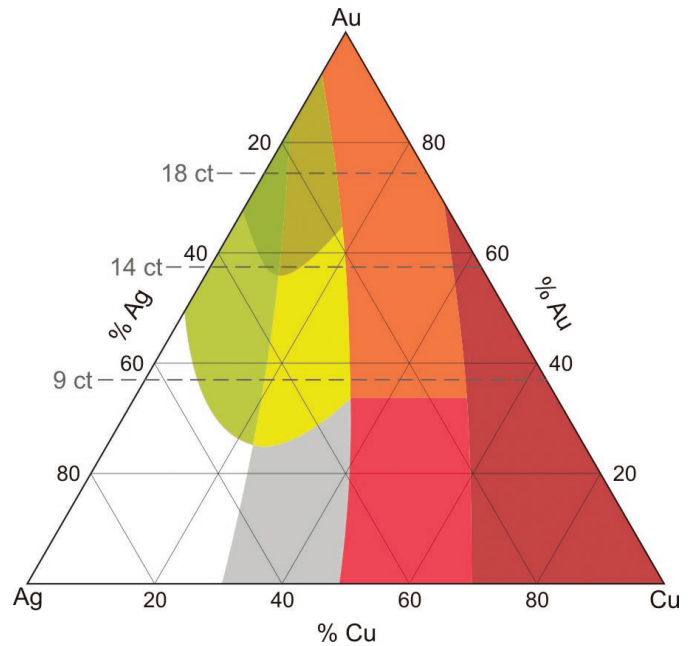
If deformation takes place at elevated temperature, softening occurs at the same time, in processes referred to as dynamic recovery and dynamic recrystallization. As indicated by FIGURE 3, (1) low-level deformation followed by annealing and (2) slow deformation at elevated temperature can both lead to the growth of large crystals in pure gold. Similar crystal growth occurs in Au–Ag alloys, such as those found in natural native gold. However, alloying elements (base metals) with low solubility in the Au matrix can drastically reduce grain-boundary mobility, and hence the size of resultant crystals. This is because the alloying elements tend to migrate to the boundaries and therefore need to be able to move with them during recrystallization and grain growth (Humphreys and Hatherly 2004). Recrystallization and grain growth can also be inhibited by fine particles formed by alloy additions, impurities and/or the reaction products of these materials (e.g. oxides). Depending on particle size and distribution, such particles can effectively pin and stabilize grain boundaries, a mechanism referred to as Zener pinning, and can have a significant influence on crystal size. The minimum temperature at which annealing recrystallization occurs increases with the Ag content. For example, pure gold anneals at about 80°C, whereas an alloy with 5% Ag anneals at about 250°C. The effect is more extreme with base metals, which increase the recrystallization temperature of Au to ~250–400°C even if they are present at only 0.1–0.5 wt% (Ott 1997).

## GOLD GRAINS

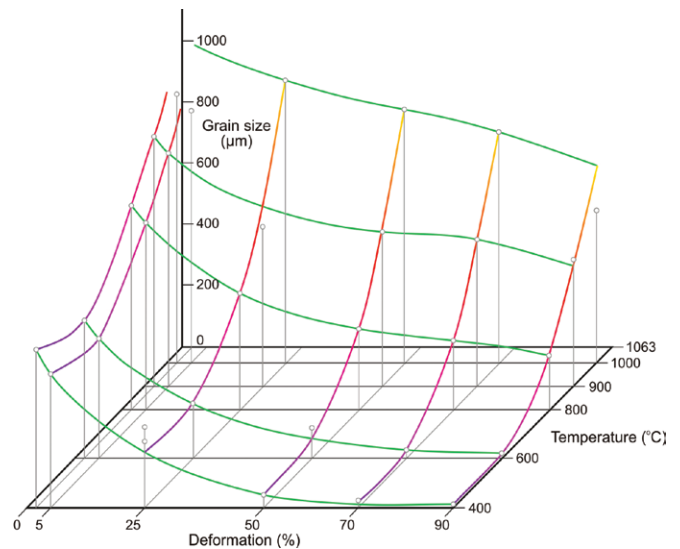
### Alloy Composition

Gold grains found in stream sediments and soils have long been exploited as a resource and used as a guide in exploration for primary mineralization. Numerous studies of gold grains from alluvial and regolith settings worldwide, in a great variety of geological and geographical environments, have attempted to link morphology and composition to process and origin. Morphology has rarely proved diagnostic of origin, but is relevant to transport. Compositionally, these deposits are generally of higher fineness than the primary source, due to partial leaching of silver and the precipitation of secondary gold. With the advent of micro-analytical techniques, the alloy composition of gold is providing information about provenance and genesis.

Townley et al. (2003) found that the Au, Ag and Cu contents of alluvial gold grains in Chile provided the best link to their source. Silver-rich (5%) grains with low Cu (0.1%) were found to come from epithermal systems, and grains even richer in Ag (8%) but with low Cu (0.1%) were from Au-rich porphyries. Grains richer in Cu (up to 0.75%), with



**FIGURE 2** Colour variations in the ternary Au–Ag–Cu system (modified after Grimwade 2000). The colours shown are indicative of the actual gold colours. The dashed lines refer to the gold content of the alloy in carats.



**FIGURE 3** Recrystallization diagram for pure gold, showing the dependence of grain size on annealing temperature and level of deformation. Modified from Degussa et al. (1995)

variable Ag contents, not surprisingly represented Au-rich Cu porphyries. Chapman et al. (2000) found that alluvial gold grains in SW England contained appreciable Pd (3.1%), similar to the local primary mineralization. They also studied mineral inclusions in gold grains to obtain further insights into source mineralization and the chemical nature of the ore-depositing fluid. For example, some grains contained selenide and telluride inclusions, rather than the more common sulphides, which suggested more oxidizing conditions were present during one phase of gold mineralization. A combination of shape and composition of gold grains was used by Knight et al. (1999) to interpret distance of transport in stream sediments in the Yukon (Canada). They found that the roundness and flatness of grains increased rapidly over the first 5 km of transport

from the source. They also measured the development of rims of pure gold on the grains and concluded that these were due to depletion of Ag from the alloy, not to addition of Au. Together, the extent of depletion and the amount of flattening of the grains provided an indication of whether the grains were proximal or distal to their source and thus allowed gold grains to be separated into different populations related to transport.

### Silver Depletion

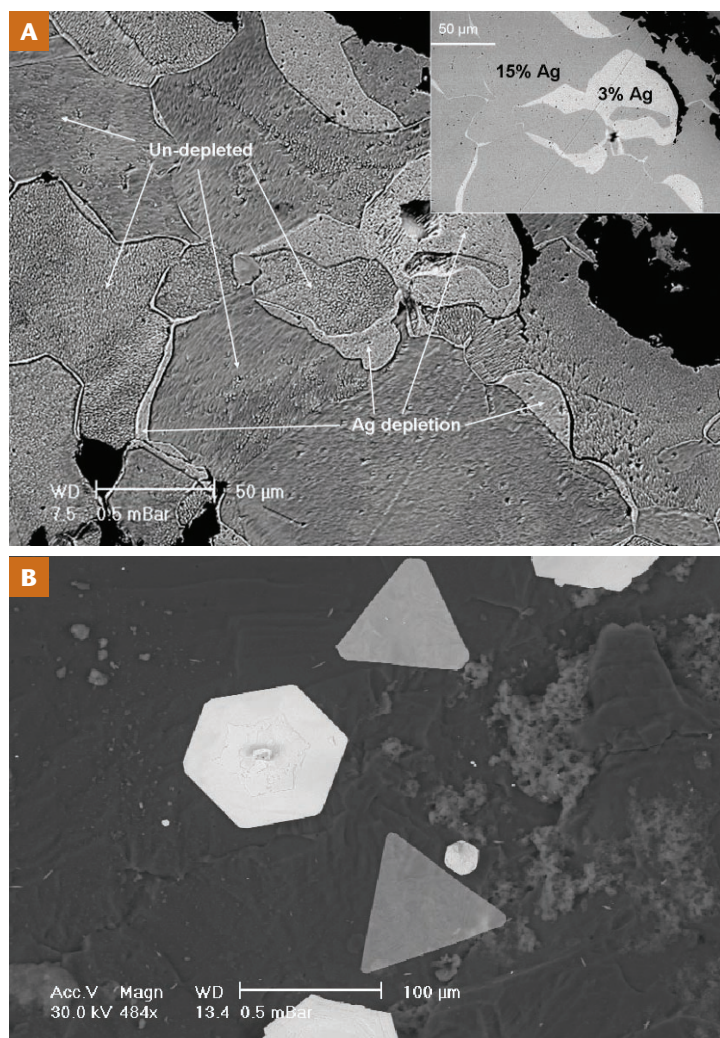
The higher fineness of gold recovered from placers and regolith deposits relative to the primary source is manifested as external rims and coatings, internal veinlets and void walls of pure Au in relict primary Au–Ag grains (FIG. 4A). Whether the veinlets and rims of pure gold are due to secondary precipitation of gold or to depletion of Ag from the host alloy has long been debated (e.g. Groen et al. 1990). The intricate structure of some pure gold rims, the lack of inclusions, the presence of zones of intermediate Ag concentrations in otherwise homogeneous grains and the recent observation (Hough et al. 2007) that, internally at least, these zones and veinlets follow crystal boundaries,

confirm that, in most cases, Ag depletion is the probable cause. Indeed, the crystallinity of the grains has not been considered in most studies, but it explains the observation that internal veins and patches of pure gold are controlled by crystal structure. The preferential dissolution of the more soluble Ag leaves an enriched zone, rarely more than a few tens of microns thick, on the exposed surface and internally along crystal boundaries. Silver depletion of alloys has also been described in the jewellery, decorative arts and metallography literature (Grimwade 1999). Depletion gilding was used by many ancient civilizations to modify the surfaces of artefacts so that they appeared to be made of pure Au. The science of depletion is also exploited in the nanotechnology industry to produce thin films possessing novel nanoporous structures with unique properties (Erlebacher et al. 2001; Cobley and Xia 2009 this issue).

### Secondary Gold

Gold precipitated in the surface or weathering environment is referred to as **secondary** or **supergene gold**. Most secondary gold is nearly pure (i.e. of high fineness), containing <1% Ag (Freyssinet et al. 2005). It can thus generally be differentiated from primary Au–Ag alloy, although rare secondary electrum is reported from some environments (Webster and Mann 1984; Clough and Craw 1989). Secondary gold has been found in soil, deep regolith, stream sediments and placers, from the Arctic to the humid tropics; it commonly forms delicate structures – convincing evidence for growth in situ. Gold can be mobilized as complexes with several organic and inorganic ligands (Freyssinet et al. 2005). Secondary gold probably precipitated from organic complexes occurs widely in tropical swamps, soils and lateritic regoliths (e.g. Ashanti, Ghana; Bowell 1992). However, where similar lateritic regoliths are preserved in now semi-arid regions with acid, saline groundwater, such as in Western Australia, the formation of gold halide complexes has led to strong leaching, followed by the concentration of secondary gold as mineable deposits over sub-economic primary mineralization. In these deposits, some secondary gold is coarser than most of the underlying primary gold. The secondary gold has precipitated as euhedral crystals with a variety of habits: aggregates with very delicate fern-like and dendritic structures, and wires and plates. Despite these ‘coarse’ forms, much secondary gold is very fine grained and essentially ‘invisible’, probably forming sub-micron-sized particles in Fe–Mn oxides, clays, carbonates and sulfates (Freyssinet et al. 2005). Even in such cases, trace analysis by laser ablation ICP–MS shows the secondary Au to be particulate: in transects across samples of Au-bearing laterites and calcretes, the Au profile is spiky rather than a plateau (Lintern et al. 2009). Once reduced from solution or colloid, gold is particulate at all scales, to nanometres or less.

Much secondary gold has precipitated as single crystals with hexagonal or triangular habit. These forms are abundant in saline environments (Lawrance and Griffin 1994) and are reminiscent of those resulting from the reduction or evaporation of Au colloids in the laboratory and imaged by transmission electron microscopy (Sun and Xia 2002; Noble et al. 2009). In such studies, various organic compounds and bacteria have been used to reduce Au chloride solutions to form colloids, from which nanoplates and nanoparticles of pure Au can ultimately be deposited. Identical colloidal gold crystals have been observed occurring naturally in weathering gold deposits in Western Australia, where highly saline, Au-rich groundwaters are precipitating visible Au plates (100–300 µm) (FIG. 4B) at the water table (Hough et al. 2008). These plates host a nanoparticulate population of hexagonal and triangular gold crystals as small as 50 nm. The Au crystals grow in the colloid by a



**FIGURE 4** Back-scattered electron images. (A) Silver depletion (labelled) in the interior of an etched Au–Ag nugget from Queensland, Australia. The depletion proceeds along crystal boundaries and also affects specific crystals. Inset: same polished surface prior to etching; Ag depletion shows as bright features. SPECIMEN (REPOLISHED AND ETCHED) FROM THE LIVERSIDGE COLLECTION, COURTESY OF THE NATURAL HISTORY MUSEUM, LONDON (B) Single secondary Au crystals from the Golden Virgin deposit, Western Australia (the differing white and grey shades are due to thickness variation).

twinning-controlled mechanism, forming thin triangular and hexagonal plates in a single evaporative event. These attain their maximum thickness early during growth (within 24 hours) and then grow laterally.

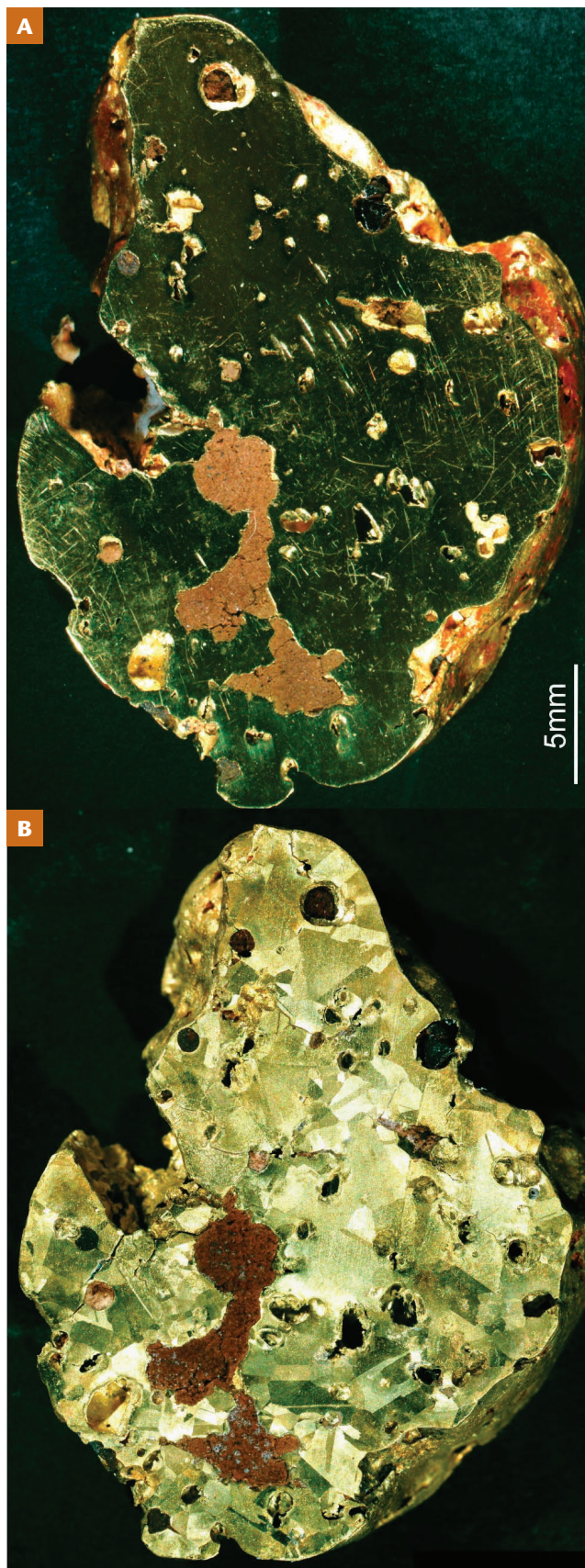
### THE NUGGET CONTROVERSY

Gold nuggets have long captured the popular imagination. To the public and prospectors, they represent a romantic and fortuitous route to instant wealth; to geologists, they are a curiosity of imprecisely known origin. Defined as masses weighing >1 g or measuring >4 mm, nuggets were commonly discovered during the early gold rushes in North America and Australia. By far the majority came from alluvial deposits and regions with a deeply weathered, residual regolith. The Victorian goldfield of southeastern Australia was the most prolific source, producing both the greatest numbers and the largest. By 1910, at least 1200 nuggets weighing, each, more than 20 troy ounces (622 g) had been documented; many exceeded 1000 oz (31.1 kg), and the two largest, the Welcome and the Welcome Stranger, were 2218 oz (~69 kg) and 2315 oz (72 kg), respectively. Large nuggets are still being found today (Fig. 5).



**FIGURE 5** This 8 kg gold nugget (Kingower, Victoria, Australia) was found in the near surface with a metal detector in 1995.

The origin of nuggets has been debated for over 160 years, but very little scientific study has been carried out. Many prospectors and geologists consider most nuggets to be secondary, formed in alluvial or weathering environments. Their relative abundance in these environments compared to their rarity in lode deposits, the rounded or mamillary form of some nuggets and the overgrowths on others, as well as observations of delicate structures and small pristine crystals in recent sediments support a supergene origin. The early debate was summarized by Liversidge (1893) who, although demonstrating that gold could be dissolved in groundwater and reprecipitate under surface conditions, nevertheless concluded on geological grounds that nuggets in alluvium and weathered rock are of primary origin. He also showed that nuggets are internally polycrystalline (Liversidge 1897). Unfortunately, Liversidge's conclusions and, in particular, his petrographic observations and techniques were forgotten. Wilson (1984) incorrectly concluded that nuggets from Western Australia had accreted around secondary Fe oxides and clays, but Wilson did not etch his specimens and saw only featureless, shiny surfaces, not the crystals, the twins and the relationship of secondary minerals to crystal boundaries and the exterior (Fig. 6).



**FIGURE 6** A section of a nugget from Bayleys Reward, Coolgardie, Western Australia, imaged by optical microscopy: (A) polished, (B) polished and etched. Etching reveals a polycrystalline structure, with twinning diagnostic of annealing. The ferruginous material is not enclosed but entered through numerous interconnecting voids that are open to the exterior. SPECIMEN COURTESY OF QUEENSLAND MUSEUM, BRISBANE

The 'inclusions' actually occupy voids dissolved by weathering solutions that had permeated along these boundaries, over a distance of 30 mm in some large nuggets. The dissolved gold was leached, some precipitating elsewhere as secondary crystals.

Recently, Hough et al. (2007) studied nuggets from a wide range of geological and secondary environments, mainly in Australia, and subsequently re-examined those studied by Liversidge and Wilson. Nearly all are Au–Ag alloys similar in compositions to primary gold, with Ag depletion on crystal boundaries open to the exterior. The nuggets have event-textured, polycrystalline fabrics, with many crystals exhibiting coherent and incoherent twinning (FIG. 6). Petrovskaya (1973) provides numerous examples of hypogene and alluvial gold from Russia with similar crystallographic features. These textures and fabrics are the same as those observed in metallographic studies, where they are considered characteristic of thermal annealing of Au–Ag alloys at >250°C. These similarities conclusively demonstrate a hypogene origin for the nuggets. The relative abundance of nuggets in surficial environments is due to physical concentration by chemical wasting and fluvial transport, not by chemical growth. Nuggets are weathering, not forming, in the supergene environment.

## REFERENCES

- Bowell RJ (1992) Supergene gold mineralogy at Ashanti, Ghana: Implications for gold dissolution and re-precipitation. *Mineralogical Magazine* 56: 545-560
- Boyle RW (1979) The Geochemistry of Gold and Its Deposits. Geological Survey of Canada, Bulletin 280, 584 pp
- Chapman RJ, Leake RC, Moles NR (2000) The use of microchemical analysis of alluvial gold grains in mineral exploration: experiences in Britain and Ireland. *Journal of Geochemical Exploration* 71: 241-268
- Clough DM, Craw D (1989) Authigenic gold-marcasite association: evidence for nugget growth by chemical accretion in fluvial gravels, Southland, New Zealand. *Economic Geology* 84: 953-958
- Cobley CM, Xia Y (2009) Gold and nanotechnology. *Elements* 5: 309-313
- Corti CW (1999) Metallurgy of microalloyed 24 carat golds. *Gold Bulletin* 32(2): 39-47
- Degussa AG, Beck G, Gerhartz W, Heuber J, Zimmer U (eds) (1995) *Edelmetall Taschenbuch*. Heidelberg, 210 pp
- Erlebacher J, Aziz MJ, Karma A, Dimitrov N, Sieradzki K (2001) Evolution of nanoporosity in dealloying. *Nature* 410: 450-453
- Freyssinet P, Butt CRM, Morris RC, Piantone P (2005) Ore-forming processes related to lateritic weathering. *Economic Geology* 100<sup>th</sup> Anniversary Volume, pp 681-722
- Grimwade M (1999) The surface enrichment of carat gold alloys – Depletion gilding. *Gold Technology* 26: 16-23
- Grimwade M (2000) A plain man's guide to alloy phase diagrams: Their use in jewellery manufacture – Part 2. *Gold Technology* 30: 8-15
- Groen JC, Craig JR, Rimstidt JD (1990) Gold-rich rim formation on electrum grains in placers. *Canadian Mineralogist* 28: 207-228
- Hough RM, Butt CRM, Reddy SM, Verrall M (2007) Gold nuggets: supergene or hypogene? *Australian Journal of Earth Sciences* 54: 959-964
- Hough RM and 12 co-authors (2008) Naturally occurring gold nanoparticles and nanoplates. *Geology* 36: 571-574
- Humphreys FJ, Hatherly M (2004) *Recrystallization and Related Annealing Phenomena*, 2<sup>nd</sup> edition. Elsevier, Oxford, 628 pp
- Knight JB, Mortensen JK, Morison SR (1999) Lode and placer gold composition in the Klondike District, Yukon Territory, Canada: Implications for the nature and genesis of Klondike placer and lode gold deposits. *Economic Geology* 94: 649-664
- Lawrance LM, Griffin BJ (1994) Crystal features of supergene gold at Hannan South, Western Australia. *Mineralium Deposita* 29: 391-398
- Lintern MJ, Hough RM, Ryan CG, Watling J, Verrall M (2009) Ionic gold in calcrete revealed by LA-ICP-MS, SXRF and XANES. *Geochimica et Cosmochimica Acta* 73: 1666-1683
- Liversidge A (1893) On the origin of gold nuggets. *Journal and Proceedings of the Royal Society of New South Wales* 27: 303-343
- Liversidge A (1897) The crystalline structure of gold and platinum nuggets and gold ingots. *Journal of the Chemical Society London* 71: 1125-1131
- Noble RRP, Hough RM, Grenik E (2009) Natural and experimental clues to understand the transport and deposition of colloidal gold. *Explore* 142: 1-8
- Ott D (1997) The effects of small additions and impurities on properties of carat golds. *Gold Technology* 22: 31-38
- Palenik CS, Utsunomiya S, Reich M, Kesler SE, Wang L, Ewing RC (2004) "Invisible" gold revealed: Direct imaging of gold nanoparticles in a Carlin-type deposit. *American Mineralogist* 89: 1359-1366
- Palme H, O'Neill HSC (2003) Cosmochemical estimates of mantle composition. In: Carlson RW, Holland HD, Turekian KK (eds) *The Mantle and Core. Treatise on Geochemistry Volume 2*, Elsevier, New York, pp 1-38
- Petrovskaya NV (1973) *Native Gold*. Nauka, Moscow (in Russian)
- Reich M, Kesler SE, Utsunomiya S, Palenik CS, Chryssoulis SL, Ewing RC (2005) Solubility of gold in arsenian pyrite. *Geochimica et Cosmochimica Acta* 69: 2781-2796
- Reich M, Utsunomiya A, Kesler SE, Wang L, Ewing RC, Becker U (2006) Thermal behavior of metal nanoparticles in geologic materials. *Geology* 34: 1033-1036
- Saeger KE, Rodies J (1977) The colour of gold and its alloys: The mechanism of variation in optical properties. *Gold Bulletin* 10: 10-12
- Sun Y, Xia Y (2002) Shape-controlled synthesis of gold and silver nanoparticles. *Science* 298: 2176-2179
- Tomkins AG, Mavrogenes JA (2002) Mobilization of gold as a polymetallic melt during pelite anatexis at the Challenger Deposit, South Australia: A metamorphosed Archean gold deposit. *Economic Geology* 97: 1249-1271
- Townley BK, Hérail G, Maksiav V, Palacios C, Parseval Ph, Sepulveda F, Orellana R, Rivas P, Ulloa C (2003) Gold grain morphology and composition as an exploration tool: application to gold exploration in covered areas. *Geochemistry: Exploration, Environment, Analysis* 3: 29-38
- Webster JG, Mann AW (1984) The influence of climate, geomorphology and primary geology on the supergene migration of gold and silver. *Journal of Geochemical Exploration* 22: 21-42
- Wilson AF (1984) Origin of quartz-free gold nuggets and supergene gold found in laterites and soils — a review and some new observations. *Australian Journal of Earth Science* 31: 303-316

## CONCLUSIONS

As gold is both a mineral and a metal, any study needs to take into account both its crystallography and its composition because these play a key role in understanding its physical properties and behaviour (i.e. its metallography). Metallography provides insights into the features displayed by natural gold, such as grain size, annealing fabrics and colours of alloys. These, in turn, may assist in exploration, by identifying the provenance of detrital particles, and in paragenesis, by providing constraints relating to the thermal and tectonic history of deposits. We are only now beginning to realize the extent of the distribution of nanoparticulate gold in ore systems. Potentially, nanoparticulate gold may play an important role in the transport and deposition of gold in both hydrothermal and supergene environments and lead to improved understanding of the genesis of deposits in these environments.

## ACKNOWLEDGMENTS

We are indebted to our late colleague Ernie Nickel for many insightful discussions over the last few years. Ernie passed away whilst this paper was being completed. Financial support was provided by the CSIRO Minerals Down Under National Research Flagship. ■



# The Biogeochemistry of Gold

Gordon Southam<sup>1</sup>, Maggy F. Lengke<sup>2</sup>, Lintern Fairbrother<sup>3</sup> and Frank Reith<sup>4</sup>

1811-5209/09/0005-0303\$2.50 DOI: 10.2113/gselements.5.5.303

**The biosphere catalyzes a variety of biogeochemical reactions that can transform gold. Microbial weathering contributes to the mobilization of gold by releasing elemental gold trapped within minerals and by solubilizing gold via oxidation-promoting complexation. Subsequent microbial destabilization of gold complexes coupled with bioprecipitation and biomineralization can immobilize gold, completing the cycle. Secondary gold can occur as colloidal particles, crystalline gold and bacteriomorphic structures, the latter being a controversial form of 'biogenic' gold.**

KEYWORDS: gold biogeochemistry, secondary gold, gold complexes, bacteria

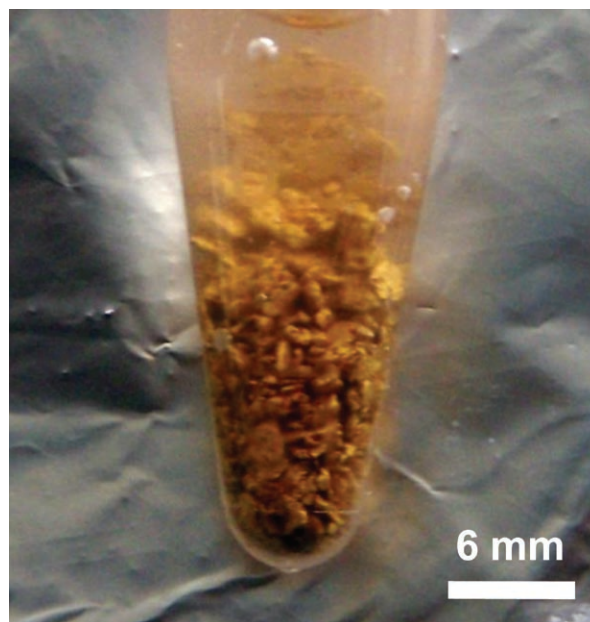
## INTRODUCTION

The origin of secondary aggregates and individual particles of crystalline gold and of gold grains (FIG. 1) in soils and shallow, alluvial placer deposits (Wilson 1984; Watterson 1992; Craw and Youngson 1993) has long been debated by geologists studying the formation of secondary gold deposits. Three models have been established to explain the formation of secondary gold: detrital origin, (bio) chemical accretion and a combination of both (Boyle 1979). One major problem with the detrital model is that gold grains in supergene and placer environments are commonly 'coarser' (i.e. larger, up to millimetre scale) than those observed in potential source rocks (primary mineralization; Craw and Youngson 1993). Gold grains and nuggets are also commonly coated by organic matter containing secondary gold in colloidal form, as octahedral crystals or as 'bacterioform' gold (FIGS. 2 AND 3), implying a role for organics in their formation. Another problem is the wide range of morphologies associated with secondary gold, which are not commonly observed in potential source rocks. These morphologies include wire, dendritic, octahedral, porous and sponge gold (Wilson 1984; Márquez-Zavallía et al. 2004; Lengke and Southam 2006, 2007) (FIGS. 2 AND 3). These observations suggest that transformation (solubilization, fining, reprecipitation and mineralization) of primary gold and *ab initio* formation of secondary gold occur in weathering environments where the biosphere is most active.

The solubilization, precipitation, fractionation and speciation of a wide variety of metals and metal ions and complexes are directly and indirectly influenced by microbial activity (Newman and Banfield 2002). However, relative to most base metals, gold is extremely rare, 'inert', non-essential, and unstable as a free ion in aqueous solution under surface conditions (Boyle 1979; Southam and Beveridge 1996). However, there is growing evidence that an active biogeochemical cycle for

gold exists under surface and near-surface conditions, and a microbe-driven biogeochemical cycle for gold has been proposed (Reith et al. 2007).

Individual aspects of this cycle have been assessed in a number of laboratory and field studies (e.g. Reith et al. 2006). At the Earth's surface, this cycle begins with the weathering of gold-bearing rocks and minerals, resulting in the release of the hypogene gold-silver electron and the oxidation and complexation of some gold. The dissolution and precipitation of gold in the near-surface environment is directly linked to the biogeochemical cycling of a range of elements, for example, iron and sulphur (Southam



**FIGURE 1** Photograph of secondary gold grains recovered by panning and kept hydrated for later microbiological experimentation

1 Department of Earth Sciences, The University of Western Ontario, London, ON, N6A 5B7, Canada  
E-mail: gsoutham@uwo.ca

2 Geomega Inc., Boulder, CO 80301, USA

3 School of Chemistry, Physics and Earth Sciences  
Flinders University, Adelaide, SA 5001, Australia

4 Centre for Tectonics, Resources and Exploration  
School of Earth and Environmental Sciences, The University of  
Adelaide, CSIRO Land and Water, Waite Laboratories, Urrbrae  
SA 5005, Australia

and Saunders 2005). The aim of this article is to highlight the influence of microorganisms on the weathering and precipitation of secondary gold, and compare these features with secondary and 'bacterioform' gold found in surface and near-surface environments (Bischoff 1997).

## THE WEATHERING OF GOLD AND GOLD-BEARING MINERALS

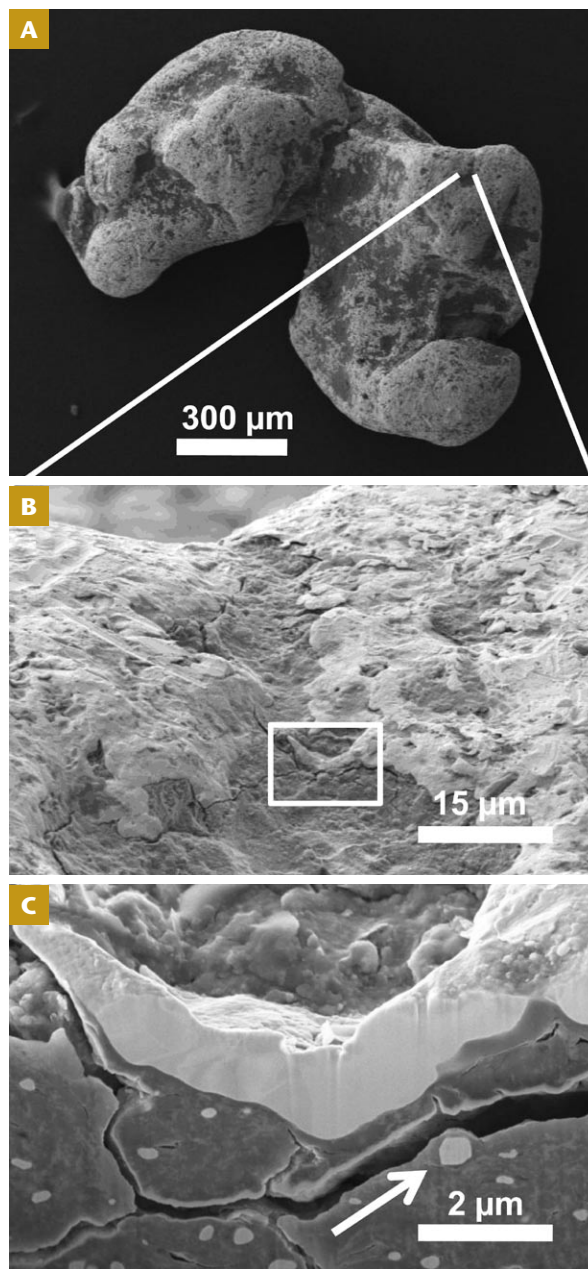
Under surface conditions, gold occurs in aqueous 'solution' in colloidal form [Au(0)] and in aurous [Au(I)] and auric [Au(III)] complexes; the standard redox potentials of Au<sup>+</sup> (1.68 V) and Au<sup>3+</sup> (1.50 V) exceed that of water (1.23 V), which makes the existence of free gold ions thermodynamically unfavourable (Boyle 1979; Vlassopoulos and Wood 1990). Based on thermodynamic calculations and natural abundances of possible ligands, aqueous gold(I/III) thiosulphate and chloride complexes appear to be the most important complexes in waters that contain little dissolved organic matter (Boyle 1979; Vlassopoulos and Wood 1990; Vlassopoulos et al. 1990).

Microbially mediated gold solubilization can occur as a consequence of the production of a number of gold-complexing metabolites, for example, thiosulphate, amino acids and cyanide, in the presence of oxygen. Gold solubilization via the thiosulphate mechanism is expected to occur in environments poor in organic matter. In these environments, lithoautotrophic ('rock'-eating, carbon dioxide-fixing) processes and populations dominate the microbial communities found on primary sulphide minerals. Iron- and sulphur-oxidizing bacteria (e.g. *Acidothiobacillus thiooxidans* and *A. ferrooxidans*) are known to break down gold-hosting sulphide minerals in zones of primary mineralization and release associated gold in the process. Gold is presumably released as alloy particles if it occurs as visible primary gold, and as gold(I) thiosulphate complexes [Au(S<sub>2</sub>O<sub>3</sub>)<sub>2</sub><sup>3-</sup>] if it occurs as invisible primary gold; gold solubilization occurs via the oxidation and complexation of the gold by thiosulphate produced during the (bio)oxidation of sulphide minerals (Southam and Saunders 2005). The solubilization of gold observed in a study of microcosms with quartz-vein materials containing sub-microscopic gold in arsenopyrite and pyrite from the Tomakin Park gold mine in New South Wales, Australia, may have been mediated by this process (Reith and McPhail 2006). Where acid, oxidizing groundwater possesses a high dissolved chloride content, common in arid and semi-arid zones, the solubilized gold will occur as gold(I/III) chloride complexes (AuCl<sub>2</sub><sup>-</sup>, AuCl<sub>4</sub><sup>-</sup>; Krauskopf 1951).

Gold also forms complexes with organic ligands (Freise 1931; Boyle 1979; Vlassopoulos et al. 1990; Williams-Jones et al. 2009 this issue). Thus, organic gold complexes may be important in soil solutions with high concentrations of dissolved organic matter, especially when these organic compounds serve as food for microorganisms. However, the complexity of these soil organics has produced contradictory results in solubilization/precipitation experiments. In a microcosm study with organic matter-rich auriferous soils from the Tomakin Park gold mine, the biologically active microcosm displayed up to 80 wt% gold solubilization within 20 to 45 days of incubation, after which it was re-adsorbed to the solid soil fractions (Reith and McPhail 2006). DNA fingerprinting and assessment of the metabolic function of the bacterial community during the incubation of the microcosms, combined with gold and amino acid analyses of the solution phase, indicated that the bacterial community dissolved proteinaceous (amino acid-containing) matter before consuming the amino acids concurrently with the solubilization and precipitation of secondary gold (Reith and McPhail 2006). Vlassopoulos et al. (1990)

showed that gold binds preferentially to organic S under reducing conditions, whereas under oxidizing conditions it binds mostly to organic N and C. The latter include cyanide produced by microorganisms and plants, resulting in gold(I)-cyanide [Au(CN)<sub>2</sub><sup>-</sup>] complexes (Boyle 1979; Campbell et al. 2001).

Gold solubilization via the amino acid and/or cyanide mechanisms may occur in organic matter-rich topsoil and root zones (the rhizosphere) in soils, where plant by-products may directly and indirectly lead to gold solubilization. Root by-products provide nutrients for resident microbiota, such as cyanogenic fungi and bacteria (e.g. *Pseudomonas* sp.), which may further increase gold solubilization (Bakker and Schippers 1987).



**FIGURE 2** Scanning electron micrographs of a secondary gold grain (from the sample in Figure 1) illustrating (A) its curved and twisted shape derived from transport in the natural environment, (B) the presence of darker organic coatings associated with secondary gold on the grain's surface (highlighted by lines drawn from A), and (C) an ion mill 'excavation' of the gold-organic coating (see box in B) revealing the presence of colloidal and octahedral gold (arrow) within the organic material.

## THE FORMATION OF SECONDARY GOLD

Secondary gold is generally much purer (up to 99.5 wt% gold) than primary gold, and some individual aggregates of secondary gold can be larger than the primary grains in potential source rocks (Wilson 1984; Watterson 1992; Mossman et al. 1999) implying that growth of gold grains can occur. Sorption of gold complexes and colloidal gold to organic matter, clays, and iron and manganese minerals as well as bioaccumulation and biomineralization by bacteria, archaea and fungi may lead to the formation of secondary gold particles, commonly observed close to primary deposits (Boyle 1979; Webster and Mann 1984).

Gold concentrations in soil solutions from auriferous soils can exceed 100 ppb (Reith and McPhail 2006) and are possibly even higher in solutions immediately surrounding gold nuggets. Thus, microorganisms in these zones are likely to experience toxic effects, and the development of

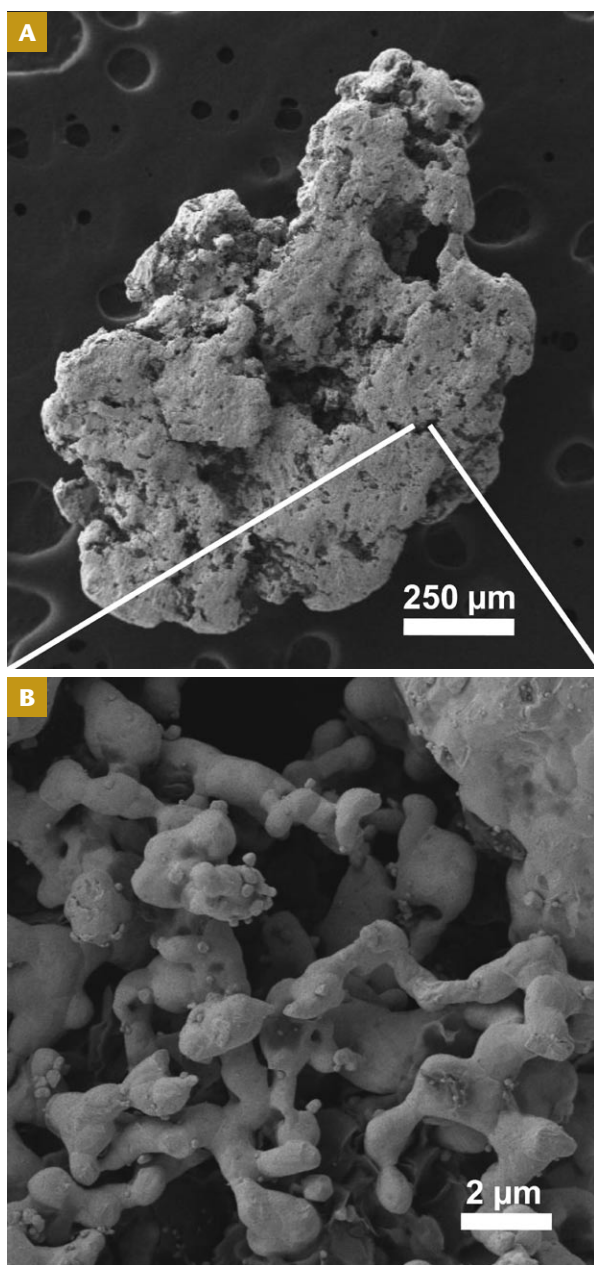
mechanisms to detoxify the immediate cell environment would certainly prove advantageous for survival. A number of bacteria and archaea are capable of catalyzing the precipitation of toxic gold(I/III) complexes. Reductive precipitation of gold from these complexes may improve survival rates of bacterial populations that are capable of (1) gaining metabolic energy by utilizing gold-complexing ligands, (2) detoxifying the immediate cell environment by detecting and excreting gold (e.g. *Salmonella enterica*; Pontel et al. 2007) and by reducing (precipitating) gold at the cell surface and shedding it with the help of membrane vesicles (e.g. *Plectonema boryanum*; Lengke et al. 2006a) or (3) using gold as a metal centre in enzymes (*Micrococcus luteus*; Levchenko et al. 2001).

The precipitation of gold from gold(I) thiosulphate solutions has been observed in the presence of thiosulphate-oxidizing bacteria that utilize thiosulphate as a source of energy (*A. thiooxidans*; Lengke and Southam 2005). The gold precipitated by *A. thiooxidans* was accumulated inside the bacterial cells as fine-grained colloidal particles ranging between 5 and 10 nm in diameter and in the bulk fluid phase as crystalline micrometre-scale gold. Whereas gold was deposited throughout the cell, it was concentrated along the cytoplasmic membrane, suggesting that gold precipitation was probably enhanced by electron transport processes associated with energy generation.

Sulphate-reducing bacteria (e.g. *Desulfovibrio* spp.) are anaerobic, heterotrophic bacteria that reduce sulphate and thiosulphate to hydrogen sulphide ( $H_2S$ ) and release it as a by-product of metabolism. *Desulfovibrio* spp. have also demonstrated the ability to reduce the thiosulphate from gold thiosulphate complexes; this destabilizes the gold in solution, which may then be precipitated intracellularly or incorporated into the newly forming sulphide minerals (Lengke and Southam 2006, 2007). Intracellular minerals included cytoplasmic gold nanoparticles (10 nm) and 100 nm gold particles localized within the cell wall, again likely due to the bacterial electron transport process (Lengke and Southam 2006, 2007). In laboratory studies, the immobilization of gold by these sulphate-reducing bacteria produced structures with forms resembling bacteriomorphic gold observed in natural systems, thus suggesting a mechanism of formation for such natural gold (FIG. 4A; see discussion below).

When *Plectonema boryanum*, a photosynthetic cyanobacterium, faces high concentrations of  $Au(S_2O_3)_2^{3-}$ , the cells release membrane vesicles (Lengke et al. 2006a). These vesicles remain associated with the cell envelope, 'coating' the cells, and help prevent intracellular uptake of  $Au(S_2O_3)_2^{3-}$ , keeping it away from sensitive cellular components. Interaction of the  $Au(S_2O_3)_2^{3-}$  with the vesicle components causes precipitation of elemental gold on the surfaces of the vesicles, possibly through reaction with phosphorus, sulphur or nitrogen ligands in the vesicle components (Lengke et al. 2006a). Membrane vesicles are thought to play an active role in redox cycling of metals by bacteria (Gorby et al. 2008).

In systems containing gold chloride complexes, the chloride does not serve as a nutrient; however, the complexes are very reactive in biological systems. A recently discovered Au(III)-specific resistance system was shown to regulate Au(III)-detoxification by pumping gold out of the cytoplasm (Pontel et al. 2007). A study by Kashefi et al. (2001) demonstrated that Fe(III)-reducing bacteria (*Thermotoga maritime*) and archaea (*Pyrobaculum islandicum* and *Pyrococcus furiosus*) are able to extracellularly precipitate gold from gold(III) chloride at 100°C under anoxic conditions in the presence of  $H_2$ . In this system, the precipitation

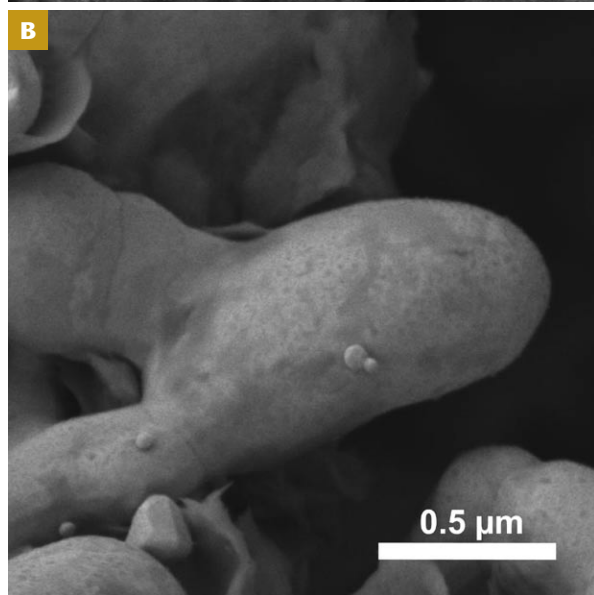
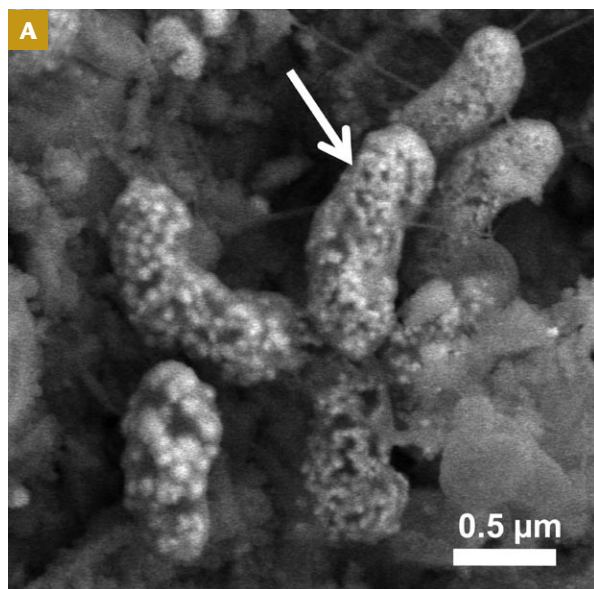


**FIGURE 3** Scanning electron micrographs of (A) a secondary gold grain in which bacterioform gold occurs within all physical recesses on the surface, and (B) bacterioform gold within one such recess, which has protected this gold from any damage via abrasion during transport.

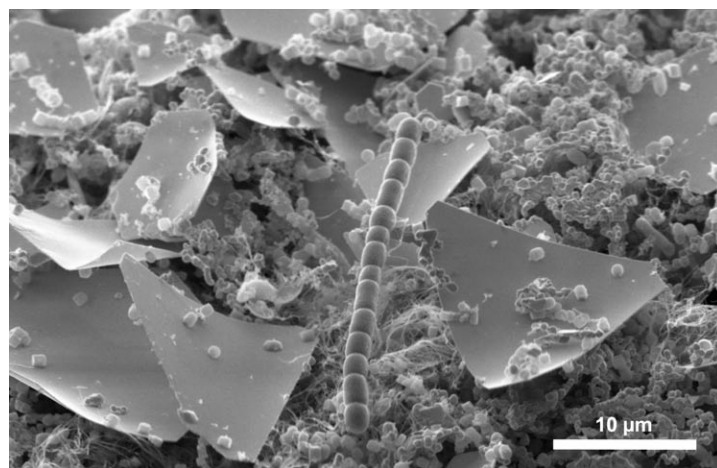
of gold was the result of an enzymatically catalyzed reaction that depends on  $H_2$  as the electron donor and that may involve a specific membrane-bound hydrogenase (Kashefi et al. 2001). Intracellular gold precipitation was also shown in *P. boryanum* (Lengke et al. 2006a, b, c). The mechanism of gold bioaccumulation by *P. boryanum* from gold(III) chloride solutions has been studied using XAS (Lengke et al. 2006c). The results show that the mechanism by which gold(III) chloride is reduced to metallic gold by the cyanobacterium involves the formation of an intermediate gold(I) species, similar to a gold(I) sulphide. This sulphide presumably originates from organic components, for example, cysteine or glutathione. These gold sulphide complexes are not stable, and reduction of the gold continues, initially forming colloidal gold and eventually crystalline octahedral gold.

Octahedral secondary gold platelets are common in oxidized zones surrounding primary deposits (Lawrance and Griffin 1994; Hough et al. 2008). Southam and Beveridge (1996) demonstrated the formation of metallic gold with octahedral habit by organic phosphate and sulphur

compounds derived from bacteria at pH 2.6. Lengke et al. (2006a, b, c) observed octahedral gold formed by *P. boryanum* at pH 1.9–2.2 and at 25–200°C (Fig. 5). The bacteria, which were killed in this process, were able to intracellularly immobilize more than 100 mg Au/g dry weight bacteria. In these systems, bacterial autolysis (cell breakdown by self-produced enzymes) was initialized, proteins were released and pseudo-crystalline gold was formed, which was transformed into crystalline octahedral gold platelets (up to 20 µm in diameter; Southam and Beveridge 1996; Lengke et al. 2006a, b). The ability of bacteria to transform gold complexes into octahedral gold in all of these reaction systems suggests that bacteria might contribute to the formation of secondary gold in natural environments.



**FIGURE 4** Scanning electron micrographs: (A) A cohesive coating of colloidal gold has formed on the cell surfaces (arrow) of *Desulfovibrio* spp. after reaction of the bacteria with gold thiosulphate; (B) bacterioform gold on the surface of a placer gold grain



**FIGURE 5** Scanning electron micrograph of *Plectonema boryanum* (segmented filament), which has reacted with gold (III) chloride complexes, forming colloidal gold (small particles) and relatively large octahedral gold crystals (in the form of platelets)

## BACTERIOFORM GOLD

Watterson (1992) first reported structures that resembled gold-encrusted microfossils on placer gold specimens from Lillian Creek in Alaska, and postulated a biological mechanism for the formation of these gold grains. Similar textures have been observed on placer gold without using the somewhat controversial nitric acid wash employed by Watterson. Numerous specimens from different locations in Australia, South America and Canada have been studied, and many of the crevices in these gold grains were covered by bacteria-like pseudomorphs similar to those described from the Alaskan specimens (FIGS. 3B AND 4B; see Reith et al. 2006, 2007). Bud-like gold growths are common on the surfaces of authigenic gold from low-redox-potential placer settings in southern New Zealand (Falconer et al. 2006). The latter examples show a range of textures in a transition, with increasing mineralization, from isolated buds to coalesced buds to chains of buds and ultimately to infilled cavities (Falconer et al. 2006). Despite the apparent similarity of these buds to Watterson (1992)'s *Pedomicrobium*-like pseudomorphs, no direct connection between bacteriomorphic gold and bacteria was established in these samples.

A recent study of untreated secondary gold grains with bacteriomorphic structures from two field sites in Australia has provided an important link between the geosphere and the biosphere. Using scanning electron microscopy and scanning confocal laser microscopy combined with nucleic acid staining, bacterial pseudomorphs and active bacterial biofilms, respectively, were revealed on the surfaces of these grains (Reith et al. 2006). Molecular profiling showed that unique, site-specific bacterial communities are associated

with gold grains and that they are different from those commonly found in the surrounding soils. The detection of *Cupriavidus metallidurans* on all DNA-positive gold grains, combined with the bacterium's ability to accumulate gold from solution and form native gold, may provide a critical link between the precipitation of gold observed in the laboratory and the observed 'bacterioform' gold in natural systems (Reith et al. 2006; Fig. 4B).

## FUTURE DIRECTIONS

The biosphere clearly plays a key role in the geochemistry of gold in natural systems. However, this biogeochemical gold cycle is incompletely understood. Research is needed on the kinetics of gold-affecting processes in environmental systems, that is, under environmentally relevant gold concentrations, and on the genomic and biochemical pathways used in gold cycling. What exactly are these bacteriomorphic structures and how do they form? Future work might also include investigations of the role of bacteria in precipitating silver-rich gold. Studying the

precipitation of secondary gold and silver in mixed reaction systems would contribute to the debate surrounding the origin of such grains in regolith and placer deposits; in particular, we could discover how diagnostic silver is in discriminating primary from secondary gold. Very fine-grained (tens of nanometres) secondary gold is no longer invisible in natural materials, which allows us to examine, as never before, the link between gold weathering and gold precipitation. The importance of these nanomaterials in mineral processing needs to be addressed, as does the role of micro-organisms in the production of nanomaterials with biotechnological applications.

## ACKNOWLEDGMENTS

We thank Dr. John Moreau and the editors at *Elements* for providing constructive reviews, which have improved the clarity and presentation of the manuscript. Support was provided in part by Natural Sciences and Engineering Research Council of Canada Discovery and Australian Research Council Grants. ■

## REFERENCES

- Bakker AW, Schippers B (1987) Microbial cyanide production in the rhizosphere in relation to potato yield reduction and *Pseudomonas* SPP-mediated plant growth-stimulation. *Soil Biology & Biochemistry* 19: 451-457
- Bischoff GCO (1997) The biological origin of bacterioform gold from Australia. *Neues Jahrbuch für Geologie und Paläontologie-Abhandlungen* H6: 329-338
- Boyle RW (1979) The Geochemistry of Gold and Its Deposits. Geological Survey of Canada Bulletin 280, 583 pp
- Campbell SC, Olson GJ, Clark TR, McFeters G (2001) Biogenic production of cyanide and its application to gold recovery. *Journal of Industrial Microbiology and Biotechnology* 26: 134-139
- Craw D, Youngson JH (1993) Eluvial gold placer formation on actively rising mountain ranges, Central Otago, New Zealand. *Sedimentary Geology* 85: 623-635
- Falconer DM, Craw D, Youngson JH, Faure K (2006) Gold and sulphide minerals in Tertiary quartz pebble conglomerate gold placers, Southland, New Zealand. *Ore Geology Reviews* 28: 525-545
- Freise FW (1931) The transportation of gold by organic underground solutions. *Economic Geology* 26: 421-431
- Gorby Y, McLean J, Korenevsky A, Rosso K, El-Naggar MY, Beveridge TJ (2008) Redox-reactive membrane vesicles produced by *Shewanella*. *Geobiology* 6: 232-241
- Hough RM and 12 co-authors (2008) Naturally occurring gold nanoparticles and nanoplates. *Geology* 36: 571-574
- Kashefi K, Tor JM, Nevin KP, Lovley DR (2001) Reductive precipitation of gold by dissimilatory Fe(III)-reducing bacteria and archaea. *Applied and Environmental Microbiology* 67: 3275-3279
- Krauskopf KB (1951) The solubility of gold. *Economic Geology* 46: 858-870
- Lawrance LM, Griffin BJ (1994) Crystal features of supergene gold at Hannan South, Western Australia. *Mineralium Deposita* 29: 391-398
- Lengke MF, Southam G (2005) The effect of thiosulfate-oxidizing bacteria on the stability of the gold-thiosulfate complex. *Geochimica et Cosmochimica Acta* 69: 3759-3772
- Lengke MF, Southam G (2006) Bioaccumulation of gold by sulfate-reducing bacteria cultured in the presence of gold(I)-thiosulfate complex. *Geochimica et Cosmochimica Acta* 70: 3646-3661
- Lengke MF, Southam G (2007) The deposition of elemental gold from gold(I)-thiosulfate complexes mediated by sulfate-reducing bacterial conditions. *Economic Geology* 102: 109-126
- Lengke MF, Fleet ME, Southam G (2006a) Morphology of gold nanoparticles synthesized by filamentous cyanobacteria from gold(I)-thiosulfate and gold(III)-chloride complexes. *Langmuir* 22: 2780-2787
- Lengke MF, Fleet ME, Southam G (2006b) Bioaccumulation of gold by filamentous cyanobacteria between 25 and 200°C. *Geomicrobiology Journal* 23: 591-597
- Lengke MF, Ravel B, Fleet ME, Wanger G, Gordon RA, Southam G (2006c) Mechanisms of gold bioaccumulation by filamentous cyanobacteria from gold(III)-chloride complex. *Environmental Science & Technology* 40: 6304-6309
- Levchenko LA, Sadkov AP, Lariontseva NV, Koldasheva EM, Shilova AK, Shilov AE (2001) Methane oxidation catalyzed by the Au-protein from *Micrococcus luteus*. *Doklady Biochemistry and Biophysics* 377: 123-124
- Márquez-Zavalía MF, Southam G, Craig JR, Galliski MA (2004) Morphological and chemical study of placer gold from the San Luis Range, Argentina. *Canadian Mineralogist* 42: 169-182
- Mossman DJ, Reimer T, Durstling H (1999) Microbial processes in gold migration and deposition: Modern analogues to ancient deposits. *Geoscience Canada* 26: 131-140
- Newman DK, Banfield JF (2002) Geomicrobiology: How molecular-scale interactions underpin biogeochemical systems. *Science* 296: 1071-1077
- Pontel LB, Pérez Audero ME, Espariz M, Checa SK, Soncini FC (2007) GoS controls the response to gold by the hierarchical induction of *Salmonella*-specific genes that include a CBA efflux-coding operon. *Molecular Microbiology* 66: 814-825
- Reith F, McPhail DC (2006) Effect of resident microbiota on the solubilization of gold in soils from the Tomakin Park Gold Mine, New South Wales, Australia. *Geochimica et Cosmochimica Acta* 70: 1421-1438
- Reith F, Rogers SL, McPhail DC, Webb D (2006) Biomineralization of gold: Biofilms on bacterioform gold. *Science* 313: 233-236
- Reith F, Lengke MF, Falconer D, Craw D, Southam G (2007) The geomicrobiology of gold. *International Society of Microbial Ecology Journal* 1: 567-584
- Southam G, Beveridge TJ (1996) The occurrence of sulfur and phosphorus within bacterially derived crystalline and pseudocrystalline gold formed in vitro. *Geochimica et Cosmochimica Acta* 60: 4369-4376
- Southam G, Saunders JA (2005) The geomicrobiology of ore deposits. *Economic Geology* 100: 1067-1084
- Vlassopoulos D, Wood SA (1990) Gold speciation in natural waters: I. Solubility and hydrolysis reactions of gold in aqueous solution. *Geochimica et Cosmochimica Acta* 54: 3-12
- Vlassopoulos D, Wood SA, Mucci A (1990) Gold speciation in natural waters: II. The importance of organic complexing—Experiments with some simple model ligands. *Geochimica et Cosmochimica Acta* 54: 1575-1586
- Watterson JR (1992) Preliminary evidence for the involvement of budding bacteria in the origin of Alaskan placer gold. *Geology* 20: 315-318
- Webster JG, Mann AW (1984) The influence of climate, geomorphology and primary geology on the supergene migration of gold and silver. *Journal of Geochemical Exploration* 22: 21-42
- Williams-Jones AE, Bowell RJ, Migdisov AA (2009) Gold in solution. *Elements* 5: 281-287
- Wilson AF (1984) Origin of quartz-free gold nuggets and supergene gold found in laterites and soils—A review and some new observations. *Australian Journal of Earth Sciences* 31: 303-316 ■

# More Capability—you've got it! More Analysis Power—you bet!

Designed for materials identification, the Powder Diffraction File offers comprehensive, high-quality data. Independent of whether phase identification is performed by classic d,l pair analysis or by total pattern comparisons, the accuracy of the reference in comparison to an unknown is improved with higher quality reference data. Enhance your competitive analysis with more high-quality data, more capability and more analysis power—found only in the Powder Diffraction File!

708,455

**Comprehensive: 708,455 published material data sets**

Improve your ability to analyze minor and trace phases

Exploit a full suite of data simulation programs enabling the use of neutron, electron, synchrotron, and X-ray data

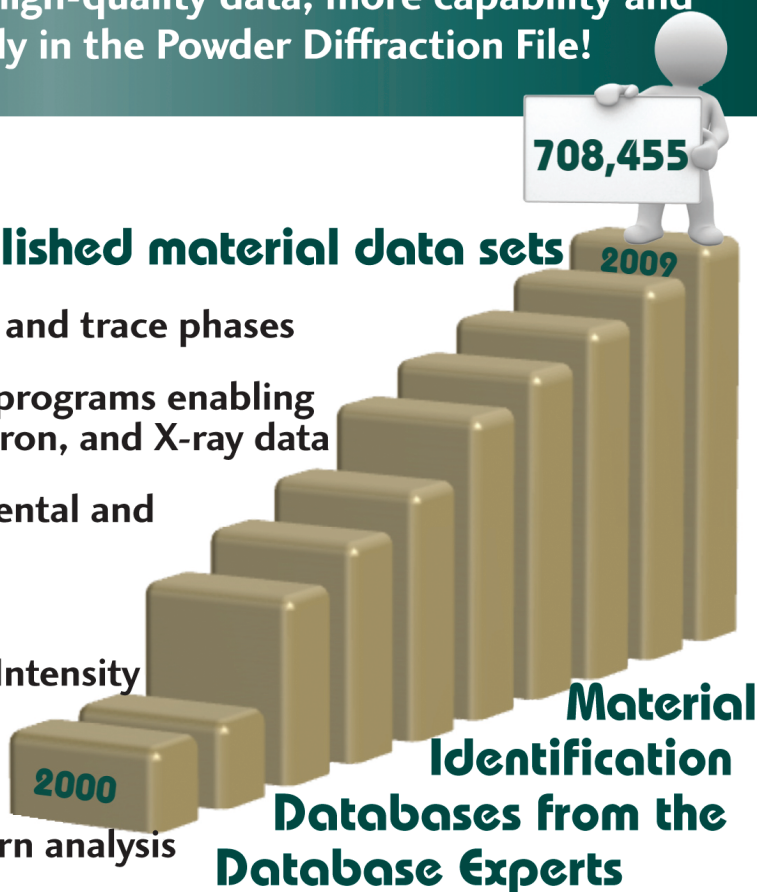
Tailor simulations for various instrumental and specimen characteristics

Utilize quantitative analysis methods:

Atomic parameters for Reference Intensity Ratio (RIR)

$I/I_c$  for Rietveld analysis

Full digital patterns for total pattern analysis



## The Powder Diffraction File

PDF-2 Release 2009	218,610 material data sets
PDF-4+ 2009	291,440 material data sets
PDF-4/Minerals 2009	34,212 material data sets
PDF-4/Organics 2010	406,773 material data sets

The  
International  
Centre  
for  
Diffraction  
Data



marketing@icdd.com  
www.icdd.com ❖ 610.325.9814  
Toll-free US & Canada:  
866.378.9331



ICDD and PDF are registered in the U.S. Patent and Trademark Office.

The ICDD logo and Powder Diffraction File are trademarks of JCPDS—International Centre for Diffraction Data.

# Gold and Nanotechnology

Claire M. Cobley and Younan Xia\*

1811-5209/09/0005-0309\$2.50 DOI: 10.2113/gselements.5.5.309

**The properties of gold change dramatically at the nanoscale. Gold nanoparticles and nanoporous gold have remarkable optical and catalytic properties, which are being investigated for applications in biomedicine and manufacturing. Using a variety of synthetic methods, the shape, size and properties of these materials can be optimized, making them a powerful platform for the development of new contrast agents for optical imaging of biological tissues, photothermal destruction of tumours and catalysis of various reactions.**

**KEYWORDS:** gold, nanotechnology, shape-controlled synthesis, photothermal therapy, biomedical imaging, catalysis

## INTRODUCTION

Gold has been valued since the beginning of recorded history for its beautiful yellow colour and its ability to resist tarnishing. These remarkable optical and chemical properties change dramatically when gold is at the nanoscale – but in ways that make this precious metal even more fascinating and valuable for modern-day applications in biomedicine and catalysis (Eustis and El-Sayed 2006).

Gold nanoparticles typically display an intense red rather than a golden yellow colour. Known since ancient times, this phenomenon was appreciated long before its origins were understood. Craftsmen were taking advantage of this property to create stained-glass windows and other works of art over a thousand years ago (see Figure 1 in Williams-Jones et al. 2009 this issue). Understanding of this phenomenon began in 1857 when Michael Faraday synthesized and studied the first stable gold colloid – an aqueous suspension of gold nanoparticles. His samples are still well preserved and on display today at the Royal Institute Museum (formerly the Faraday Museum) in London. In 1908, Gustav Mie took our understanding a step further by solving Maxwell's equations and developing formulae that are still in use for explaining and predicting the optical properties of these and other small particles (Mie 1908).

In the last few years, the development of improved synthesis and characterization techniques has sparked a renaissance of interest in metal nanoparticles. Now that we have more powerful tools to decipher the structure–property relationship, methods have been developed to synthesize gold nanoparticles in a wide variety of shapes and sizes (Grzelczak et al. 2008). By controlling the structure and understanding the mechanisms at work, the properties of these fine particles can be tuned for specific applications, making them useful for far more than just artistic expression. In fact,

gold nanoparticles are emerging as a key component of nanotechnology, enabling a myriad of applications in many different areas.

Some of the most exciting applications for gold nanoparticles are in the biomedical field (West and Halas 2003; Hu et al. 2006; Liao et al. 2006; Xia 2008). Optical imaging techniques in biomedicine are highly desirable because of their low cost and non-invasive nature compared to current methods, but their usefulness is limited because of low contrast between normal and

malignant tissues. For this reason, contrast agents are being investigated to increase the resolution and sensitivity possible with these optical techniques, and gold nanoparticles stand out as an ideal candidate. The biocompatibility of gold, its strong optical absorption/scattering and the possibility of targeted uptake (see below) have made this an exciting area of research (Skrabalak et al. 2008). In addition to providing contrast, the optical absorption of gold nanoparticles can be used in photothermal therapy. In this technique, gold nanoparticles are irradiated by a laser, the light absorbed by the particles is converted into heat, and the heat kills cells in the surrounding region (Chen et al. 2007).

A change in the properties of gold films can also be brought about by introducing nanoscale features. Several research groups have investigated the generation of nanoscale holes by removing the silver from a film made of a gold–silver alloy (Erlebacher et al. 2001; Xu et al. 2007). When the synthesis is controlled such that the features are smaller than 10 nanometres (nm), these porous films exhibit interesting catalytic abilities just like their solid nanoparticle counterparts with features of similar size (Xu et al. 2007).

In this article we briefly discuss the origin of the fascinating optical phenomenon associated with gold nanoparticles – surface plasmon resonance – and then explain how we can manipulate the size, shape and properties of gold nanoparticles through careful control of synthetic conditions. We also present some of the intriguing biomedical applications and conclude with a discussion of how to prepare nanoporous gold and its use in catalysis.

## SURFACE PLASMON RESONANCE

The striking ruby red colour displayed by gold colloids is caused by a phenomenon known as surface plasmon resonance (Kreibig and Vollmer 1995). To understand this property, it is useful to think of a gold nanoparticle as a lattice of positive gold ions bathed in a cloud of mobile conduction electrons. When an electromagnetic field (such as a light wave) interacts with this cloud of electrons, the cloud is

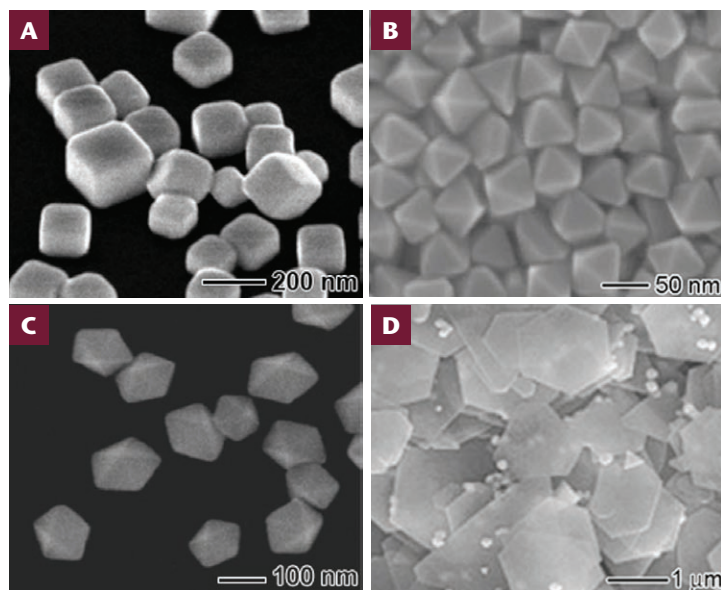
\* Department of Biomedical Engineering, Washington University  
Campus Box 1097, St. Louis, MO 63130, USA  
E-mail: xia@biomed.wustl.edu

displaced to one side. Coulomb forces between the positive ions and negative electrons provide a restoring force, setting up a collective oscillation of the electron cloud. In this way, the nanoparticle is able to absorb light at specific resonance frequencies, which depend on the size, shape and structure (solid versus hollow) of the particle. Some of the absorbed light will be released as photons with the same frequency but in all directions, and this process is referred to as scattering. At the same time, some of the absorbed light will be converted into heat or phonons (i.e. vibrations of the lattice). As the size, shape or structure of the particle is altered, the resonant frequencies at which the light is absorbed change. In particular, controlling the shape and structure provides a powerful means for tailoring the optical properties of nanoparticles of gold (and other metals) (Xia et al. 2008).

Controlling the resonance wavelengths of gold nanoparticles is critical for their biomedical applications because biological tissues do not absorb evenly at all wavelengths. In the near-infrared region (in particular, 800–900 nm), the absorption of water and haemoglobin is minimal. Consequently, these wavelengths of light pass more easily in and out of tissue than others, resulting in deeper penetration of light and an enhanced signal in optical imaging (Skrabalak et al. 2008).

## SHAPE-CONTROLLED SYNTHESIS

In this article, we focus only on shape-controlled synthesis of gold nanoparticles in the solution phase. This method is best suited for the mass production of gold nanoparticles as it is more easily scalable than other techniques, such as lithography, which is a time- and cost-intensive technique. The general method is as follows: A gold salt is dissolved in water or another solvent and converted to solid gold by adding a reducing agent. In this method, the reducing agent transfers electrons to the gold ions in the solution, forming zero-valent gold atoms and then small clusters (nuclei) that serve as seeds for the reduction of additional gold ions.



**FIGURE 1** A selection of different geometries seen in gold nanocrystals using scanning electron microscopy. (A) Cubes (MODIFIED WITH PERMISSION FROM SEO ET AL. 2006; COPYRIGHT AMERICAN CHEMICAL SOCIETY). (B) Octahedra (MODIFIED WITH PERMISSION FROM LI ET AL. 2007; COPYRIGHT WILEY-VCH). (C) Decahedra (MODIFIED WITH PERMISSION FROM SEO ET AL. 2008; COPYRIGHT AMERICAN CHEMICAL SOCIETY). (D) Thin plates (MODIFIED WITH PERMISSION FROM SUN ET AL. 2004; COPYRIGHT WILEY-VCH).

The surface of nanoparticles must be stabilized by a capping agent, either a small molecule or a polymer. The capping prevents the particles from agglomerating and forming large, uninteresting clumps. Careful selection of a capping agent and introduction of trace ionic species are powerful means to control the synthesis of a variety of metal nanoparticles (El-Sayed 2001; Tao et al. 2008; Xia et al. 2008). These species can preferentially attach to certain crystallographic facets of the growing nuclei, causing faster growth in specific directions and creating anisotropic shapes such as rods, cubes with sharp corners and edges, octahedra, decahedra and thin plates. Some of the many possible shapes are described below. FIGURE 1 shows scanning electron microscopy images of a few of these shapes. Refer to the review by Xia et al. (2008) for a comprehensive discussion of exotic shapes and the mechanisms for their growth.

## Gold Nanospheres

In the absence of a shape-directing agent, gold will form more or less spherical particles, because this shape minimizes the surface area and thus the interfacial surface energy. One of the most common methods for synthesizing small spherical particles, called the Turkevitch method, uses the citrate ion as both a reducing agent and a capping agent in a simple water-based system. By modifying parameters such as the ratio of citrate to gold salt, the size can be easily controlled in the range of 15–150 nm (Daniel and Astruc 2004). Numerous other methods have also been developed to synthesize even smaller particles or improve the uniformity.

## Gold Nanorods

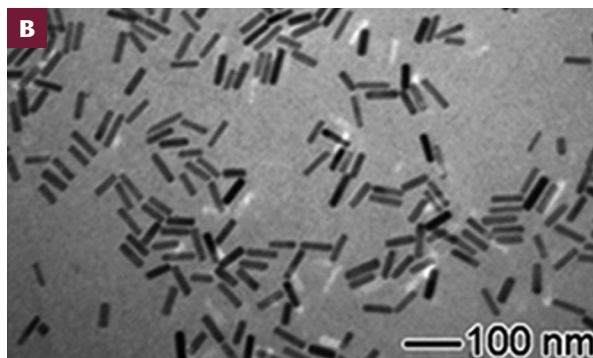
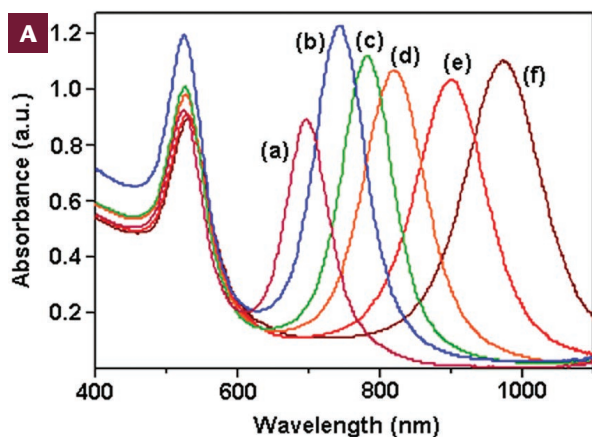
Though the size of spherical gold nanoparticles can be easily tuned, this size change alone is not enough to shift the resonance peak from its usual position near 500 nm to the near-infrared region, which is more interesting for biological work. In order to do so, more complex shapes have been investigated. Gold nanorods, in particular, are an active area of research due to the fact that the resonance peak can be tuned by simply controlling the aspect ratio (length : width) of the rod (Jana et al. 2001; Murphy et al. 2005). FIGURE 2 shows how the resonance peak shifts as the aspect ratio increases and presents a representative transmission electron micrograph of a sample of nanorods. The peak around 500 nm is due to a resonance across the width of the rod, and the shifting peak is due to a resonance along the length of the rod (FIG. 2A).

The most common way to produce nanorods is seed-mediated growth. In this approach, small gold spheres are produced first, and then added to a growth solution where they extend into rods. The length of the rods can be controlled by changing the number of seeds added to the growth solution. If more seeds are added, the solution uses all the available gold sooner and the rods do not grow as long. The capping agent added during the growth step is also thought to be critical to this highly anisotropic growth. It has been proposed that the surfactant hexadecyltrimethylammonium bromide that is used in this synthesis technique promotes the rod shape by forming a micellar template around the growing particles and may also selectively bind to specific crystallographic facets of the seeds (Jana et al. 2001).

## Gold Nanocages

Hollow gold nanoparticles can be synthesized in one step by templating against nanoparticles of a more reactive metal. This synthesis relies on a process known as galvanic replacement. The Xia research group has used this simple and rapid reaction to transform silver nanocubes into gold nanocages – hollow particles with porous walls (Sun and





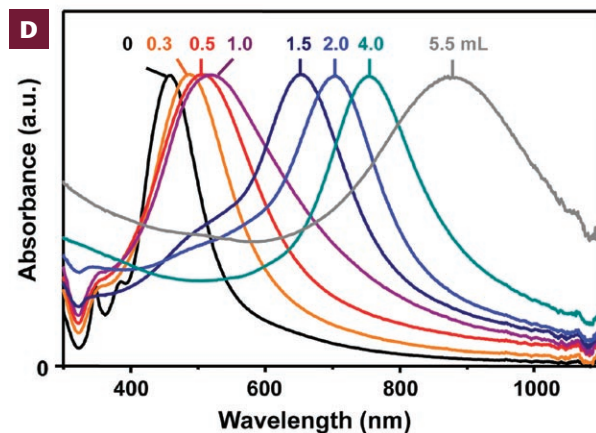
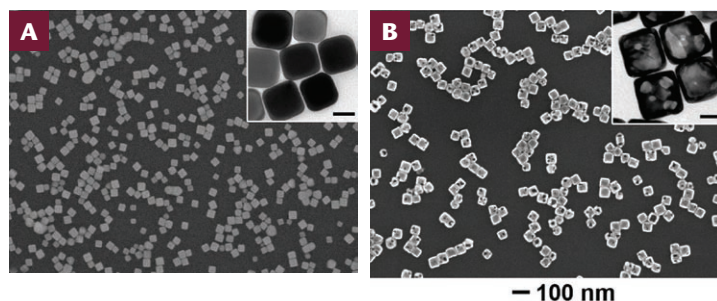
**FIGURE 2** (A) UV-visible spectra of gold nanorods with different aspect ratios. The width of all rods was ~20 nm and the average lengths were (a) 46, (b) 61, (c) 73, (d) 75, (e) 89 and (f) 108 nm, respectively. MODIFIED WITH PERMISSION FROM HU ET AL. 2003; COPYRIGHT AMERICAN CHEMICAL SOCIETY (B) Representative transmission electron micrograph of gold nanorods. MODIFIED WITH PERMISSION FROM GOU AND MURPHY 2005; COPYRIGHT AMERICAN CHEMICAL SOCIETY

Xia 2004; Skrabalak et al. 2007). Electron micrographs of the silver cube template are shown in FIGURE 3A and the resultant gold nanocages in FIGURE 3B. Like nanorods, the optical resonance peaks of these hollow particles can be easily tuned into the near-infrared region, but in this case by changing the wall thickness instead of the aspect ratio. The continuous red shift in resonance peak can be seen in both the colours of the solutions (FIG. 3C) and their UV-visible spectra (FIG. 3D).

In this synthesis, gold salts are again dissolved in solution, but the electrons needed for reduction come from an electrochemical reaction with the silver template instead of a separate reducing agent. Many different templates have been used, allowing for a variety of hollow shapes to be produced. However, in all cases, a metal must be chosen with a lower electrochemical potential than gold so that it will give up its electrons and allow the reaction to proceed. In terms of mechanism, the reaction between the template and the dissolved gold salt begins at a defect site on the surface, simultaneously dissolving the silver and plating the gold on the surface. The outside of the cube becomes coated with gold while the inside is gradually dissolved away. Due to the small size regime, the gold and silver atoms easily interdiffuse, and a gold-silver-alloyed wall is formed in the intermediate stages. As the reaction proceeds and all the non-alloyed silver is dissolved, the gold salt begins to react with the silver in the alloy as well. This begins the process of dealloying and causes pores to develop on the surface as silver is removed from the walls. The final product is a stable suspension of porous nanoboxes, which are referred to as nanocages.

## BIOMEDICAL APPLICATIONS

There is great interest in improving the quality of optical imaging techniques for biomedical applications. Unlike current imaging techniques (such as magnetic resonance imaging, MRI, and computerized tomography, CT), optical modalities have the advantages of relatively low cost, smaller size (greater portability) and non-ionizing radiation. One of the primary difficulties in developing optical imaging techniques is the low contrast between normal and malignant tissues. For this reason, a variety of contrast-enhancing agents are being investigated, including various types of gold nanoparticles, such as nanorods, nanoshells and nanocages (Averitt et al. 1999; Murphy et al. 2005; Skrabalak et al. 2008). Gold is particularly desirable for this type of application due to its high biocompatibility, a resonance peak tunable to the near-infrared region, and straightforward surface modification. Due to the strong interaction of gold with thiol groups, it is easy to modify the surface of gold nanoparticles with antibodies or other targeting units that can selectively bind to specific markers on cancer cells. In this way, imaging techniques and therapies based on gold nanoparticles can be selectively applied to tumours, leaving the rest of the tissue unharmed and limiting harsh side effects that are common with current therapies.



**FIGURE 3** Tuning the optical properties of gold nanocages. (A, B) Scanning electron micrographs (with transmission electron micrographs as insets; the scale bars represent 25 nm) of (A) silver nanocubes and (B) gold nanocages. MODIFIED WITH PERMISSION FROM YANG ET AL. 2007; COPYRIGHT AMERICAN CHEMICAL SOCIETY (C) Photograph showing the bright colours of gold nanocages suspended in water. (D) UV-visible spectra showing how the replacement reaction is controlled by varying the volume of chloroauric acid solution added. MODIFIED WITH PERMISSION FROM SKRABALAK ET AL. 2007

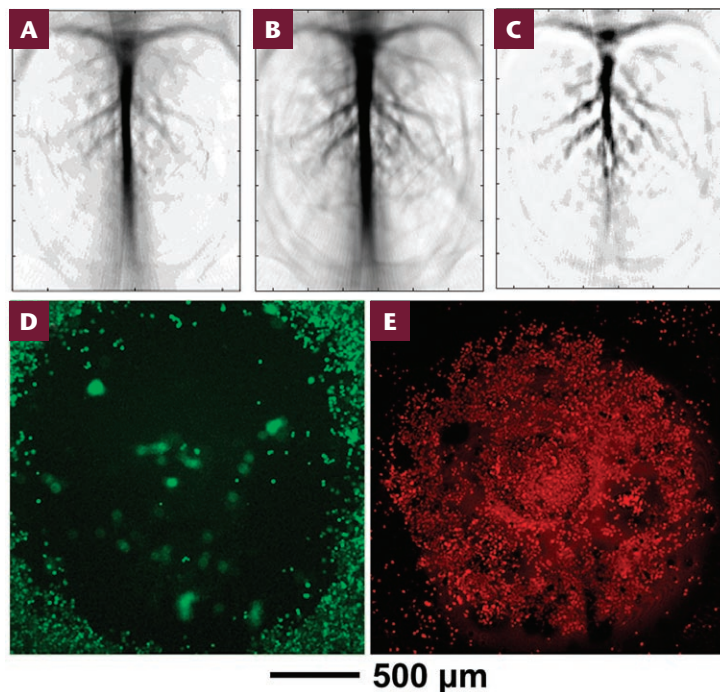
Gold nanocages are particularly promising for these applications, due to the simplicity of the synthesis and spectral tuning, compact size, and the possibility of loading therapeutic agents in the hollow interiors. Two examples of their application in biomedical research are described below.

### Photoacoustic Tomography

Photoacoustic tomography has been used to image the cerebral cortex of a rat *in vivo* (Yang et al. 2007). In this non-invasive technique, optical absorption is converted to thermal expansion, which creates a sound wave that can be measured by an ultrasonic detector. FIGURE 4 A–C shows the photoacoustic images obtained (1) without the addition of any contrast agent (Fig. 4A), (2) when a suspension of gold nanocages was injected into the bloodstream via the tail vein (Fig. 4B) and (3) the difference between the two (Fig. 4C). The contrast enhancement by gold nanocages (Fig. 4C) was as high as 81%. This technique could potentially be used to detect tumours in the brain and in other parts of the body, as it would show enhanced blood flow due to angiogenesis at the tumour site.

### Photothermal Therapy

The strong absorption of light by gold nanocages has also been shown to generate enough heat to kill cancer cells (Chen et al. 2007; Au et al. 2008). In FIGURE 4D AND E, breast cancer cells were incubated with gold nanocages and then irradiated with a pulsed near-infrared laser; green fluorescence indicates live cells and red fluorescence indicates dead cells. The resonance peak of the nanocages was tuned to 810 nm, the central wavelength of the laser. The circular region of laser irradiation can clearly be seen in both



**FIGURE 4** Biomedical applications of gold nanocages. (A–C) Photoacoustic tomography is used to image the brain of a rat *in vivo*: (A) before nanocage injection, (B) after nanocage injection and (C) difference between the two images. MODIFIED WITH PERMISSION FROM YANG ET AL. 2007; COPYRIGHT AMERICAN CHEMICAL SOCIETY (D, E) Results of laser irradiation of breast cancer cells targeted with gold nanocages: (D) calcein acetoxymethyl ester (calcein AM) assay, where green fluorescence indicates live cells, and (E) ethidium homodimer-1 (EthD-1) assay, where red fluorescence indicates dead cells. Scale bar is for D and E only. MODIFIED WITH PERMISSION FROM CHEN ET AL. 2007; COPYRIGHT AMERICAN CHEMICAL SOCIETY

images, showing that only cells exposed to the laser beam were killed. Control experiments also showed that cells not incubated with nanocages survived this laser treatment unharmed. When combined with the targeting abilities described above, this technique could provide a route to destroy tumours without affecting healthy cells, unlike current therapies.

### NANOPOROUS GOLD AND CATALYSIS

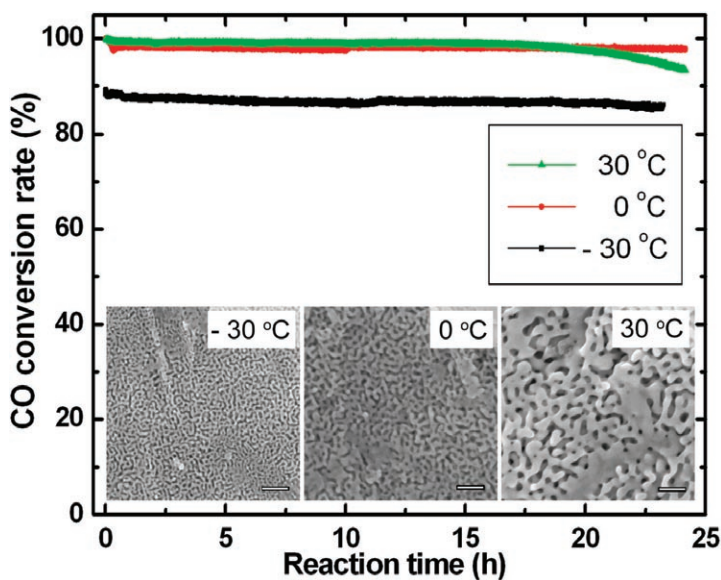
Gold does not necessarily have to be divided into particles for nanoscale properties to emerge: if a substrate has nanoscale features, the properties of the material can also change. A prime example of this type of material is nanoporous gold. The small feature sizes possible in nanoporous gold (<10 nm) make it an interesting substrate for catalysis.

#### Synthesis

Nanoporous gold is created when a thin sheet of a silver–gold alloy is exposed to corrosive nitric acid in a controlled manner (Erlebacher et al. 2001). Due to the difference in the willingness of these metals to give up electrons, the silver selectively dissolves, leaving behind gold atoms and many vacancies, a process known as dealloying. This diffuse arrangement of atoms is highly unstable due to the extremely high surface area and correspondingly high surface energy. Consequently, the remaining atoms are constantly diffusing across the surface to reduce the surface energy and form more thermodynamically stable arrangements. As a result, small clusters of pure gold form on the surface of the alloy. This movement reveals fresh regions of alloy that can then continue the dealloying process, allowing the reaction to continue beyond just a small number of surface atoms. In this way, a full piece of foil can be transformed into a nanoporous material.

#### Catalytic Properties

Though corrosion is usually thought of as a destructive process, in this situation the resultant material has interesting catalytic properties. Bulk gold is known for being highly inert; yet as its size decreases below 10 nm, catalytic properties emerge and become stronger with smaller size. One of the reasons for this change is the much higher ratio



**FIGURE 5** Catalytic performance of nanoporous gold at three different temperatures. Insets show scanning electron micrographs of the substrate after catalytic reactions. The scale bars are 100 nm. MODIFIED WITH PERMISSION FROM XU ET AL. 2007; COPYRIGHT AMERICAN CHEMICAL SOCIETY

of reactive surface atoms to interior atoms; nevertheless, multiple mechanisms for the enhanced performance are possible, especially in the supported systems that are typically studied. A number of reactions have been enhanced with the catalytic abilities of nanoscale gold catalysts, including carbon monoxide oxidation, nitric oxide reduction and the selective oxidation of a variety of compounds (Della Pina et al. 2008). If the quantity of reagents required for industrial processes can be reduced or the temperature of reactions lowered through the use of gold catalysts, these processes become much more cost-efficient and environmentally friendly.

Nanoporous gold was studied as a catalyst for carbon monoxide oxidation at different temperatures (Fig. 5) (Xu et al. 2007). It was found that this material achieved a conversion rate of >99.5% for nearly 20 hours at room temperature, after which the activity declined slowly. Interestingly, at low temperatures, no decline was observed after 30 hours, though the activity was slightly lower at 85%. These results are also interesting because they suggest that gold itself could be responsible for a large portion of the catalytic ability of gold catalysts. Typically catalytic systems using gold nanoparticles also include a support, as well as surface-modifying agents from the synthesis or special pre-treatment conditions to activate the catalyst, all of which can affect the performance.

## REFERENCES

- Au L, Zheng D, Zhou F, Li Z-Y, Li X, Xia Y (2008) A quantitative study on the photothermal effect of immuno gold nanocages targeted to breast cancer cells. *ACS Nano* 2: 1645-1652
- Averitt RD, Westcott SL, Halas NJ (1999) Linear optical properties of gold nanoshells. *Journal of the Optical Society of America B – Optical Physics* 16: 1824-1832
- Chen J, Wang D, Xi J, Au L, Siekkinen A, Warsen A, Li Z-Y, Zhang H, Xia Y, Li X (2007) Immuno gold nanocages with tailored optical properties for targeted photothermal destruction of cancer cells. *Nano Letters* 7: 1318-1322
- Daniel M-C, Astruc D (2004) Gold nanoparticles: Assembly, supramolecular chemistry, quantum-size-related properties, and applications toward biology, catalysis, and nanotechnology. *Chemical Reviews* 104: 293-346
- Della Pina C, Falletta E, Prati L, Rossi M (2008) Selective oxidation using gold. *Chemical Society Reviews* 37: 2077-2095
- El-Sayed MA (2001) Some interesting properties of metals confined in time and nanometer space of different shapes. *Accounts of Chemical Research* 34: 257-264
- Erlebacher J, Aziz MJ, Karma A, Dimitrov N, Sieradzki K (2001) Evolution of nanoporosity in dealloying. *Nature* 410: 450-453
- Eustis S, El-Sayed MA (2006) Why gold nanoparticles are more precious than pretty gold: Noble metal surface plasmon resonance and its enhancement of the radiative and nonradiative properties of nanocrystals of different shapes. *Chemical Society Reviews* 35: 209-217
- Gou L, Murphy CJ (2005) Fine-tuning the shape of gold nanorods. *Chemistry of Materials* 17: 3668-3672
- Grzelczak M, Pérez-Juste J, Mulvaney P, Liz-Marzán LM (2008) Shape control in gold nanoparticle synthesis. *Chemical Society Reviews* 37: 1783-1791
- Hu M, Wang X, Hartland GV, Mulvaney P, Juste JP, Saders JE (2003) Vibrational response of nanorods to ultrafast laser induced heating: Theoretical and experimental analysis. *Journal of the American Chemical Society* 125: 14925-14933
- Hu M, Chen J, Li Z-H, Au L, Hartland GV, Li X, Marquez M, Xia Y (2006) Gold nanostructures: Engineering their plasmonic properties for biomedical applications. *Chemical Society Reviews* 35: 1084-1094
- Jana NR, Gearheart L, Murphy CJ (2001) Wet chemical synthesis of high aspect ratio cylindrical gold nanorods. *Journal of Physical Chemistry B* 105: 4065-4067
- Kreibig U, Vollmer M (1995) *Optical Properties of Metal Clusters*. Springer, Berlin, 532 pp
- Li C, Shuford KL, Park QH, Cai W, Li Y, Lee EJ, Cho SO (2007) High-yield synthesis of single-crystalline gold nano-octahedra. *Angewandte Chemie* 119: 3328-3322
- Liao HW, Nehl CL, Hafner JH (2006) Biomedical applications of plasmon resonant metal nanoparticles. *Nanomedicine* 1: 201-208
- Mie G (1908) Contributions to the optics of turbid media, particularly of colloidal metal solutions. *Annals of Physics* 25: 377-445
- Murphy CJ, Sau TK, Gole AM, Orendorff CJ, Gao J, Gou L, Hunyadi SE, Li T (2005) Anisotropic metal nanoparticles: Synthesis, assembly, and optical applications. *Journal of Physical Chemistry B* 109: 13857-13870
- Seo D, Park JC, Song H (2006) Polyhedral gold nanocrystals with  $O_h$  symmetry: From octahedra to cubes. *Journal of the American Chemical Society* 128: 14863-14870
- Seo D, Yoo CI, Chung IS, Park SM, Ryu S, Song H (2008) Shape adjustment between multiply twinned and single-crystalline polyhedral gold nanocrystals: Decahedra, icosahedra, and truncated tetrahedra. *Journal of Physical Chemistry C* 112: 2469-2475
- Skrabalak SE, Au L, Li X, Xia Y (2007) Facile synthesis of Ag nanocubes and Au nanocages. *Nature Protocols* 2: 2182-2190
- Skrabalak SE, Chen J, Sun Y, Lu X, Au L, Cobley CM, Xia Y (2008) Gold nanocages: Synthesis, properties and applications. *Accounts of Chemical Research* 41: 1587-1595
- Sun Y, Xia Y (2004) Mechanistic study on the replacement reaction between silver nanostructures and chloroauric acid in aqueous medium. *Journal of the American Chemical Society* 126: 3892-3901
- Sun X, Dong S, Wang E (2004) Large-scale synthesis of micrometer-scale single-crystalline Au plates of nanometer thickness by a wet-chemical route. *Angewandte Chemie* 116: 6520-6523
- Tao AR, Habas S, Yang P (2008) Shape control of colloidal metal nanocrystals. *Small* 4: 310-325
- West JL, Halas NJ (2003) Engineered nanomaterials for biophotonics applications: Improving sensing, imaging, and therapeutics. *Annual Review of Biomedical Engineering* 5: 285-292
- Williams-Jones AE, Bowell RJ, Migdisov AA (2009) Gold in solution. *Elements* 5: 281-287
- Xia Y (2008) Nanomaterials at work in biomedical research. *Nature Materials* 7: 758-760
- Xia Y, Xiong Y, Lim B, Skrabalak SE (2008) Shape-controlled synthesis of metal nanocrystals: Simple chemistry meets complex physics? *Angewandte Chemie International Edition* 48: 60-103
- Xu C, Su J, Xu X, Liu P, Zhao H, Tian F, Ding Y (2007) Low temperature CO oxidation over unsupported nanoporous gold. *Journal of the American Chemical Society* 129: 42-43
- Yang X, Skrabalak SE, Li Z-Y, Xia Y, Wang LV (2007) Photoacoustic tomography of a rat cerebral cortex in vivo with Au nanocages as an optical contrast agent. *Nano Letters* 7: 3798-3802

## SUMMARY

Gold nanoparticles and nanoporous gold are fascinating materials with a wide variety of applications in biomedicine and catalysis. The properties of these materials can be optimized through careful control of their morphologies. Gold nanoparticles can be synthesized using a variety of techniques: simple solution-phase reduction of gold salts, seeded growth of small particles and galvanic replacement reactions with templates of another metal are all useful methods to control the final structures. The strong scattering/absorption of light by these gold particles can be used both to enhance optical imaging techniques and to generate heat for photothermal destruction of cells, hopefully enabling new types of cancer treatment. A number of promising studies have been performed in small animals for both of these applications, demonstrating the great potential of these novel materials. Phase I clinical trials are underway for targeted delivery of a chemotherapeutic drug attached to the surface of gold nanoparticles, and preliminary results show that the gold nanoparticles are well tolerated. Clinical trials have also recently begun for photothermal treatment with gold nanoshells, a gold nanostructure similar to nanocages. In manufacturing applications, supported gold nanoparticles and nanoporous gold are promising substrates for catalysis, enabling greener processes and higher efficiencies. ■

# GOLDSCHMIDT 2010

Earth, Energy, and the Environment

June 13–18  
Knoxville, Tennessee

The twentieth Goldschmidt conference will be held in Knoxville, Tennessee, June 13–18, 2010, hosted by the University of Tennessee and Oak Ridge National Laboratory. The conference will be held at the Knoxville Convention Center in World Fair Park, site of the 1982 World's Fair.



The theme of the meeting is Earth, Energy, and the Environment, which is reflected in twenty scientific thematic topics. The sessions will be complemented by short courses, field trips, and a social program highlighting the richness of East Tennessee.



European Association of  
Geochemistry

Knoxville lies in the foreland fold-and-thrust belt in the foothills of the Great Smoky Mountains. The southern Appalachian Mountains offer a rich diversity of geology, flora, and fauna to enjoy while visiting Knoxville.

[www.goldschmidt2010.org](http://www.goldschmidt2010.org)





# Italian Society of Mineralogy and Petrology

[www.socminpet.it](http://www.socminpet.it)

## GABeC SUMMER SCHOOL, LATINA, 23–26 JUNE 2009

A summer school titled Stone Materials as Georesource and Cultural Heritage was organized by GABeC (Gruppo Nazionale Georisorse, Ambiente e Beni Culturali) under the auspices of SIMP and was held at the Engineering Faculty of the University of Roma “La Sapienza” in Latina (Museum of Art and Ore Deposits) from 23 to 26 June 2009; it was organized by R. Cabella, A. Langella, and G. Saviano. The school was attended by some 30 students from all over the country; most of them were PhD students, and some were from research institutes and from the professional world. The teaching staff included P. Primavori, A. Borghi, A. Renzulli, D. Calcaterra, G. Eramo, R. Quaresima, A. Aveta, A. Buccaro, E. Galan Huertos, and B. Fitzner.

The first part of the school considered geological aspects of the stone resource, the production cycle and uses of ornamental stones, and the legislative and technical norms from a mineralogical and petrophysical point of view. The second part explored the relationship between ornamental stones and cultural heritage, with presentations on the evaluation of the decay phenomena and the diagnosis and mapping of weathering. Particularly remarkable were the case histories presented by Galan and Fitzner on the last day of the school.

Worth mentioning was an interesting excursion to the travertine quarries in Guidonia (Roma), where the complete production cycle, from in situ exploitation to final polishing of this important historical ornamental stone, was examined. A social dinner was held in the medieval Caetani Palace in Cisterna di Latina. It followed a fascinating visit to the underground cellars, which were excavated in an ignimbrite deposited during volcanic activity in the Colli Albani district.



Participants in the GABeC summer school

Participants were invited to present their research in a poster session open throughout the entire school period. These contributions, along with the presentations by the teaching staff, will be published in a special issue of the series *Lecture di Georisorse e Ambiente*, edited by the Museum of Art and Ore Deposits.

## A BOOK ON ITALIAN TYPE MINERALS



*Italian Type Minerals*  
by Marco E. Ciriotti, Lorenza Fascio,  
and Marco Pasero  
Edizioni PLUS – Pisa University Press, 357 pp, €40  
ISBN 978-88-8492-592-3

After a first edition as a CD-ROM, which was distributed to participants at the International Geological Congress in Firenze (August 2004), we are pleased to announce the new fully updated hard-copy version of the book *Italian Type Minerals*, published by Edizioni Plus – Pisa University Press. This book describes all the 264 mineral species first discovered in Italy, from 1546 up to the end of 2008. Moreover, 28 minerals discovered outside Italy and named after Italian individuals and institutions are included in a parallel section. Both parts are alphabetically arranged. The introductory chapter includes information about how the volume is organized and subdivided, as well as more general information. For each mineral, all basic data (chemical formula, space group symmetry, type locality, general appearance of the species, main geologic occurrences, curiosities, references, etc.) are included in a full page, together with one or more high-quality color photographs from

both private and museum collections, and with small snapshots of the people or places that lent each mineral its name. The appendices provide lists of Italian minerals sorted by crystal chemical classification, by region, by mineralogical district, and by year of discovery. A list of the authors who first described each mineral, along with general references, is also given.

The book was published under the patronage of the Italian Society of Mineralogy and Petrology (SIMP) and the Italian Micro-Mineralogical Association (AMI), and with the financial support of the University of Pisa through a special grant for research monographs. A preview of the first pages of the book (the entire introduction and the first 14 minerals in alphabetical order, from adranosite to apthitalite) can be found at [www.socminpet.it/Uploads/Pubblicazioni/ITM09\\_sel.pdf](http://www.socminpet.it/Uploads/Pubblicazioni/ITM09_sel.pdf). Copies may be purchased through Plus at the cost of 40 euros plus postage (contact: Edizioni Plus, Lungarno Pacinotti 43, 56126 Pisa, Italy; e-mail: [aseymons@edizioniplus.it](mailto:aseymons@edizioniplus.it)).

## GÜNTHER FRIEDRICH'S 80<sup>th</sup> BIRTHDAY SYMPOSIUM AND CELEBRATION

An 80<sup>th</sup> Birthday Symposium celebrating Professor Günther Friedrich's contributions to mineralogy and economic geology was held on Saturday, April 18, 2009, at the RWTH Aachen University. More than 130 of Günther's students, colleagues, and friends packed the Ford lecture theatre in the new SuperC building. The symposium featured a full afternoon of popular lectures by distinguished scientists, including Professor Peter Herzig (Director of the Leibniz Institute of Marine Sciences, IFM-GEOMAR, Kiel, Germany) on the topic "Marine Gas-Hydrates – Science Fiction or Technology of the Future?" and Professor Steve Scott (University of Toronto), who spoke on the subject "Mines in the Deep Ocean – Mineral Resources of the Future." The final speaker of the day was Professor Franz Michael Meyer (Head of the Department of Mineralogy and Economic Geology, RWTH Aachen University), whose lecture was entitled "Search for Gold." The day of talks was capped off by a superb banquet at the Pullman Aachen Quellenhof, featuring Günther's son Peter as the after-dinner speaker. He presented a thoroughly entertaining talk and slide show, many of the pictures secretly provided by "anonymous sources."

Günther Friedrich has dedicated his life to bringing high standards of excellence to the profession of economic geology. In 1954, he obtained his PhD degree from the University of Heidelberg under the guidance of Paul Ramdohr. Subsequently, he joined the staff of the Institute of Mineralogy and Economic Geology at the RWTH Aachen University where he obtained his "Habilitation" in 1962. He spent two years as visiting scientist at the University of Missouri–Rolla and the University of California–Berkeley, and time with the U.S. Geological Survey in Denver and the Geological Survey of Canada in Ottawa. He then returned to Aachen where he accepted the position of professor and head of the Division of Applied Ore Deposit Research. He remained in that position until 1975, when he was appointed Chair of Mineralogy and Economic Geology and promoted to director of the institute. In August 1994, he became "actively retired" from the university and was awarded the title Professor Emeritus for his more than 30 years of dedicated service.

Günther Friedrich's knowledge of ore deposits is expansive, and his remarkable ability to home in on fundamental problems has resulted in a wide range of research interests. For many years, Günther Friedrich's interests focused on the development of methods of geochemical exploration, including the use of mercury as a pathfinder element. Much of his scientific life, however, was dedicated to the study of marine mineral deposits, and he was a pioneer in manganese nodule research. Numerous cruises to the manganese nodule areas of the Pacific Ocean, were planned and carried out under his guidance. Landmark papers



Günther Friederich (left) and Michael Meyer

on the formation and the geochemical characteristics of manganese nodules were published by Günther and his colleagues in leading international journals. Later in his career, he concentrated his research on marine placer deposits and polymetallic massive sulfide deposits on the modern seafloor.

Other topics studied by Günther Friedrich include the mineralogy and geochemistry of the Kupferschiefer deposits; the study of laterite deposits and their gold, chromium, and nickel potential; the formation of alkaline rocks and associated ore deposits; and the genesis of epithermal gold deposits. Within the German Continental Deep Drilling Project, Günther Friedrich took an active role in the study of ore mineralogy and in developing models for ore formation in metamorphic rocks. The formation of ore deposits by intraformational processes was the subject of a long-term priority research program coordinated by Günther Friedrich and funded by the Deutsche Forschungsgemeinschaft. Günther and his students also worked on gold metallogenesis in Africa, which resulted in the discovery of an economic, currently exploited gold deposit. Günther Friedrich's scientific work has been summarized in more than 200 publications and 70 conference abstracts, reflecting his broad scientific interests. His enthusiasm and almost endless energy have been the driving force not only for him but also for many of his students, some of whom are now leading professionals in many different parts of the world.

Günther Friedrich's tenure was distinguished by extensive service to the Earth science community, including membership on the Earth Science Committee of the Deutsche Forschungsgemeinschaft (DFG) and several offices in the Society of Geology Applied to Mineral Deposits (SGA), including president in 1982–1984. He was instrumental in the inauguration of the German Forschungskollegium Lagerstätten (FKL) in 1988. He served for many years on the council of the German National Committee for the Geological Sciences to the IUGS and was president and vice-president of the Deutsche Mineralogische Gesellschaft (DMG) in 1990–1993. During this time Günther initiated the idea of raising seed funds for the Paul-Ramdohr Award, which was established by him in 1994. The award is given to a young scientist for presenting an outstanding paper or poster at the DMG annual meeting.

**Michael Meyer**, RWTH Aachen University

## DMG POSTGRADUATE SHORT COURSES

### *High-Pressure Experimental Techniques and Applications to the Earth's Interior*

Bayerisches Geoinstitut Bayreuth • February 15–19, 2010  
 Contact: Stefan Keyssner (stefan.keyssner@uni-bayreuth.de)  
[www.bgi.uni-bayreuth.de/ShortCourse2010](http://www.bgi.uni-bayreuth.de/ShortCourse2010)

### *Applications of Solid-State NMR Spectroscopy in Mineralogy and Earth Sciences*

Ruhr-Universität Bochum • May 25–28, 2010  
 Contact: Michael Fechtelkord (Michael.Fechtelkord@ruhr-uni-bochum.de)  
[www.ruhr-uni-bochum.de/dgk-ak12/indexdmgshort.htm](http://www.ruhr-uni-bochum.de/dgk-ak12/indexdmgshort.htm)

### *Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences*

Geoforschungszentrum Potsdam • October 4–8, 2010  
 Contact: Michael Wiedenbeck (michawi@gfz-potsdam.de)  
[www.gfz-potsdam.de/SIMS/](http://www.gfz-potsdam.de/SIMS/)

### *Kinetics of Geological Materials*

Universität Wien • August 30–September 3, 2010  
 Contact: Rainer Abart (rainer.abart@univie.ac.at)  
[www.for741.de/short\\_courses.html](http://www.for741.de/short_courses.html)

### *X-Ray Absorption Fine Structure (XAFS) Spectroscopy:*

**Introduction, Measurement, Data Evaluation**  
 Synchrotron ANKA at Research Center Karlsruhe (Karlsruhe Institute of Technology) • Fall 2010, duration 3 days  
 Contact: Jörg Göttlicher (dmgankaphdcourse2010@iss.fzk.de)  
[http://ankaweb.fzk.de/phdcourse2010/first\\_page.html](http://ankaweb.fzk.de/phdcourse2010/first_page.html)

## DMG PETROLOGY / PETROPHYSICS SECTION MEETING IN MAINZ

This year's annual meeting of the Petrology / Petrophysics Section of the German Mineralogical Society (DMG) took place on May 15–16, 2009, at the Institute of Geosciences of the Johannes Gutenberg University Mainz. The 55 participants from 13 different German institutes were gathered to share knowledge and experience. Young scientists were given the chance to present their work for the first time in front of an audience of specialists. Collegiate contributions were supported by the DMG with travel grants as in previous years.



Group picture of this year's annual Petrology / Petrophysics Section meeting at the Johannes Gutenberg University, Mainz, Germany. PHOTO: S. BUHRE

After a short introduction by Stephen Foley, the scientific program of 25 talks covering a broad range of scientific themes started on Saturday morning. The chairmen indicated that this workshop should include not only questions from the audience but also explanations by the presenters about problems related to their work; this format led to a provocative exchange of ideas and technical information. The presented research stretched across the globe, including Asia (Tien Shan xenoliths; basalts from Mutnovsky volcano in Kamchatka), North and South America (Mont Saint-Hilaire in Canada; Lascar volcano in the central Andes), Africa (mantle xenoliths from Kimberley, RSA), and Europe (Macedonian ophiolites; Menderes lithosphere in Turkey). The laboratory and field studies touched on all dimensions/layers of our planet, from the Earth's core (e.g. nonideality of core-forming metal phases), through the rocks and minerals of the mantle (e.g. water in wadsleyite; ammonium in high-pressure minerals, etc.), to near-surface crustal processes (e.g. experimental silicification of wood; hydrothermal experiments). It was shown that theoretical modeling can play a supportive role and that analytical methods from other scientific fields, such as medical computer tomography, may have an impact on solving petrological problems. This wide spectrum of topics may have provided new perspectives to those who participated, giving their work a new direction.

The well-organized meeting ended with a delicious BBQ and a camp fire in front of the faculty building. A big "thank you" goes to the organizers from Mainz University, to the DMG for their financial support, to Springer Publishing who provided 100 liters of beer, and to all participants for their contributions and interest.

**Sarah B. Cichy**  
Hannover, Germany

## SHORT COURSE REPORT – "APPLICATIONS OF SOLID STATE NMR SPECTROSCOPY IN GEOSCIENCES AND MINERALOGICAL RESEARCH" – BOCHUM, 2–5 JUNE 2009

"Du bist keine Schönheit – vor Arbeit ganz grau" (I know you're no beauty, for work's lined your face, from H. Grönemeyer's song "Bochum") – that was the first impression when we arrived in Bochum on Tuesday afternoon (June 2), and that impression was strongly influenced by an apparently never-ending drive of ten hours, with a complete standstill of about six hours on highway A2. The next obstacle to get over was the oversupply of parking opportunities in the university's multi-storey car park (hard to handle for people coming from Berlin and Potsdam). But finally we could get started on the short course.

The course was arranged by the DMG (German Mineralogical Society) and the DGK (German Society for Crystallography), both of which granted financial support to their student members. The group consisted of undergraduate students, graduates and postdocs from all over Germany. The organizer of the course, PD Dr. Michael Fechtelkord of the Institute of Geology, Mineralogy, and Geophysics of the Ruhr-Universität Bochum, started out with a general introduction to NMR spectroscopy. He explained the basics of the method and pointed out its relevance to structure determination and the assessment of dynamic processes in solids. Its advantage over other structure-determination methods (e.g. diffraction) is the possibility of examining short-range order, especially in amorphous solids. Through discussions with other participants, it became apparent that the combination of both methods is the key to structure determination.

The workshop was organized into a theoretical part in the morning and a practical one in the afternoon. The first day started with instructions about the spectrometer. We learned the rules of conduct close to the machine and the details of sample preparation. Afterwards we conducted temperature-dependent experiments on tetramethylammonium iodide in order to determine the activation energies and the correlation times of the different processes (spin-lattice relaxation). Wednesday's topic was the chemical shift and magnetic dipolar interactions between homo- and heteronuclear atoms. The magic angle spinning method was explained theoretically and practically using



Participants in the NMR spectroscopy short course in Bochum

the mineral phlogopite. Analyses of the spectra were conducted using the program WinFit. On Thursday, different multipulse methods were introduced. In the practical part, we determined interatomic distances (H–Si). The last day dealt with electric quadrupolar interactions and different methods related to that subject: double rotation (DOR), multi-quantum magic angle spinning (MQMAS), and satellite

transition spectroscopy (SATRAS). The practical part covered analysis of  $^{23}\text{Na}$  MAS and  $^{27}\text{Al}$  SATRAS spectra.

The short course was very informative and interesting for all participants. The practical application of the theory gave clear insight into the various applications of NMR spectroscopy. The composition of the group, from different geoscientific and materials science backgrounds, helped us to understand how the method can be used in various ways. The social evenings were congenial, and we enjoyed a pleasant atmosphere during the whole workshop.

We would like to thank Michael Fechtelkord and his PhD student Ramona Langner for the organization of these evenings and the workshop as a whole.

**Maria Mrosko and Fiorenza Deon**  
Potsdam, Germany

NEXT COURSE • MAY 25-28, 2010



# The Clay Minerals Society

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

## THE PRESIDENT'S CORNER



The 2009 annual meeting of the CMS seems to be disappearing quickly into the past, and already I am discovering what is required of me as the President. Many tasks need to be done in the immediate aftermath of the meeting, and now that these have been completed, I can look ahead to the wider needs of the Society. But the meeting remains quite fresh in my mind as I have always found the annual meetings of CMS to be special among the conferences and meet-

ings I have attended over the years. As I mentioned in my last President's Corner, a very friendly, almost family atmosphere prevails, and one of the reasons for this is that many society members attend with great regularity, and clearly many give the CMS annual meeting high priority in their annual schedule of meetings and conferences. The best example of this is that this year's Pioneer Lecturer, Haydn Murray, who is a founding member of the Society, has missed only one annual meeting since they began in 1963 – a remarkable record. Not only is it clear that Haydn sees the annual CMS event as a “must go” meeting, the Society is very grateful for his continual unstinting support, and long may it continue.

But time moves on, and the Society looks to the next annual meeting, which will be rather special in that it is a trilateral meeting with the Spanish and Japanese clay societies to be held in Spain on 6–11 June 2010. Plans are well advanced and include a workshop in Madrid on 6 June titled “Clays and Materials”, followed the next day by a symposium on sepiolite and a field trip to sepiolite deposits. The general meeting will be in Seville on 8–11 June and will be complemented by a field trip to the Rio Tinto mine. A limited number of student grants will be available to assist with the expenses of postgraduate students and young researchers belonging to one of the organizing societies. **More information** can be obtained at <https://cms.clays.org/meetings>.

One of the highlights of all annual meetings is the presentation of awards and listening to the lectures given by the awardees, and this issue's society news is given over largely to details of the winners of these awards and brief summaries of their talks.

Andy Thomas is now the Past President, and he is a very hard act to follow. He was CMS Treasurer for several years before being President and has the interests of the Society close to his heart. He was very diligent and conscientious in all his efforts on behalf of the Society, and members are very much indebted to him for his devotion. Many thanks Andy; although I know you will continue to be involved in CMS affairs, you can relax more now, knowing that yours was a job well done.

I look forward to a challenging year as President of CMS and encourage members to contact me about any issues which they feel need to be addressed or to pass on any ideas for improving our activities.

**Derek Bain**

President, The Clay Minerals Society  
The Macaulay Institute, Aberdeen, UK  
[d.bain@macaulay.ac.uk](mailto:d.bain@macaulay.ac.uk)

## WHAT THE STUDENTS SAID!

The CMS has always regarded itself as a very student-oriented society. Here is what some of the students attending the CMS meeting in Montana had to say...

This was the first CMS meeting that I have attended, and I enjoyed it thoroughly. Of particular benefit were the comments I received regarding my talk – very useful.

I would absolutely recommend that other students take the time to attend the conference. Having the opportunity to talk to and interact with both students and renowned scholars on a subject that you're working on in a very intimate setting is not an opportunity that many other societies are capable of providing. In fact, I've already convinced the other graduate student in our lab group that she missed out by not coming this year, and the two of us are working on plans to go to Spain for next year's joint conference.

As a relatively small group, interaction among students, researchers and industry was excellent. It was also interesting to note how the scientific knowledge gained in universities in clay and geosciences is applied in the real world for humankind and industry. The lectures by the various award winners were quite inspiring.

I really enjoyed the meeting and would definitely recommend it to other students! It was well worth traveling to the other side of the world for. Everyone I met was really nice, helpful and enthusiastic about what they were doing, and this was really encouraging for a student new to the Society. I had a group of other students 'adopt' me, which was great since I was traveling alone and didn't know anyone. Having a whole meeting devoted to clays was fantastic and there was a great range of talks.

I really enjoyed the CMS meeting, and I will be recommending next year's meeting to some of the first-year grad students just starting their projects. This was my first CMS meeting, and right away the members seemed approachable and genuinely interested in my work. I received valuable feedback on my talk. I only have good things to say about this year's meeting.

I would strongly recommend other students in geosciences (soil, geology, archaeology, etc.) to attend such meetings as it would help re-shape their research.

I felt that the analysis portion of the meeting allowed me to meet other researchers and ask some important questions related to my own research. It also afforded me the opportunity to speak with individuals who have a vast knowledge about clay minerals and the current analysis of those minerals.

This was my first time in the U.S. and I think I will remember it very well. I consider taking part in scientific meetings as something worthwhile, and this was also the case of the CMS conference. I met some people with whom I think I will cooperate, which is in my opinion one of the reasons for going to conferences.

The meeting was like nothing I'd ever experienced before as it was my first professional conference. The sheer breadth and depth of knowledge of the participants was astounding; I felt like a very small fish! I also didn't expect listening to talks all day to be so tiring, but keeping up and changing the track my brain was on every 20 minutes really took a lot. It was very enlightening.

We won't embarrass any of them by revealing who said what, but thanks for the feedback to Natalie-Jane Reid, Bruce Pauly, Erin Hunter, Courage Bangira, Michael Bishop, Marek Szczerba, Zachary Day and Keith Morrison. We hope to see you all again soon.



## THE CMS AWARDS 2009

The four awards of the CMS were presented at the annual meeting in Billings, Montana, USA, to scientists outstanding in their own sphere of clay mineralogy. The awardees were Joe Stucki, Michael Hochella, Lynda Williams and Haydn Murray.

The **Marilyn and Sturges W. Bailey Distinguished Member Award** is the highest honor bestowed by The Clay Minerals Society and is awarded solely for scientific eminence in clay mineralogy (in its broadest sense) as evidenced by the publication of outstanding original scientific research and by the impact of this research on the clay sciences. The 2009 recipient was Dr. Joseph W. Stucki of the Department of Natural Resources and Environmental Sciences at the University of Illinois. Joe's lecture at the annual meeting was entitled "Iron Redox Reactions in Smectites."



Joe Stucki (right) receives the Marilyn and Sturges W. Bailey Distinguished Member Award from outgoing President Andrew Thomas.

He affirmed that iron in the crystal structure of smectite clay minerals plays a significant role in determining the chemical and physical properties of these ubiquitous phyllosilicate minerals and indicated that the importance of Fe is attributed largely to its redox activity. The latter may be studied either synthetically under controlled conditions or in situ in soils and sediments in response to bacterial respiration or other environmental redox processes. He pointed out that many studies have examined cause-and-effect relationships between changes in Fe oxidation state and changes in clay properties and behavior and that the effects on the surrounding chemical and physical environments of the clay have also been investigated. Joe then provided an overview and analysis of these studies, including some of his own, in order to give an appreciation of the state of the science in this area and to plant seeds of curiosity that will lead others to delve further into this intriguing aspect of clay science.

The 2009 **G.W. Brindley Lecturer** was Dr. Michael F. Hochella of the Department of Geosciences at Virginia Polytechnic Institute and State University, and his topic was "Nanominerals, Mineral Nanoparticles and



Andrew Thomas (left) congratulates Michael F. Hochella Jr., the 2009 G. W. Brindley Lecturer.

Earth Systems." Mike's talk was based on the fact that minerals are more complex than previously thought, because of the discovery that their chemical properties change when their size is smaller than a few to perhaps several tens of nanometers in at least one dimension. He pointed out that we now recognize that such variations in this smallest of size regimes are most likely due, at least in part, to differences in surface and near-surface atomic structure, as well as crystal shape and surface topography. This knowledge broadens and enriches our view of how minerals influence the hydrosphere, pedosphere, biosphere, and atmosphere. Mike then reviewed nanominerals, their properties as related to their size and how their physical dimensions can influence reactions. The G.W. Brindley Lecture Award recognizes an outstanding scientist, who is both a dynamic speaker and involved in innovative research, and charges the recipient to deliver a lecture that will infuse The Clay Minerals Society with new ideas. Mike met these criteria admirably.

Dr Lynda B. Williams of the School of Earth & Space Exploration, Arizona State University, was the recipient of the 2009 **Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist Award**. This award recognizes a mid-career scientist for excellence in the contribution of new knowledge to clay minerals science through original and scholarly research. Lynda's presentation was entitled "Stable Isotopes of Clay Minerals Archive Organic Sources." She highlighted how the stable isotope geochemistry of clay minerals has proven useful in determining the paleofluid compositions recorded by illite and other diagenetic minerals precipitated during burial. Variations in trace element concentrations and isotope compositions as a function of clay crystal size record paleofluid chemical changes over time as crystals grow and incorporate those elements. Studies of fundamental illite particles separated by size have given insights into fluid changes during crystal growth and can allow us to make reasonable interpretations of stable isotopes and evaluate the geologic history of a sedimentary unit from a single core sample. Lynda showed how a variety of stable isotope systems of major elements (C, H, O, N, S) have been used to derive important information about how rocks



Lynda Williams receives the Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist Award and is congratulated on her innovative idea to use her dress rather than a powerpoint slide to illustrate clay mineral structures.

exchange components with aqueous fluids and hydrocarbons during burial diagenesis. Recently, B and Li isotope systematics have been applied to geologic problems in the sedimentary environment. New analytical instruments, such as the secondary ion mass spectrometer (SIMS), have allowed studies of stable isotope systems of trace elements in clay minerals that were not possible in the past.

The **Pioneer in Clay Science Lecture** award recognizes research contributions that have led to important new directions in clay mineral science and technology. The 2009 lecture was delivered by Dr. Haydn H. Murray of the Department of Geological Sciences, Indiana University. A founding member of The Clay Minerals Society, Haydn gave a very informative and entertaining account of his "60 years as a clay mineralogist," during which he worked in academia, industry, and state government and also as a consultant. Peppering his talk with personal anecdotes, he showed many pictures of what he considers to be some of the world's most important clay deposits. He outlined the highlights of his career chronologically, revealing a tremendous diversity of interests in clays, particularly kaolins, smectites, and palygorskites. After presenting the physical and chemical properties of clay minerals and their relation to the primary applications of clays, he discussed future trends and predicted which world-class deposits will be most utilized.



Haydn Murray (left) receives the Pioneer in Clay Science Award.



# Mineralogical Society of Great Britain and Ireland

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

## NATURE'S TREASURES II: THE WONDER OF MINERALS AND GEMS

*The second in our 'Nature's Treasures' series of meetings will take place on Sunday, 13 December 2009.*

THE EXCITING LINE-UP OF TALKS INCLUDES:

- **Alan Collins** – Diamond: A unique mineral and the ultimate gemstone
- **M. Feely** – Teaching gemmology in the Emerald Isle: A geologist's perspective
- **N. Moles** – The Russell Society: Promoting mineralogy and helping mineralogists in the UK and Ireland
- **R. Siddall** – Nature's palette: Minerals and crystals in pigments and paints
- **Guy Clutterbuck** – Gems from mines to market
- **J. Faithfull** – 250 years of mineral collecting at the Hunterian Museum
- **C. Carlon** – Mining the ocean
- **J. Ralph** – title to be confirmed

Go to [www.minersoc.org/pages/meetings/nature2/nature2.html](http://www.minersoc.org/pages/meetings/nature2/nature2.html) for abstracts and details of how to register. See the report of last year's event at [www.minersoc.org/pages/meetings/nature/nature-archive.html](http://www.minersoc.org/pages/meetings/nature/nature-archive.html).

## FUTUROCLAYS: ADVANCES IN CLAY SCIENCE FOR FUTURE GEOLOGICAL, ENVIRONMENTAL AND INDUSTRIAL APPLICATIONS

*Annual meeting of the Clay Minerals Group of the Mineralogical Society • Newcastle, UK, December 14–16, 2009*

Clays and clay minerals are abundant and widespread in soils and sediments worldwide, and clays form well over 50% of the sedimentary rocks, which occupy about three-quarters of the Earth's surface. They are widely used in agricultural, industrial and environmental engineering applications due to their remarkable physical and chemical properties, such as large surface area, low permeability, large cationic exchange capacity, swelling behaviour, etc. In recent years, scientific research has largely focused on the development of new clay-based technologies. In particular, several teams of researchers have been studying Fe reduction and reoxidation in Fe-bearing clays and clay minerals and the application of the process to the remediation of contaminated land and waters. Many others have concentrated their research on the development of organoclay materials, pillared clays, and other clay-based materials for environmental and agricultural applications.

NEW ADVANCES IN THESE TOPICS WILL BE ADDRESSED BY A NUMBER OF EMINENT KEYNOTE SPEAKERS INCLUDING:

- Prof. **Joseph W. Stucki** (University of Illinois at Urbana Champaign, USA) (the 10<sup>th</sup> George Brown Lecture) – Evolution of the study of redox reactions of Fe in smectites
- Dr **Ravi Kukkadapu** (Pacific Northwest National Laboratory, Richland, WA, USA) – Effect of Fe mineral (oxides and clays) reductive biotransformations on remediation of radioactive metals from contaminated aquifers
- Dr **Eric Ferrage** (HydrASA Laboratory, Université de Poitiers, France) – Recent advances in the characterization of organizational properties of water in expandable clays
- Dr **Deeba M. Ansari** (Imerys Minerals Ltd., St Austell, Cornwall, UK) – Current and future demands for clay minerals – an industrial perspective

ORGANIZING COMMITTEE: David Manning (chair), Claire Fialips, Maggie White, Andy Aplin, Joe Harwood, Uzochukwu Ugochukwu, Phil Renforth and Sani Yahaya.

Please go to [www.minersoc.org/pages/groups/cmgi/cmgi.html#fialips](http://www.minersoc.org/pages/groups/cmgi/cmgi.html#fialips) for details. Online registration is now open.

## MINABS ONLINE ARCHIVE FINDS NEW HOME

As *Elements* readers will know, *Mineralogical Abstracts* ceased publication of new abstracts at the end of 2008. The contract which covers the online service, minabs.com, has also come to an end. The Mineralogical Society has been working to ensure continued availability of the existing online body of abstracts, which covers the years from 1982 to 2008.

We are pleased to announce that the abstracts are being transferred to the custodianship of GeoRef, where they will be available free for the foreseeable future. It is intended that the process be complete by the time you read this. During transfer of the data, MinSoc has taken steps to correct a problem endemic to the online service, namely that some scientific and technical characters, such as Greek letters and algebraic symbols, did not display correctly on many browser platforms. Our focus has been on accurate transfer of the online data. We would be grateful if users could report any obvious and systematic errors.

The existing URL for the service, [www.minabs.com](http://www.minabs.com), at present is still directed to the historic service. The new MinAbs Online service will also be available from this URL. More recent abstracts now display their digital object identifier (DOI), which links to the original article referenced in the abstract, though it will not guarantee access unless the user has an appropriate subscription. There is a new search interface, which we hope users will find helpful.

MinSoc would like to thank GeoRef for offering to host MinAbs Online, and also for their considerable help in resolving problems during the data transfer.

## EMpower Lecture Programme 2009

8 October – University of East Anglia  
**Legacy liability research challenges at the Atomic Weapons Establishment** Laura Peacock, AWE Aldermaston

13 October – University of Leeds  
**Science and Technology at Sellafield**  
Mike James, Sellafield

29 October – University of Edinburgh  
**Research & development challenges and decommissioning**  
Graham Fairhall, National Nuclear Laboratory

4 November – Lancaster University  
**Regulating the build of new nuclear power reactors**  
Dave Watson, HSE – Nuclear Installations Inspectorate

12 November – Imperial College, London  
**Opportunities & challenges of nuclear new build**  
Jeremy Western, British Energy – part of EDF Energy

26 November – Cardiff University  
**Regulating risk we can't see – how we use science to protect the environment from radiation**  
David Copplestone, Environment Agency

Sponsor: Environment Agency

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



# Geochemical Society

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

## BLOGGING INTO THE 21<sup>st</sup> CENTURY

The Geochemical Society experimented with a new communications strategy at this year's Goldschmidt Conference: conference blogging<sup>1</sup>. Nine conference attendees blogged on a variety of topics. These were mainly drawn from the scientific proceedings, but also from the "Earth's Future" panel discussion and social events. This test was part of a new outreach plan designed to bring the Goldschmidt meeting to geochemists who did not attend and to increase the visibility of the Geochemical Society to a wider public.

Blogging has become a popular and even transformative means of communication in some fields, such as technology and politics. But science is a more deliberative endeavor, and it remains an open question whether blogs will be an effective tool in scientific communication. Conferences are a particular sticking point—a recent editorial in *Nature*<sup>2</sup> suggested that it is now imperative for conference organizers to decide if their conference will be "open," where attendees are allowed to immediately broadcast proceedings worldwide via blogs and twitter, or "closed," where such activity is prohibited.

Blogging is likely to change the nature of conferences. Given the possibility that the proceedings of a small plenary are made instantly available on the Internet, speakers may become more cautious about the information and ideas they are willing to present. Such a development would be unfortunate. But in the best scenario, blogs could serve as a means for enriching fruitful conversations, including voices not physically present, and as a forum for keeping conference deliberations alive after the convention center has emptied. The Geochemical Society has decided that conference blogs are more advantageous than not, and has embraced the new medium. As blogging evolves, the Geochemical Society will adapt so that speakers and bloggers alike have a clear idea of what the ground rules are.

Scientists will not be the only ones served by conference blogs. With science journalism in decline, blogs may be an efficient way for scientists to communicate with the general public. The Internet is a major source of science information for nonscientists<sup>3</sup>. Internet content generated by scientific societies has credibility. In sponsoring conference blogs, scientific societies can provide the public with relevant and reliable information that is up to date and timely. These blogs can help inform the public and be a starting point for journalists considering story ideas. By offering a variety of viewpoints, blogs can even introduce the public to debates within scientific communities, improving public understanding of how scientific ideas are developed and tested. It remains to be seen what the impact of this new communication medium will be, but the genie is out of the bottle: conference blogs are here to stay.

Alex Bradley, Harvard University

1 <http://geochemicalnews.wordpress.com/>

2 How to stop blogging. *Nature* 460: 152

3 The internet as a resource for news and information about science. Pew Internet & American Life Project, 2006. <http://www.pewinternet.org/Reports/2006/The-Internet-as-a-Resource-for-News-and-Information-about-Science.aspx>



Check Goldschmidt 2010 advertisement on page 314.

## GS AT GSA-PORTLAND MEETING

The 2009 and 2010 GS Program Committees worked very diligently this year to help propose eight sessions for the GSA meeting in Portland, Oregon (October 18–21, 2009). **Seth Davis** (GS Business Manager) will be at the GS exhibit booth (**Booth 659**) during the conference if you would like to renew your membership or address a specific issue in person. The GS booth is located close to the MSA booth, which will have several RiMG volumes for sale. We will also be sponsoring the **2009 Ingerson Lecture** and the **MSA/GS Joint Reception**. The reception is a ticketed event. Check your GSA program for locations.

## 2010 MEMBERSHIP DRIVE

### 2010 Member Rates (US\$)

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

**2010 Subscription Rates (US\$)**  
*Subscription rates are at cost. GS does not make money from member subscriptions.*

*Elements* – Free!  
(included with membership)

**GCA hardcopy + online access**  
(1995 to date)  
– Professional: \$137  
– Student or senior: \$69

**GCA online access only**  
(1995 to date)  
– Professional: \$87  
– Student or senior: \$44

**G-cubed Online Access**  
– Professional or senior: \$80  
– Student: \$44

### Member Discounts

**Publication Discounts**

- 40% off GS Special Publications
- 25% off most MSA publications, including RiMG volumes
- 25% off Elsevier book orders

### Registration Discounts

- AGU Joint Assembly
- V.M. Goldschmidt Conference™
- GSA Annual Meeting & Exposition
- AGU Fall Meeting

### Community

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

Join online:

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

## 2010 COMMITTEE CHANGES

Everything we do as a society is impossible without the enormous efforts of our volunteers. Many thanks go to the volunteers who stepped down on June 30 this year:

- **NOMINATIONS COMMITTEE:** Lisa Pratt (chair), Alan Matthews
- **V.M. GOLDSCHMIDT AWARD COMMITTEE:** Christopher Martens
- **F.W. CLARKE AWARD COMMITTEE:** Christian Koeberl (chair), Douglas E. Hammond
- **C.C. PATTERSON AWARD COMMITTEE:** Candace E. Martin (chair), Richard T. Wilkin
- **GS/EAG FELLOWS COMMITTEE:** Jacques Schott (chair), Harry Elderfield

Below are the committee changes and additions for 2010. Welcome aboard! For a complete list of committee members go to [www.geochemsoc.org/society/committeesandpersonnel/](http://www.geochemsoc.org/society/committeesandpersonnel/).

### Board of Directors Nominations Committee

CHAIR: Janne Blichert-Toft  
NEW MEMBERS: Dominique Weis,  
Mark Rehkamper

### Program Committee

CHAIR: Troy Rasbury  
NEW MEMBERS: Pat Castillo, Bridget Bergquist

### V.M. Goldschmidt Selection Committee

CHAIR: Paul Asimov  
NEW MEMBER: Victoria Bennett

### F.W. Clarke Award Selection Committee

CHAIR: Robert Ayuso  
NEW MEMBERS: Jiwchar Ganor,  
Suzanne Golding

### C.C. Patterson Selection Committee

CHAIR: Jenny Webster-Brown  
NEW MEMBERS: Kenji Mibe,  
Alakendra Roychoudhury

### GS/EAG Fellows Selection Committee

CHAIR: Barb Dutrow



# The European Association for Geochemistry

www.eag.eu.com

## THE ROAD TO DAVOS – GOLDSCHMIDT 2009 CONFERENCE REPORT

With over 3100 abstracts submitted and more than 2800 registered delegates (28% students), the meeting at Davos in June 2009 was the biggest Goldschmidt Conference to date. The top ten countries in terms of delegates were the United States (578), Germany (338), the UK (265), Switzerland (232), France (223), the People's Republic of China (157), Japan (140), Australia (78), Russia (75) and Canada (69). Just over half of all delegates were from Europe. The success of a meeting cannot be and isn't judged by its size, but by the quality of the science presented and the environment for meeting colleagues and friends. As an organizer it is easy to get a distorted view of how well a meeting has worked. That is why we thank all the delegates, just under 15%, who took the time to fill in the post-conference questionnaire; they provided an essential reality check and very important feedback. With respect to overall satisfaction for the meeting, 55% judged it as good and 40% as very good. Forty percent of delegates ranked the science content as good and 60% as excellent. Goldschmidt has never had feedback in this form before. With the community's help, the organizers now have a base from which to improve meetings and to assess whether future meetings are reaching the high standard expected.

Past European meetings have been organised by a single institute or a local consortium of institutes, and without exception they have been great successes. Davos 2009 is the first Goldschmidt meeting to be organised directly by the European Association for Geochemistry (EAG). The motivation for organisation by the EAG was the increasing size of the meeting. The infrastructure and time commitment required to run an expanding Goldschmidt means that it is becoming increasingly harder to find European institutes or local consortia willing to take on and effectively subsidise future meetings. Goldschmidt is a meeting that has become so important for geochemistry that it is both unwise and unfair to have its future success or failure rest solely on one institute's shoulders. With EAG involvement in the organisational process of European Goldschmidt Conferences, an infrastructure has been created that removes the burden from local organisers and provides a stronger base for institutional memory and continuity for future meetings.

As the site of the successful 2002 Goldschmidt meeting, Davos was an obvious candidate for a return visit. The principal convenors were the organising committee chairman, Chris Ballentine; the local convenor, Judith McKenzie (ETH Zurich); and EAG vice-president/president, Eric Oelkers. The committee chairman was responsible for forming the science committee. The convenors were aided by an organising committee that included the then EAG president, Alex Halliday; EAG secretary, Susan Stipp (later Steve Banwart); and EAG treasurer, Catherine Chauvel (later Christa Gopel). The administration of the conference was run by Cambridge Publications, which also had a place on the organising committee (Paul Beattie). It was very important to form a European rather than a national core science team, and we were very pleased when Philippe Van Capellen (University of Utrecht) and Janet Hering (EAWAG) joined the science committee to complete the full Goldschmidt 2009 organising committee. The committee first met in Davos in May 2007.

From the outset we wanted to involve many top geochemists from around the world in constructing the science program. The committee identified 19 science themes and potential chairs who, along with the co-chairs of their choosing, were to put together a team to identify the key theme topics that would form the conference sessions. This inter-

national science panel was 149 strong (30% women), the largest ever. The sessions proposed initially were checked by the Goldschmidt 2009 science committee for consistency and possible overlap, and 107 approved sessions were advertised shortly before the Vancouver Goldschmidt meeting in 2008. An open call to the community brought in a further 20 sessions. From comparisons with other meetings, we predicted an attendance of 2300–2500 (Fig. 1)

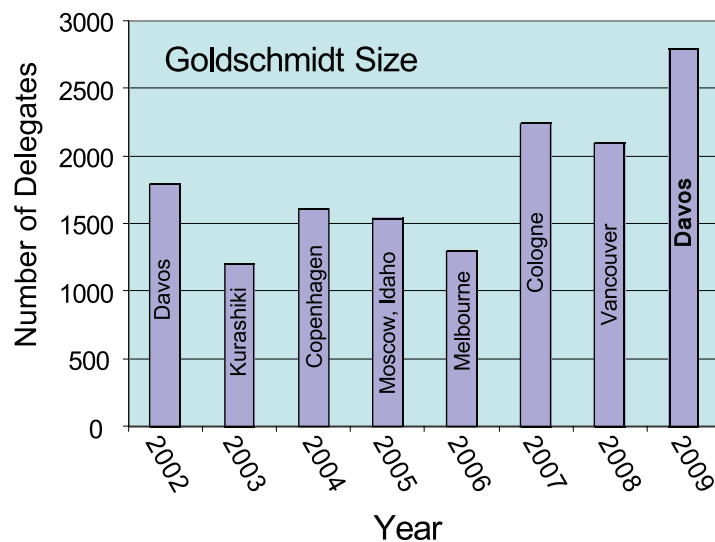


Figure 1 – Growth of Goldschmidt meetings since 2002

### The Conference

By the 22 February 2009 abstract submission deadline, we had received 3099 abstracts for the meeting. We hired four extra speaker rooms in a nearby hotel and made the hard, but essential, decision to reduce congestion by running the posters in parallel with the oral sessions. Light food, lunch bags and beer throughout the afternoon, only available in the poster hall, helped bring in delegates to view the posters, which were also on display during lunch and after the oral sessions had closed in the afternoon. On Monday and Tuesday, throughout the day there were between 400 and 550 delegates continually in the poster hall. By Thursday, numbers during the day had dropped but they increased during lunch and in the evening. While most delegates would clearly have preferred oral and poster sessions not be scheduled in parallel and, even better, be held in the same building, we were nevertheless pleased to see that the overall conference satisfaction rating by the poster presenters was the same as the average.

### Workshops, Field Trips and Social Events

A total of 270 delegates took part in a range of field trips before and after the conference. Three one-day trips, two three-day trips and one five-day trip were held. All field trips reached the minimum number of participants required, with the three-day trip to the Damma Glacier at capacity. The field trips were led by volunteers from institutes across Switzerland, but some leaders came from as far afield as Torino and Copenhagen. Feedback from participants was excellent, despite some adverse weather. In addition to the field trips, five workshops ran in conjunction with Goldschmidt, three on site, one in Zurich and the other in Nancy, France (with a Nancy–Davos shuttle provided). The Thermodynamics and Kinetics MSA short course was at capacity (125 delegates). The organising committee would like to echo the participants in thanking all the field trip and workshop organisers for their hard work in making these events such a success.

The well-attended Sunday icebreaker featured live music provided by Double Scotch, a band of geochemists from CRPG, Nancy, whose rock covers were particularly popular with younger delegates. The conference dinner on Wednesday was attended by 1120 people and held in Davos' Valliant Arena, the ice stadium also used for the poster displays. The catering company provided an outstanding selection of Swiss local specialities, in volumes sufficient to satisfy the hungriest. Live Brazilian jazz music and a DJ got many on their feet, resulting in a stage full of dancing bodies that only cleared when the music stopped at 1 am. Other social events were also popular, with alpine views, high dining and a sell-out glacier restaurant train attracting 370 delegates to three smaller events.



Dancing at the conference dinner takes over the stage.

### ***Pens, Bags and Organisation***

We followed the footsteps of other Goldschmidt meetings on innovations that worked well. Instead of thick paper volumes, reusable pen drives (memory sticks) containing the conference abstracts were issued, conference programmes were pocket sized and paper handouts were discouraged. With so little conference material to carry, we decided to make conference bags optional, and only 402 of a potential 2800 bags were ordered.

Cambridge Publications provided the Internet infrastructure and support office that administered the science program construction; the liaison with exhibitors; abstract submission; registration for the conference, field trips, social events and workshops; help desk; and much more. Previous Goldschmidt organisers have all praised Paul Beattie's team for the quality and good value of their product. EAG and the Goldschmidt 2009 organising committee had an equally good experience with the service, as did delegates and session chairs who returned the questionnaire.

### ***Press and Earth's Future***

As the conference grows larger, its potential for drawing attention to the importance of geochemistry grows. This year we were able to attract to an 'Earth's Future' event several key scientists who have made a significant impact in the implementation of science in policy: Sir David King, former chief scientific adviser to the UK government; 'Ram' Ramanathan, member and subcommittee chair of the IPCC; Bill Chameides, recently chief scientist of the U.S. Environmental Defence Fund; and Janet Hering, director of EAWAG, one of Europe's most prestigious environmental research institutes. On Wednesday afternoon, attendance was high for the Earth's Future event, featuring lectures followed by a panel discussion. The conference hired a professional science journalist to generate a press release package highlighting this event, as well as other high-profile lectures given at the meeting. This package was released through a media agency specialising in science. We are waiting for a report on its impact, but we have no illusions that it will take time to build up a conference presence in this area.



Sir Prof. David King, former Chief Scientific Advisor to Her Majesty's Government (UK) and Director of the Smith School of Enterprise and the Environment, University of Oxford, was one of four high-profile speakers on 'The Earth's Future' panel.

### ***Bloggers and Student Support Staff***

The future of geochemistry lies in the gifted students whom our subject can attract and retain. We have to provide a stimulating conference environment for younger scientists, and feedback from students and early-career scientists is essential. The Geochemical Society, in addition to administering the student and developing-country grants, also recruited nine scientists to provide a Goldschmidt blogger forum – a direct form of feedback guaranteed to be read by all on the organising committee as well as by a wider audience. Doing this was no small time commitment. Judging by the blogs, everyone seemed to enjoy the process and the conference (see inset) as much as the committee and others enjoyed following the blog content. In addition to the conference bloggers, 38 BSc, MSc and early-PhD Earth science students recruited from Switzerland and southern Germany formed the core of the conference support staff. The students worked diligently at the registration desk and later with the session chairpersons, and their raw energy and infectious enthusiasm lasted the entire week; Georgi Laukert, who looked after the conference photography, deserves a special mention. Our thanks to you all.

On behalf of the Goldschmidt 2009 Organising Committee,

**Chris Ballentine**, Chair

### **THE GEOCHEMICAL SOCIETY'S GOLDSCHMIDT CONFERENCE BLOG**

Nine people covered the whole event giving their views and thoughts about the meeting and spreading news, information, debates and lots of nice geochemistry 'chit-chat'. If there is one useful application of blogs, it's following a conference like Goldschmidt in almost real-time. Why? Because in my opinion the bloggers were taking the essence of the event, bringing its 'spirit' to the general public, to those who could not attend it and even to the participants who contributed with talks and posters. This spirit that we transmitted was made of 'take-home messages' from participants, discussions, chats and interactions during coffee breaks, lunch or dinner-time. In other words, it is made of what we remember when we come back home after enjoying great science.

**Juan Diego Rodriguez Blanco**  
Blogger, University of Leeds



# Mineralogical Society of America

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

## FROM THE PRESIDENT



### MSA Networks

Barb Dutrow, the 2007 MSA president, has long advocated the use of new tools online by the MSA to expand the network of mineral scientists and to help young scientists advance their careers. She was the first to recommend that MSA develop a Facebook group page, and now, thanks to MSA councilor Marc Hirschmann, MSA has one. I was

the 193<sup>rd</sup> member to join the MSA Facebook group. This group provides an opportunity for networking and contributing information, discussion, and comments of relevance to MSA and for advertising the activities of MSA to the wider community.

As my final days in office wind down, I am working to establish another type of network, a global network of MSA representatives at two- and four-year colleges, universities, government laboratories, museums, and industries. The primary job of an MSA representative will be to provide information about the Society and its mission to students and professional colleagues. An "MSA information kit" will be sent to the representatives, which will include information on MSA publications, short courses and workshops, education and outreach resources, awards and recognition, policy statements, special interest groups, mineralogical resources, and meetings. Representatives will also be sent e-mails about new developments and approaching deadlines. If you are interested in serving as an MSA representative, please contact me (nross@vt.edu).

As I close my final letter to you, I welcome the incoming 2010 president of the Society, John B. Brady, and the 2010 vice president, David L. Bish. Mickey Gunter was reelected to another term as secretary and Darrell J. Henry, treasurer, remains in office. The new councilors are Wendy Bohrson and Sumit Chakraborty, who replace Jean Morrison and Klaus Mezger. Continuing councilors are Peter C. Burns, Carol D. Frost, Marc M. Hirschmann, and Penelope L. King.

I am also pleased to announce that Martin Kunz of Lawrence Berkeley National Laboratory has agreed to succeed Dana Griffen as editor of *American Mineralogist*. Dana has done a superlative job as editor, and he will be working with Martin until December 2009, when Martin officially joins editors Jenny Thomson and Bryan Chakoumakos. Martin is part of the experimental systems group at the Advanced Light Source, where he developed an X-ray microdiffraction beamline for materials research in geo- and environmental sciences. He brings a breadth of expertise to the position, with his research interests in mineralogy, crystal chemistry, phase transitions, high-pressure mineralogy, and, most recently, the development of microdiffraction techniques and their applications.

It has been an honor to serve with such a great team on behalf of the Society. Special thanks go to the staff at MSA, who keep us on track and serve as our invaluable corporate memory. The past year has passed very quickly as MSA president, and I have come to the conclusion that a one-year term is not long enough!

**Nancy Ross**  
2009 MSA President

## NOTES FROM CHANTILLY

- Regular member dues for 2010 will be \$65, offset by a \$5 discount for members who renew online before October 31, 2009, reflecting cost savings for the MSA by members who renew promptly. Student dues remain at \$10. Sustaining membership will remain at \$150 + regular dues.

Member subscription rates for the 2010 *American Mineralogist* will continue to be different for domestic and foreign members in order to reflect actual costs of producing paper copies and mailing them, and to shift a portion of first-copy costs from institutional subscribers to individual subscribers. US member subscription price (paper and electronic) will be \$80 (currently \$70), and foreign member subscription price will be \$90 (currently \$80). Member electronic-only subscription will remain at \$30. US institutional subscription price (paper and electronic) will be raised to \$875 (from \$825), and foreign institutional subscription will be raised to \$900 (from \$850). Included with the institutional subscription are all the current-year issues of *Reviews in Mineralogy & Geochemistry*, *Elements*, and access to the electronic journal on the MSA website.

- Membership renewals for 2010 will start in October, when renewal notices will be sent electronically. This will be followed by electronic reminders, and a paper copy will be sent to those who do not renew online by the end of October.

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

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

**J. Alex Speer**, Executive Director  
[j\\_a\\_speer@minsocam.org](mailto:j_a_speer@minsocam.org)

## DANA MEDAL TO COHEN

At the June 2009 Goldschmidt Conference in Davos, Switzerland, the Mineralogical Society of America awarded its **Dana Medal to Ronald E. Cohen** of the Carnegie Institution of Washington, Washington, DC. This medal recognizes continued outstanding scientific contributions to the mineralogical sciences through original research by an individual in mid-career. Dr. Cohen was recognized for bringing modern methods for the investigation of atomic bonding and electronic structure into the mainstream of mineralogy, and for leading the field in developing and applying state-of-the-art theoretical methods for predicting and understanding the properties of minerals, particularly at extreme pressures and temperatures.



Nancy Ross presenting the Dana Medal to Ronald E. Cohen

## AMERICAN MINERALOGIST UNDERGRADUATE AWARDS FOR OUTSTANDING STUDENTS

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

### JAMES P. ADAMS

George Mason University  
Sponsored by Dr. Julia Nord Cooper

### ELIZA M. ANDREWS

Georgia State University  
Sponsored by Dr. Timothy La Tour

### TREVOR H. BRISCO

Acadia University  
Sponsored by Dr. Sandra Barr

### CALLUM BRUCE

University of Otago  
Sponsored by Dr. J. Palin

### NIKOLAUS J. DEEMS

George Mason University  
Sponsored by Dr. Julia Nord Cooper

### ROHANNA GIBSON

University of Victoria  
Sponsored by Prof. Dante Canil

### DANIEL J. HUNT

Georgia State University  
Sponsored by Dr. Timothy La Tour

### SUKRU GOKHAN KOSE

Middle East Technical University  
Sponsored by Dr. M. Camur

### ANDREA F. LISI

George Mason University  
Sponsored by Dr. Julia Nord Cooper

### MATTHEW A. MILLER

University of Oklahoma  
Sponsored by Dr. David London

### JUSTIN G. OLSEN

George Mason University  
Sponsored by Dr. Julia Nord Cooper

### PAUL E. PRIBYL

University of Wyoming  
Sponsored by Mr. John Kaszuba

### ROXANNE N. RENEDO

Smith College  
Sponsored by Dr. John Brady

### BRYANT D. SHUE

University of Pittsburgh–  
Johnstown  
Sponsored by Dr. Elizabeth Goeke

### VACLAV SPILLAR

Charles University  
Sponsored by Dr. David Dolejs

### LAURA ANN STEVENS

Wellesley College  
Sponsored by Dr. David Hawkins

### VOJTECH VLCEK

Charles University  
Sponsored by Dr. David Dolejs

### MICHAEL L. WOODWARD

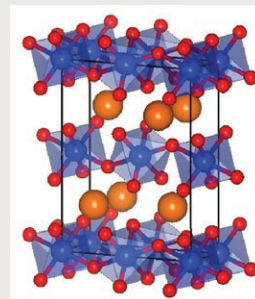
Georgia State University  
Sponsored by Dr. Timothy La Tour

### BISSETT YOUNG

Indiana University  
Sponsored by Prof. David Bish

## Mineralogical Society of America and Geochemical Society Short Course Announcement

THEORETICAL AND COMPUTATIONAL METHODS IN MINERAL PHYSICS: APPLICATIONS TO GEOPHYSICS



December 10–12, 2009

Doubletree Hotel, Berkeley, CA, USA  
(before Fall AGU Meeting)

**Convenors:** RENATA WENTZCOVITCH  
*University of Minnesota* and LARS  
STIXRUDE *University College London*

The short course will consist of a review of the important techniques used in theoretical and/or computational mineral physics today, along with exemplary applications that have

contributed to the advancement of the field of high-pressure mineral physics and geophysics.

More information and registration:  
<http://www.minsocam.org>

## IN MEMORIAM

NEIL A. WINTRINGHAM – Senior Member, 1951

LUCIAN W. ZELAZNY – Member, 1978

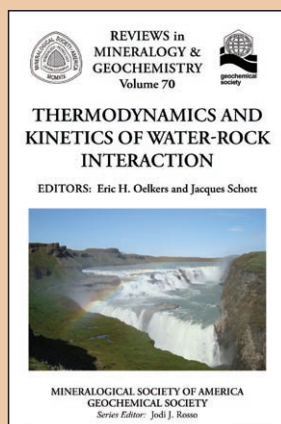
## How to use GeoScienceWorld: Even if you haven't (yet) gotten your library to subscribe!

1. Search the archives to find the **references you need**.
2. **Search the archives** by topical keyword! Or author! Or date! Explore!
3. **Read the abstracts** — they **pop up** in your browser.
4. All articles are available via **pay-per-view**: click on the "full article" or "PDF" view and follow the instructions!
5. Of course, you can *Email the author* via the "**hotlink**" and request an e-print or offprint!
6. **Click** on the abstract, then look at the boxes on the right. ● *Email the abstract to a friend*. ● **Find similar articles**. ● Download to various *citation managers*. ● View the Citation Map.
7. **Sign up FREE for the Alerting Functions!**  
(<http://www.geoscienceworld.org/cgi/register>)  
● Tables of contents ● New issue available ● CiteTrack ● Multi-Journal alerts  
● Citation Alerts ● Corrections Alerts!
8. View the **upcoming articles** on the home page and sign up for an "etoc" — a "future table of contents" emailed to you when posted.
9. Check out the "**most read**" and "**most cited**" lists on the home page!
10. Surf our "Special Issues" **collections links** on the home page.
11. **Explore** an online sample issue — a real issue of *American Mineralogist* showing the **full text**, PDF views, **links** to figure views and supplemental data, reference linking, and so on — *enjoy this and show it to your librarian!*
12. **Links** to information about MSA, submission how-to's, *American Mineralogist* editors, GSW, and so much more!

It's all here:

<http://ammin.geoscienceworld.org/>

## NEW TITLE



## Reviews in Mineralogy and Geochemistry

MINERALOGICAL SOCIETY OF AMERICA AND THE GEOCHEMICAL SOCIETY

**Volume 70** Thermodynamics and Kinetics of Water-Rock Interaction, Eric H. Oelkers and Jacques Schott, editors. US\$40

For description and table of contents and online ordering visit [www.minsocam.org](http://www.minsocam.org) or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110 USA • phone: +1 (703) 9950 fax: +1 (703) 652-9951 e-mail: [business@minsocam.org](mailto:business@minsocam.org)



# Mineralogical Association of Canada

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

## FROM THE PRESIDENT



### *Hello Solid-State Geochemistry*

Rod Ewing, past-president of the Mineralogical Society of America and founding editor of *Elements*, provided a provocative Triple Point in the most recent past issue of *Elements* (4: 205). Read his article for details, but Rod observes that the geochemical research community is vibrant and populated with many young scientists and students, whereas for some decades the discipline of mineralogy has declined in population, stature, and impact. Few graduate students and young researchers identify themselves as mineralogists today, and even fewer are likely to in the coming years.

Why has mineralogy as a discipline declined while a broader discipline that actually encompasses it, geochemistry, has flourished? One could argue that mineralogy is simply too narrow and too sparsely populated academically to have critical mass—as certainly seems to be the case today. As Rod noted in Triple Point, mineralogy is not a subdiscipline of geology in the ongoing National Research Council ranking of graduate programs in the United States. Recall the electronic hand-wringing on the MSA list serve when universities requested that faculty engage in the NRC data-gathering exercise and mineralogists realized their field does not exist! Perusal of the U.S. National Science Foundation website confirms there is no program dedicated to funding mineralogical research, but there are at least two covering geochemistry. Given that research universities demand that faculty bring in ever increasing levels of research funds and advise more graduate students, the future for academic mineralogy is clear in the United States. Or, at least, it is clear that young academics at research universities are not going to self-identify as mineralogists—so how about solid-state geochemists?

The marginalization of mineralogy as a scientific discipline is a simple reality of the evolution of science. Minerals that make up the bulk of Earth's crust have largely been characterized and are reasonably well understood. Sure, there are still fascinating research problems in mineralogy, but think of what has been accomplished. Mineralogists created the knowledge that underpins geochemistry and petrology. The discipline of mineralogy is a victim of its own success.

What is the future of mineralogical research in a world where funding agencies demand transformational research and where mineralogy is maturing? Rod may have a solution in that he plans to be a geochemist of solids. I do too, but I will call myself a solid-state geochemist, a materials scientist, or an inorganic chemist, whichever suits the current purpose. Those of us who grew up (or are growing up) as mineralogists have a scientific tool kit that makes us at home in the interdisciplinary arena of materials research. Our minds have been developed to think about highly complex solids in multiple dimensions, and we have created and adapted a wide range of state-of-the-art experimental and theoretical approaches.

Rod and I are moving forward as solid-state geochemists, but not much will change in how we do our science and train our students. An undergraduate course in mineralogy is a better place than most to start to learn about the complexities of the solid state, and graduate studies in solid-state geochemistry will continue the tradition of applying complex theories and techniques to important solids. In fact, a new generation of solid-state geochemists will go on to contribute to the solutions of some of science's and society's most vexing problems.

**Peter C. Burns**, University of Notre Dame  
MAC President

## 2008–2009 UNDERGRADUATE AWARDS

The MAC Undergraduate Awards are given annually to undergraduate students for excellence in one of the fields covered by MAC (mineralogy, crystallography, petrology, geochemistry, and economic geology). The award consists of one free publication and one-year subscription to *Elements* and the online version of *The Canadian Mineralogist*. We congratulate the 2008–2009 awardees.

**ERIKA B. ANDERSON**, McGill University  
**KATARINA E. BJORKMAN**, Lakehead University  
**JENNIFER BLAIN**, Université Laval  
**NICOLE J. BROOKER**, University of British Columbia–Okanagan  
**BENJAMIN GORDON DANIELS**, University of Waterloo  
**KAYLA DELL**, Brock University  
**LISA DOUGLAS**, University of Victoria  
**GREGORY HOWARD**, Saint Mary's University  
**TREVOR KELLY**, Dalhousie University  
**FRANCIS LACOURSIÈRE**, Université du Québec à Chicoutimi  
**ALANA MacKINDER**, Carleton University  
**KATHLEEN McDONALD**, Laurentian University  
**HANNAH MILLS**, University of Alberta  
**IZYAN HANI MOHD IZHAM**, The University of Western Ontario  
**PAMELA PATRASKOVIC**, University of Toronto  
**IVA PEKLOVA**, University of Windsor  
**LAURA PISIAK**, University of Manitoba  
**DYLAN QUINN**, St. Francis Xavier University  
**ANDREW JONATHAN SMITH**, University of Regina  
**GABRIEL WALTON**, Queen's University  
**ROBIN WESTLAND**, Acadia University

## CALL FOR NOMINATIONS 2010 MINERALOGICAL ASSOCIATION OF CANADA AWARDS

### PEACOCK MEDAL

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

### YOUNG SCIENTIST AWARD

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

### BERRY MEDAL

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

Please submit your nominations by December 31, 2009. Check our website, [www.mineralogicalassociation.ca](http://www.mineralogicalassociation.ca), for additional details.



**AESRC 2009**

The 8<sup>th</sup> Advances in Earth Science Research Conference (AESRC) was held March 27–28 at Queen's University in Kingston, Ontario. The conference is designed to showcase undergraduate and graduate student research in the Earth sciences. Over 50 delegates from Queen's University, the University of Ottawa, and Carleton University took part in the conference. They attended numerous talks, poster presentations, and social activities, making many new friends in the process. The event was a huge success thanks to the countless volunteer hours contributed by numerous graduate students from Queen's University.

The talks covered nearly the entire spectrum of the Earth sciences. Subjects included studies of forest rings in northern Ontario, the composition of the Bermuda shelf wall, and the genesis of precious- and base-metal mineralization in Mexico. Highlights of the conference were keynote talks by esteemed speakers from Queen's University. Dr. Mark Diederichs started with a fantastic talk entitled "Tunnelling at Niagara—Past and Present." Dr. Herb Helmstaedt followed with an informative talk titled "Diamonds in Canada—Where Are They, How Were They Discovered, and What Is the Future Outlook?" Dr. Noel James wrapped up the keynote presentations with a talk entitled "The Beauty of Being Cool: Carbonate Sedimentation and the Southern Ocean."

The conference was also a success in bringing students and industry together. The conference was attended by delegates from the Mineralogical Association of Canada, Imperial Oil Canada, and the Canadian Society of Petroleum Geologists. Students were able to meet with these representatives in a more casual atmosphere, including an evening wine-and-cheese event and a conference dinner held at the Kingston Brew Pub.

The organizing committee of the 2009 AESRC would like to thank all the sponsors, including the Mineralogical Association of Canada, for their support in making this year's conference a great success.

*Mineralogical Association of Canada***STUDENT TRAVEL/RESEARCH GRANTS**

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

- Present their research at a conference
- Visit a facility, laboratory, or field area to gather data for their research
- Pay for analyses that cannot be acquired at their university or equipment for an independent research project

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

*Eligibility*

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

For more information, see [www.mineralogicalassociation.ca](http://www.mineralogicalassociation.ca).

**Deadline to apply: January 15, 2010**

**SECONDARY ION MASS SPECTROMETRY IN THE EARTH SCIENCES**

Short course volume 41 introduces SIMS analytical techniques and assesses their applications in the Earth sciences. Topics include light stable and non-traditional isotope analysis, radiogenic isotope analysis, Quaternary geochronology, and depth profiling techniques.

ISBN 978-0-921294-50-4  
SC 41, 160 pages, 2009

CDN\$40 (in Canada)  
US\$40 (outside Canada)

(Member Price CDN\$32/US\$32)

Order your copy at [www.mineralogicalassociation.ca](http://www.mineralogicalassociation.ca)

**DON'T MISS** CANADA'S GREATEST  
CONFERENCE ON EARTH SCIENCES

**GEOCANADA 2010**

CALGARY, ALBERTA  
MAY 10–14, 2010

GeoCanada 2010 is a once-in-a-decade opportunity for anyone who works with the Earth. Whether your focus is petroleum, base and precious metals, ground water, geophysics, bedrock and seabed mapping, geohazards, uranium or environmental remediation, GeoCanada 2010 will present the latest developments across a complete spectrum of Earth Science professions.

To inquire about speaking, sponsorship or exhibit opportunities, please contact Shauna Carson, Convention Manager 403-264-5610 or [scarson@geoconvention.org](mailto:scarson@geoconvention.org).

**WORKING WITH THE EARTH**  
May 10–14, 2010 • Calgary, Alberta  
[www.GeoCanada2010.ca](http://www.GeoCanada2010.ca)  
[info@geocanada2010.ca](mailto:info@geocanada2010.ca)





# Association of Applied Geochemists

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

## 24<sup>th</sup> INTERNATIONAL APPLIED GEOCHEMISTRY SYMPOSIUM (IAGS 2009)

The biennial meeting of the Association of Applied Geochemists was held in Fredericton, New Brunswick, Canada, on June 1–4, 2009, as the 24<sup>th</sup> International Applied Geochemistry Symposium. The meeting was cosponsored by the International Association of Geochemistry (IAGC) and the International Association of GeoAnalysts (IAG), and included the North Atlantic Minerals Symposium (NAMS). It was 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 from UNB. The meeting was preceded by professional development workshops on May 31 and also featured several field trips. A conference banquet and awards ceremony was held on June 3, during which the AAG's Gold and Silver Medals as well as the 2009 student paper prize and student poster prizes were awarded. These remarkable few days in New Brunswick were attended by approximately 300 people, including about 100 students. Watch for a full report in the next issue of *Elements*.

**Beth McClenaghan**, Geological Survey of Canada

## STUDENT AWARDS AT THE 24<sup>th</sup> IAGS

Sponsored by the Engineers and Geoscientists of New Brunswick, prizes were awarded for outstanding student poster presentations at the 24<sup>th</sup> IAGS. First prize (CAN\$1000) was awarded to **Sabine Schwarz**, University of New Brunswick, for her poster entitled "The Middle River Gold Deposit, NE New Brunswick, Canada: An Example of an Orogenic Style Gold System in the Brunswick Subduction Complex," which was coauthored by David Lentz and James Walker. Second prize (\$500) was awarded to **Gabriela Budulan**, Queen's University, for her poster entitled "Indicator Mineral Signature of the Halfmile Lake Zn-Pb-Cu Volcanogenic Massive Sulphide Deposit, New Brunswick, Canada," coauthored by Beth McClenaghan, Michael Parkhill, and Dan Layton-Matthews. Third prize (\$250) was awarded to **Nathan Bridge**, University of Western Ontario, for his poster "Geology and Geochemistry of the Lac Cinquante Uranium Deposit, Nunavut," coauthored by Neil Banerjee, Craig Finnigan, Rob Carpenter, and Jeff Ward. An Honourable Mention was awarded to Rafael Cavalcanti de Albuquerque, Simon Fraser University, for his poster entitled "Risk Assessment of Arsenic Mobility in Groundwaters in Langley, British Columbia Using Geochemical Indicators," coauthored by Dirk Kirste and Diana Allen. A second Honourable Mention was awarded to Yask Shelat, University of Toronto, for his poster "Lithological Identification of Rocks in Cape Smith Fold Belt Region, New Quebec, Using Remote Sensing Applications," co-authored by James Mungall. Honourable Mention awards consisted of a gift from the University of New Brunswick.

## AAG MEDALS



The AAG presented two medals at the 24<sup>th</sup> IAGS in Fredericton, Canada. The AAG Gold Medal is awarded for scientific contributions to geochemistry. The AAG Silver Medal is given for dedicated service to the

Association, with the awardee being nominated by the immediate past president.

### AAG Gold Medal to Gerry Govett

Dr. Gerry Govett's career spans almost 40 years, from the time he received his PhD in 1958 from Imperial College in London, UK, until he retired in 1996 from the University of New South Wales in Sydney, Australia. During his career, Gerry was a research scientist at the Alberta Research Council; Professor and Director of Graduate Studies at the University of New Brunswick; and Professor, Head of the School of Applied Geology, and Dean of the Faculty of Applied Science at the University of

New South Wales in Australia. He has inspired a generation of undergraduate and graduate students from almost every continent with his energy, enthusiasm and scientific rigour. Gerry's academic career was interspersed with periods when he worked as a consultant to the United Nations Development Programme and to international mining companies. He has had extensive exploration experience in 15 countries, including Australia, Canada, Ethiopia, Fiji, Finland, Greece, Guyana, Jordan, Indonesia, the Philippines, Papua New Guinea, Turkey, Zambia and Zimbabwe. He was also geochemical adviser and consultant to the geological surveys of both Greece and Finland, and Director of Delta Gold Limited.

Gerry served on the editorial boards of *Resources Policy*, the *Journal of Geochemical Exploration*, and *Exploration and Mining Geology*. He was a founding member of the Association of Exploration Geochemists and served on Council, including a term as president. Gerry was also a member of the Canadian Geoscience Council, councilor for the Australian Mineral Foundation, and founding member of the Australian Geoscience Council, on which he served as both vice-president and president. Professor Govett has an enviable publication record, which comprises more than 90 significant papers, and he has authored and edited books on mineral economics and exploration geochemistry. While at the University of New Brunswick, he conceived the *Handbook of Exploration Geochemistry* and was Series Editor from 1974 to 2001.

### AAG Silver Medal to David Smith

The AAG Silver Medal was presented to Dr. David Smith of the United States Geological Survey (USGS). David is a research geochemist at USGS, where he has worked for over 33 years. He holds a BA and MSc in geology from Vanderbilt University, Nashville, Tennessee, and a PhD in geochemistry from Colorado School of Mines, Golden, Colorado. He started professional life during the first uranium boom, and this led to his PhD dissertation on uranium in volcanic ash. He has served in USGS management as associate chief and as chief for the geochemistry branch. He is currently the USGS leader for the soil geochemical baseline landscape project and has served as co-leader of the IAGC-IUGS global geochemical baseline since 1997. He joined AEG in 1975, has been a fellow since 1982 and has served as secretary since 1998. During this time he has worked with nine AAG or AEG presidents, and he was involved in the name change of the Association and in the overhaul of the Association's articles.



AAG president Dave Cohen and AAG Gold Medal recipient Gerry Govett (RIGHT)



AAG president Dave Cohen presenting the AAG Silver Medal to Dave Smith (RIGHT)



# Société Française de Minéralogie et de Cristallographie

[www.sfmc-fr.org](http://www.sfmc-fr.org)

## SFMC AND GFA AT THE XIV INTERNATIONAL CLAY CONFERENCE

Many members of the SFMC and the Groupe Français des Argiles (GFA) attended the 14<sup>th</sup> AIPEA meeting, the largest ever held, in Castellaneta Marina (Italy), in a beautiful and peaceful Aleppo pinewood and close to Unesco world heritage sites. In this exquisite sunny environment, delegates had the opportunity over a full week (14–20 June) to participate in exciting scientific exchanges (1028 contributions from 50 countries) and to experience the wines, cooking, villages, dances and tarantellas typical of the region. For the success of the conference highlighting the vitality of the clay community, Professor Saverio Fiore (CNR, Tito Scalo) and his efficient and welcoming team are warmly thanked. For more meeting information and photographic reports, visit [www.14icc.org/index.html](http://www.14icc.org/index.html) and see meeting report on next page.



SFMC and GFA participants at the XIV International Clay Conference  
PHOTO CREDIT J. BRENDÉ

## MEETINGS ANNOUNCEMENTS

### *LE VERRE, les enjeux de la recherche*



The “Days of the Glass Science and Technologies Union” event will be held at the Polytech’Orléans, at the University of Orléans (France), on 5–6 November 2009. The event is jointly organized by René Vacher (LCVN, Montpellier), Pernelle Barlier (Corning, Avon), Daniel R. Neuville (IPG, Paris), Patrick Echegut (CEMHTI, Orléans) and Dominique

Massiot (CEMHTI, Orléans), and will be held under the auspices of the CNRS and of several glass industry companies.

Three posters sessions and ten keynote lectures will cover a wide range of topics, including Silicate melts simulation (W. Kob, LCVN, Montpellier); Exotic glasses (J. Lucas, Rennes); Glasses for fibers and amplifiers (E. Burov, Draka); Vitroceramics (M. Comte, Corning); Physics of glasses and liquids (P. Richet, IPG Paris); SiO<sub>2</sub> and B<sub>2</sub>O<sub>3</sub>: Peculiar glasses (A. Takada, Asahi Glass Company); Technologies and inventions (H. Arribart, Saint-Gobain); Nuclear wastes, success and challenges (A. Ledieu, CEA); Heavy metals and release in glass containers: A statistical survey 1974–2008 (N. Favaro, Stazione Sperimentale del Vetro); and Sub-nanometric scale of glass structure: Topologic or chemical disorder (D. Massiot, Orléans).

For information, contact Daniel Neuville ([neuville@ipgp.jussieu.fr](mailto:neuville@ipgp.jussieu.fr)) or visit <http://verre2009.cnrs-orleans.fr/>.

Cont’d from page 270

## ASBESTOS SANS MINERALOGY? A VIEW FROM A DIFFERENT HILLTOP – Mickey Gunter’s response

narrow the definition of asbestiform when the Occupational Safety and Health Administration (OSHA) did not regulate cleavage fragments. From my point of view, the “door was closed” on using a broader definition. Even though I am very aware the term “elongated mineral particle” is not the new definition for asbestos, it is my opinion that we are headed in that direction. Greg also commented on the use, during the Libby trial, of methods other than aspect ratio to determine if a particle really is a fiber and not an elongated crystal fragment. Strohmeier et al. (2007) discussed established criteria for distinguishing a fiber from a fragment of amphibole, and one criterion to indicate the particle is a single crystal fragment is stepped sides. So, in the end, we always seem to fall back on aspect ratio to distinguish fibers from fragments of amphiboles.

One of our most important concerns should be with human exposure to potentially harmful materials. The refereed literature indicates exposure to non-asbestiform amphiboles is less harmful than to asbestiform amphiboles. In fact, this is why OSHA regulates only asbestiform amphiboles. Gunter et al. (2007) reviewed the literature in this field, and interested readers should refer to three recent articles published by other authors in the *Journal of Regulatory Toxicology and Pharmacology* (2008, volume 52, pp S154-S186, S187-S199, S200-S203), which come to similar conclusions.

Greg and I disagree on many things—from the recent legal definition of asbestos to the amount of “tolerance” we should have for the misuse of mineralogical nomenclature. I remain steadfast in not accepting the phrase “naturally occurring asbestos,” which appears to be derived from the popular media. Regardless, I hope Greg and others interested in these issues will attend and contribute to our upcoming symposium “Asbestos Issues: Past, Present, and Future” at the combined Northeast/Southeast sectional GSA meeting in Baltimore (March, 2010). I, for one, would like to get off the “hilltop” and enjoy a more harmonious life down in the valley.

Gunter ME, Sanchez MS (2009) Amphibole forensics: Using the composition of amphiboles to determine their source, the Libby, Montana example. *American Mineralogist* 94: 837-840

Gunter ME, Belluso E, Mottana A (2007) Amphiboles: Environmental and health concerns. In: Hawthorne FC, Oberti R, Della Ventura G, Mottana A (eds) *Amphiboles: Crystal Chemistry, Occurrences, and Health Concerns*. *Reviews in Mineralogy & Geochemistry* 67, Mineralogical Society of America, Chantilly, VA, pp 453-516

Meeker GP, Bern AM, Brownfield IK, Lowers HA, Sutley SJ, Hoefen TM, Vance JS (2003) The composition and morphology of amphibole from the Rainy Creek Complex, near Libby, Montana. *American Mineralogist* 88: 1955-1969

Strohmeier BR, Bunker KL, Harris KE, Hoch R, Lee RJ (2007) Complementary TEM and FESEM characterization of amphibole particles in mixed mineral dust from Libby, Montana, U.S.A. *The Microscope* 55: 173-188



**14<sup>th</sup> INTERNATIONAL CLAY CONFERENCE,  
CASTELLANETA MARINA, ITALY  
14–20 JUNE 2009**

What an amazing week! No fewer than 654 delegates from 49 different countries attended the 14<sup>th</sup> International Clay Conference, which took place at the Calané Conference Centre in the Nova Yardinia resort, just 4 km from Castellaneta Marina on the Ionian Sea. During the plenary lectures, the delegates were taken to the surface of Mars; they accompanied carbon dioxide into aquifers deep below the Earth's surface; they learned that clays, which may have played a role in the origin of life, can also harbour extremely toxic dioxin molecules; and they were treated to a historical review of clays and mudstones since their first mention by Agricola in 1556.

Given that 42 keynote lectures and 24 invited lectures set the scene for over 408 oral presentations, attendees had to be well organized to identify, locate and listen to the talks most relevant to them. The design of the conference centre ensured that accommodation, the lecture venues, the restaurant (and the pool) were all within a short distance of each other, making it easy to move among the 43 sessions covering eight different themes ranging from the bio-clay interface to nanomaterials via medical applications and planetary mineralogy.

There were also 548 posters on display over five days, and attendance at the poster sessions was first rate. Few poster authors went away without having endured a good-natured cross-examination of their work – a particularly important aspect for the very large number of student presenters, given that the development of young researchers is a key aim of AIPEA.

Several clay scientists received individual recognition during the course of the conference. Dr Jock Churchman (University of Adelaide) was named AIPEA Fellow for his long-standing contribution to clay science, and Dr Yoshiaki Fukushima (Senior Fellow at the Toyota Central Research and Development Laboratories) received the AIPEA Medal for his contribution to the field of clay nanocomposites. Note that the AIPEA Medal is provided by Tolsa SA via the Spanish Clay Society (SEA), which gives me the opportunity to congratulate the SEA on its 50<sup>th</sup> Anniversary in November 2009.

In addition to the above awards recognizing established clay scientists, AIPEA strives to encourage and support young researchers. The Bradley Award is the most prestigious and hotly contested prize, and on this occasion was won by Marek Szczerba (Polish Academy of Sciences, Kraków), who presented his work during a plenary lecture. AIPEA Student Travel Awards were given to help the following students attend the conference and present their work: Pauline Andrieux (Université de Poitiers), Michael Cheshire (Indiana University), Marian Matejdes (Comenius University, Bratislava), Adi Radiam (Hebrew University of



Reiner Neumann, Gina Gianossi, Jeanne Percival, Dave Bish, Claudia Belviso and Saverio Fiore relaxing during the conference dinner at the end of a busy week



Reiner Neumann carrying the AIPEA flag to Brazil, which will host the 15<sup>th</sup> ICC in 2013



Saverio Fiore enthusiastically participating in an evening's entertainment

Jerusalem) and Hongji Yuan (Indiana University). Behind the scenes, a team of assessors worked hard throughout the conference attending oral presentations and posters given by research students. After focused yet friendly debate, the prize for best oral presentation went to Holger Seher, with Rosa Marques and Bethany Ehlmann jointly coming second. The prize for best student poster went to Lenka Herzogová, and the runner-up was Adebukola Adegoroye. The pre-conference AIPEA School for Young Scientists, entitled "Interstratified Clay Minerals: Origin, Characterisation and Geochemical Significance" and held at the University of Bari, provides another example of AIPEA's commitment to the early-career development of clay scientists.

During the AIPEA General Assembly, President Dave Bish introduced proposed amendments to the AIPEA Statutes and By-Laws, which had been recommended by Council. The General Assembly voted in favour of the amendments. The revised Statutes and By-Laws can be accessed, along with much more information on AIPEA and the awards described above, on the recently updated AIPEA website, [www.aipea.org](http://www.aipea.org). Dave also took the opportunity to praise the efforts of Rob Schoonheydt for his 22 years of continuous service to AIPEA and to give his heartfelt thanks to Saverio Fiore and his team for the several years of hard work that went into the preparation and successful delivery of this record-breaking conference. Judging by the resounding applause from the assembled AIPEA members, they were in full agreement with Dave's sincere comments.

Saverio Fiore and his organizing committee also put tremendous effort into providing an excellent programme of entertainment each evening, and plenty of photographs were taken of individuals and groups getting into the swing of things and 'letting their hair down' (for some interesting examples visit [www.14thicc.org](http://www.14thicc.org)). The half-day excursions to the UNESCO World Heritage sites at Sassi di Matera and Trulli di Alberobello also proved very popular.

As incoming President of AIPEA, I would like to add my thanks to Saverio and his team for the conference's outstanding success. The meeting achieved an amazing level of participation against a gloomy financial background, which, as Dave Bish said in his opening message, is a powerful testament to the vitality of the international clay science community. I sincerely hope that this momentum will be maintained for the next International Clay Conference, which will take place in Rio de Janeiro in 2013. Last, I would like to formally recognize the contribution made by Dave Bish and the outgoing Council and thank them for all the hard work and resulting progress made during their term of office.

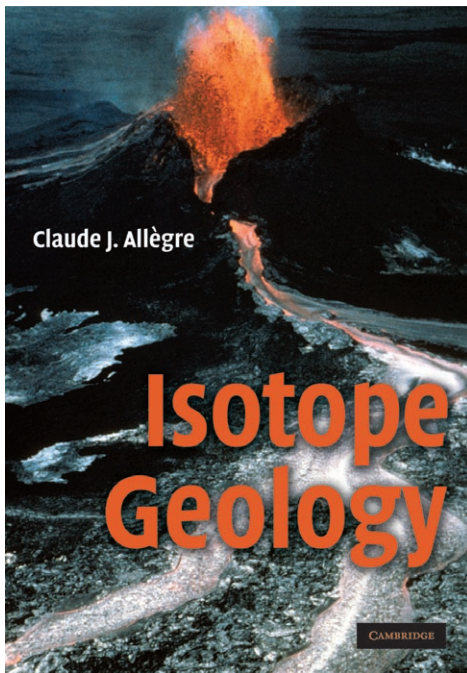
**Chris Breen**, AIPEA President

## ISOTOPE GEOLOGY<sup>1</sup>

Unlike physics or chemistry, teaching isotope geochemistry is difficult because it is such an interdisciplinary and experiential field. Learning isotope geochemistry is also difficult, not because it is technically difficult, but because geochemistry requires the synthesis of many concepts and applications. Writing an effective book on geochemistry is thus even more difficult. Claude Allègre's *Isotope Geology* is a welcome addition to the collection of Earth science textbooks, joining the two classic isotope geochemistry books by Gunter Faure and Alan Dickin.

You might ask whether there's a need for a new isotope geochemistry book, given how effective the texts by Faure and Dickin are. However, Allègre's *Isotope Geology* is presented using a fundamentally different approach. While Faure's and Dickin's texts are presented in encyclopedic format, that is, each chapter is dedicated to a given isotope system and its applications, *Isotope Geology* has distinctly avoided this format. Instead, each of Allègre's chapters deals with an over-arching concept, wherein case studies of isotope systems illustrate the meaning or importance of the concept. For example, chapters 2 and 3 are titled "The Principles of Radioactive Dating" and "Radioactive Dating Methods," respectively. In these two chapters, Allègre lays out all the radioactive decay equations that one will ever need, providing simple examples from different isotope systems to illustrate their application. He even explains the concept of "fossil" isochrons (not explicitly treated in Faure and Dickin); while the fossil isochron concept is almost mathematically trivial, I have noticed that it is a difficult concept for students to grasp. In any case, if a student can master chapters 2 and 3, he/she should be poised to examine any radioactive system. Allègre is clearly of the philosophy that one's fundamentals must be sound.

I can rave about many other aspects of this book. The most striking is Allègre's amazing ability to articulate concepts through simple and elegant figures and prose. All figures have been redrafted and distilled down to their bare essentials. The text is succinct and to the point, and the layout avoids unnecessary clutter and confusion. Whether this was intentional or not, the end product is like a clear whistle in a thick fog. A testament to the elegant simplicity of the book is that I can even make sense of my copy of the original French version, even though my French reading abilities are horrible. Another highlight is that we get



to see a little bit of Allègre's own perspective. The text is punctuated by anecdotes that liven up the discussion and provide a personal connection with the reader. In some cases, Allègre relates the history of certain ideas or controversies, thus implying that science is a human endeavor marked by fits of brilliance as well as mistakes. Allègre lays out what is now known and what still has not been resolved, inspiring the inquisitive student to explore further.

A few other highlights are worth mentioning. Chapter 7 provides an up-to-date overview of the principles of stable isotope geochemistry, focusing first on fundamentals and then touching on specific examples in low- and high-temperature geochemistry. I was pleased to see discussions on the use of mass-independent fractionation as paleoenvironment records and of "clumped" isotopes in estimating temperature. Chapter 6, "Radiogenic Isotope Geochemistry," summarizes the application of radiogenic isotope tracers in understanding planetary differentiation, clearly one of Allègre's favorite topics. In the last chapter, "Isotope Geology and Dynamic Systems," Allègre provides a much-needed overview of box modeling and mass transport modeling. A student will come away with a sound understanding of residence and response times in geochemical systems. While such concepts are also considered in Albarède's *Introduction to Geochemical Modeling and Introduction to Geochemistry*, this is the first time that such a treatment is explicitly presented in an isotope geochemistry book. This is just another example of Allègre's process-based approach.

Since this is supposed to be a critical review, I should mention how *Isotope Geology* can be improved. Given the importance of concepts and fundamentals in this book, it would have been better to delve even deeper into certain themes. For example, there is only limited discussion about nuclear chemistry and physics. What controls the mass of nuclei? What are mass defects? Why are some nuclei unstable? How would one calculate the amount of energy released by radioactive decay? One homework problem asks for the total heat released by decay of a certain amount of a radioactive element. The reader is given the heat-production rate, but it would be nice to know how this number is determined. Another example concerns the chapter on stable isotope geochemistry. Although the equations for equilibrium and kinetic isotope fractionation are presented, Allègre could have elaborated on the physics of equilibrium isotope fractionation as they relate to bond strengths and energy wells, perhaps including some key concept figures. Finally, given the recent rush to study stable isotope fractionation of the heavy metals, I would have enjoyed more than just two pages of discussion on this topic.

I can't help pointing out one egregious error. This involves the story of Lord Kelvin and why he was wrong about the age of the Earth. The almost universally accepted story, the one presented by Allègre, is that Lord Kelvin did not take radioactivity into account in his heat-conduction equations. In fact, a simple calculation shows that accounting for radioactivity doesn't improve Kelvin's situation much. The real reason why Kelvin's estimate was wrong was because of a fundamental flaw in his model, that is, the Earth loses interior heat to the surface by convection, not by conduction. For a review of the correct version of the story, see a piece by England, Molnar, and Richter in *GSA Today* (2007).

In conclusion, Allègre's book represents a long-awaited contribution, which complements those by Faure and Dickin. Read Allègre's book first, then turn to Faure or Dickin for detailed examples of applications for a specific isotope system. Not only is this trio of books on my bookshelf, but I recommend the entire set to my students. This book is accessible to all, not just geochemists, but also geophysicists. Last, I much prefer the purple-laced Kandinsky cover of the original French edition, as it looks much prettier on my bookshelf.

**Cin-Ty A. Lee**

Department of Earth Science  
Rice University

<sup>1</sup> Allègre CJ (2008) *Isotope Geology*; translated by Christopher Sutcliffe. Cambridge University Press, Cambridge, ISBN 978-52186-228-8, 512 pages, \$80

## WORKING WITH MIGMATITES<sup>2</sup>

The Mineralogical Association of Canada is well known for the short course volumes it has published over the past forty years on various geological topics. One of the most recent volumes, *Working with Migmatites*, edited by Edward W. Sawyer and Michael Brown, appeared shortly after the release of *Atlas of Migmatites*, by E. W. Sawyer, a special publication by the same association that beautifully illustrates migmatites from the outcrop to the grain scale. The nearly synchronous publication of these two volumes is not accidental, but simply demonstrates that it was an opportune moment to summarize current knowledge after a period of sustained and fruitful research on crustal melting. Numerous studies have improved our knowledge of melting reactions, melt segregation and transfer, and the role of partially melted rocks in the evolution of orogens. Nonetheless, no synthesis of the current research on migmatites has been published since the outstanding work by K. R. Mehnert in 1968, the volume edited by M. P. Atherton and C. D. Gribble in 1983, and the publication by J. R. Ashworth in 1985.

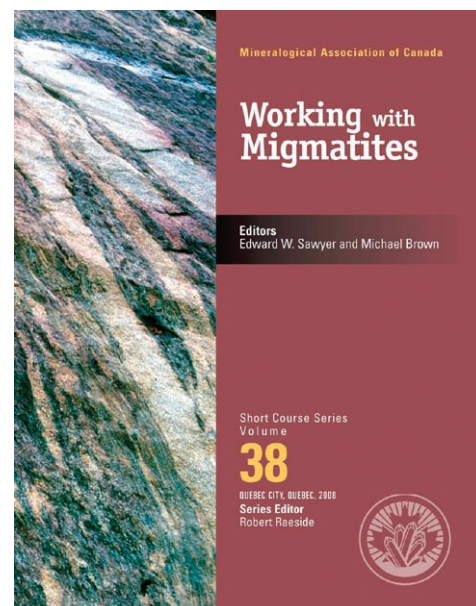
*Working with Migmatites* fills the gap, paying special attention to those who “don’t know where to start” with these fascinating or confusing rocks (depending on one’s viewpoint). The book is easily accessible to anyone having a minimum familiarity with metamorphic and igneous petrology. It addresses three main topics covering different scales of observation: (1) how to study migmatites in the field, (2) what textures tell us about the process of anatexis, and (3) how migmatites are linked to granites and to the evolution of the continental crust.

The first two chapters (by Ed Sawyer), which are echoed in the last chapter, serve essentially as a guide to studying migmatites from sample to map scale. The chapters have two main focuses: how to describe migmatites, and how to collect pertinent geological information in complex-looking rocks. E.W. Sawyer revisits the constituent parts of migmatites and proposes a simplified terminology based on the current view that migmatites are formed by partial melting. This choice offers the definite advantages of giving the terminology overall consistency—thus making it more accessible to a non-specialist—and of proposing divisions that reflect the amount and distribution of the anatectic melts and related residual rocks at the outcrop scale. Gary S. Solar, in the final

chapter, underscores the opportunity offered by the study of migmatite geometries to understand segregation and flow histories and their relationships with plutons. The main point here is that, even though migmatites look like “swirled-up soup,” they are basically structurally coherent rocks, which can provide us with information on the relationships between deformation, migmatite morphology and map-scale melt distribution. An essential point is that, due to the heterogeneity of migmatites, the scale of observation is critically linked to the object of the study: each scale provides its own specific type of information.

The next three chapters deal with phase assemblages and microstructures as indicators, from sample to grain scale, of the presence and distribution of former melt—key points for understanding rock rheology and melt segregation. However, the use of thin sections to reconstruct the anatectic event, and especially the melt distribution pattern at the grain scale in migmatites, is hampered by the fact that most microstructures result from superposition of solidification and subsolidus transformations. This difficulty may be circumvented by studying quenched, natural, melt-bearing enclaves and pyrometamorphic rocks and by modeling partial melting reactions. Bernardo Cesare (chapter 3) shows that partially melted enclaves from “erupted migmatites” allow direct insight into melting reactions, melt composition and melt distribution. An original and interesting section dealing with melt inclusions is worth noting. Marian B. Holness (chapter 4) reviews the microstructural criteria for establishing the distribution of former melt at the grain scale and discusses the effect of textural maturation, melt extraction and cooling rates on the preservation of initial melt geometries. The improvement of our understanding of microstructures in two-phase rocks (melt + solid) from field and experimental studies probably constitutes one of the main advances in the knowledge of melt-bearing rocks over the past twenty years. Of particular importance are the relationships between mineral reactions, nucleation and growth, which exert a first-order control on the production and distribution of melt. Richard W. White (chapter 5) illustrates how petrological modeling of high-variance assemblages offers, notwithstanding some difficulties, many new possibilities. These include providing a predictive framework for localizing melt production pulses in P–T space, showing how melt loss can influence melt production and back reactions, and evaluating the effect of the diffusive process on spatial focusing of reactions and melt production.

The last topic dealt with in this volume (chapter 6) concerns the migmatite–granulite–granite connection, in other words, the differentiation of the continental crust related to the transfer



of magma from the zone of production to the zone of emplacement. Michael Brown introduces the subject with a short presentation of several key issues, such as the fertility of crustal rocks, the source of heat for melting, the volume of melt generated, and the spacing of intrusions. He then reviews the processes involved in the production of magmas in the mid-crust and their transfer to the upper crust, from melting and melt extraction to magma ascent and emplacement. Emphasis is placed on the role of mantle input in crustal melting and on the effect of accessory minerals on melt chemistry, factors that complicate the quest for the source of granites. However, most of the chapter is concerned with the mechanics of melt extraction and emplacement and with the relationship between melt extraction and mesoscale structures in migmatites and granulites, starting with veins as the first drainage pathway focusing magma flow. An interesting comparison is made between numerical and experimental models, with a review of the different modes of flow leading to the development of a dynamic self-organized system. The chapter ends with an illustration of a 3-D interpretation of migmatite–granite relations in orogenic crust.

Overall, reading the seven chapters of this volume may give the impression that migmatites are relatively simple rocks to tackle. However, more than the reality, this reflects the teaching skills of the authors and the illuminating effect of integrating various approaches. I don’t know whether this landmark contribution will encourage a new generation of petrologists to take an interest in migmatites, but I have no doubt that it will be, for some time, the reference for all those interested in crustal melting, for either research or teaching purposes.

**Pierre Barbey**

CRPG-CNRS, Vandoeuvre les Nancy, France

<sup>2</sup> Sawyer EW, Brown M (eds) (2008) *Working with Migmatites*. Mineralogical Association of Canada Short Course Volume 38, ISBN 978-0-92129-446-7, 158 pp, \$40

## 2009

**November 10–12** 3<sup>rd</sup> Russian Conference on Organic Mineralogy with International Participation, Institute of Geology, Syktyvkar, Russia. Details: Olga Kovaleva, e-mail: orgmin@geo.komisc.ru; web page: www.minsoc.ru/confs

**November 11–14** Volcanoes, Landscapes and Cultures, Catania, Italy. E-mail: conf-volcano@etnacatania2009.com; website: www.etnacatania2009.com

**November 15–19** AAPG 2009 International Conference and Exhibition, Rio de Janeiro, Brazil. Web page: www.aapg.org/meetings

**November 16–19** Annual Meeting of the Lunar Exploration Analysis Group, Houston, TX, USA. E-mail: cloud@pi.usra.edu; web page: www.lpi.usra.edu/meetings/leag2009

**November 20–21** 7<sup>th</sup> Swiss Geoscience Meeting, Neuchâtel, Switzerland. [Http://geoscience-meeting.scnatweb.ch](http://geoscience-meeting.scnatweb.ch)

**November 22–26** XII Congreso Geológico Chileno, Santiago, Chile. E-mail: contact@congresogeologico2009.cl; web page: www.congresogeologico2009.cl/public

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

**December 10–12** MSA and GS Short Course Theoretical and Computational Methods in Mineral Physics: Applications to Geophysics, Berkeley, CA, USA. Webpage: www.minsocam.org/MSA/SC/#TACM

**December 14–16** Clay Minerals Group of the Mineralogical Society Annual Meeting, Newcastle, UK. Details: Claire Fialips, e-mail: C.I.M.Fialips@ncl.ac.uk; web page: www.minersoc.org/pages/groups/cm/gcmg.html#fialips

**December 14–18** AGU Fall Meeting, San Francisco, CA, USA. E-mail: meetinginfo@agu.org; web page: www.agu.org/meetings

## 2010

**January 3–9** 2010 Winter Conference on Plasma Spectrochemistry, Sanibel, FL, USA. E-mail: wc2010@chem.umass.edu; web page: [http://icpinformation.org/2010\\_Winter\\_Conference.html](http://icpinformation.org/2010_Winter_Conference.html)

**January 5–7** Sixth International Conference on Environmental, Cultural, Economic and Social Sustainability, University of Cuenca, Ecuador. E-mail: support@onsustainability.com; web page: www.SustainabilityConference.com

**January 10–15** Gordon Research Conference: Origin of Life, Galveston, TX, USA. Web page: www.grc.org/programs.aspx?year=2010&program=origin

**January 15–17** Sixth International Conference on Technology, Knowledge, and Society, Berlin, Germany. Website: www.Technology-Conference.com

**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

**February 4–7** 6<sup>th</sup> International Dyke Conference (IDC-6), Varanasi, India. E-mail: rajeshgeolbhu@gmail.com or 6idc2010@gmail.com; web page: www.igpetbhu.com

**February 8–12** Short Course on Microstructures and Physico-Chemical Properties of Earth and Planetary Materials, Verbania, Italy. Web page: www.socminpet.it/Micro/Program.html

**February 13** Friends of Mineralogy Symposium Gems and Gem Minerals, Tucson, AZ, USA. For info, Julian Gray, e-mail: juliang@tellusmuseum.org; web page: www.friendsofmineralogy.org/symposia.html

**February 14–18** The Minerals, Metals & Materials Society (TMS) 2010 Annual Meeting & Exhibition, Seattle, WA, USA. E-mail: mtgserv@tms.org; web page: www.tms.org/meetings/annual-10/AM10home.aspx

**February 15–19** High-Pressure Experimental Techniques and Applications to the Earth's Interior Short Course, Bayreuth, Germany. E-mail: stefan.keyssner@uni-bayreuth.de; web page: www.bgi.uni-bayreuth.de/ShortCourse2010

**February 21–25** Materials Challenges in Energy 2010, Cocoa Beach, FL, USA. Web page: www.ceramics.org/energy2010/index.aspx

**March 1–5**, 41<sup>st</sup> Lunar and Planetary Science Conference (LPSC 2010), The Woodlands, TX, USA. Web page: www.lpi.usra.edu/meetings/lpsc2010

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

**March 29–April 1** Sixth Institute of Mathematics and Its Applications Conference on Modelling Permeable Rocks with Special Focus on CO<sub>2</sub> Storage, Edinburgh, Scotland. Web page: www.ima.org.uk/Conferences/modelling\_permeable\_rocks.html/index.html

**April 5–9** 2010 Materials Research Society Spring Meeting, San Francisco, CA, USA. Web page: www.mrs.org/s\_mrs/index.asp

**April 6–9** 13<sup>th</sup> Quadrennial IAGOD Symposium 2010, Giant Ore Deposits Down-Under, Adelaide, Australia. Details: Ian Graham, e-mail: i.graham@unsw.edu.au; web page: www.alloccasionsgroup.com/IAGOD2010

**April 18–21** 2010 AAPG Annual Convention and Exhibition, New Orleans, LA, USA. www.aapg.org/meetings

**April 19–23** First International Conference on Mars Sedimentology and Stratigraphy, El Paso, TX, USA. E-mail: taylor@lpi.usra.edu; web page: www.lpi.usra.edu/meetings/marsed2010

**May 2–7** EGU General Assembly, Vienna, Austria. Web page: /www.egu.eu

**May 10–14** GeoCanada 2010, Calgary, AB, Canada. Website: www.geoCanada2010.ca; e-mail: info@geocanada2010.ca

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

**May 20–23** 5<sup>th</sup> Annual International Symposium on Environment, Athens, Greece. Web page: www.atiner.gr/docs/Environment.htm

**May 25–28** Anwendungen der Festkörper NMR Spektroskopie in der mineralogischen und geowissenschaftlichen Forschung, Bochum, Germany. E-mail: Michael.Fechtelkord@ruhr-uni-bochum.de; web page: www.ruhr-uni-bochum.de/dgk-ak12/indexdmgshort.htm

**May 30–June 25** Vatican Observatory Summer School: The Chemistry of the Universe, Castel Gandolfo, Vatican City State. Web page: www.voss2010.va

**May 31–June 4** Cities on Volcanoes 6 – Tenerife 2010, Canary Islands, Spain. Details: Dr. Nemesio M. Pérez, e-mail: nperez@iter.es; web page: www.citiesonvolcanoes6.com/index.html

**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 6–10** PTM 2010: Solid-Solid Phase Transformations in Inorganic Materials, Avignon, France. Web page: www.ffc-asso.fr/PTM2010

**June 6–10** Copper 2010, Hamburg, Germany. E-mail: cu2010 at gdmb.de; web page: www.cu2010.gdmb.de

**June 6–11** 2010 SEA (Spanish Clay Society)–CSSJ (Clays Science Society of Japan)–CMS (Clay Mineral Society) Trilateral Meeting on Clays, Madrid and Seville, Spain. Web page: www.sea-arcillas.es/2010TMC

**June 6–11** Gordon Research Conference: Crystal Engineering, Waterville Valley, NH, USA. Web page: www.grc.org/programs.aspx?year=2010&program=crystaleng

**June 6–11** Gordon Research Conference: Natural Gas Hydrate Systems: Hydrate-Sediment-Fluid Interactions at Pore to Regional Scale, Waterville, ME, USA. Web page: www.grc.org/programs.aspx?year=2010&program=naturalgas

**June 13–18** Gordon Research Conference: Environmental Bioinorganic Chemistry: Elements In The Environment, from Prokaryotes to Planets, Newport, RI, USA. Web page: www.grc.org/programs.aspx?year=2010&program=envbiochem

**June 14–18** Goldschmidt 2010, Knoxville, TN, USA. Web page: www.goldschmidt2010.org

**June 18–29** 11<sup>th</sup> International Platinum Symposium, Sudbury, Canada. Details: e-mail: 11ips@laurentian.ca; web page: www.11IPS.laurentian.ca

**June 21–23** Ceramic Materials Summit 2010, Baltimore, MD, USA. Web page: ceramics.org/ceramic-materials-summit-2010

**June 21–July 2** Summer Schools on Mathematical Crystallography, Nancy, France. E-mail: Mathcryst.Commission@crm2.uhp-nancy.fr; web page: www.crystallography.fr/mathcryst/nancy2010.php

**June 27–30** Ion Partitioning in Low Temperature Aqueous Systems: From Fundamentals to Applications in Climate Proxies and Environmental Geochemistry, Oviedo, Spain. Web page: www.univie.ac.at/Mineralogie/EMU

**June 27–July 2** Gordon Research Conference: Research at High Pressure, Holderness, NH, USA. Web page: www.grc.org/programs.aspx?year=2010&program=highpress

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

**June 28–July 3** Applied Mineralogy Group of the Mineralogical Society: Fieldtrip to Cornwall, UK. Web page: www.minersoc.org/pages/meetings/cornwall-fieldtrip/cornwall-field.html

**July 4–8** First International Conference for Materials on Energy, Karlsruhe, Germany. Web page: events.dechema.de/enmat2010.html

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

**July 10–18** Zeolite '10, the 8<sup>th</sup> International Conference on the Occurrence, Properties, and Utilization of Natural Zeolites, Sofia, Bulgaria. Web page: <http://inza.nmt.edu>

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

**July 26–30** 73<sup>rd</sup> Annual Meeting of the Meteoritical Society, New York, NY USA. Details: Dr. Denton Ebel, e-mail: debel@amnh.org; web page: www.metsoc2010.org

**August 1–6** Gordon Research Conference: Organic Geochemistry, Holderness, NH, USA. Web page: www.grc.org/programs.aspx?year=2010&program=orggeo

**August 8–13** Gordon Research Conference: Rock Deformation, Tilton, NH, USA. Web page: www.grc.org/programs.aspx?year=2010&program=rockdef

**August 8–13** Gordon Research Conference: Water & Aqueous Solutions, Holderness, NH, USA. Web page: www.grc.org/programs.aspx?year=2010&program=water

**August 8–13** American Geophysical Union 2010 Joint Assembly, Iguassu Falls, Brazil. Web page: www.agu.org/meetings

**August 15–18** Uranium 2010, Saskatoon, Saskatchewan, Canada. E-mail: bfarah@cim.org; web page: www.metsoc.org/u2010

**August 15–20** Gordon Research Conference: Biomineralization, New London, NH, USA. Web page: www.grc.org/programs.aspx?year=2010&program=biomin

**August 15–20** Gordon Research Conference: Solid State Studies in Ceramics, New London, NH, USA. Web page: www.grc.org/programs.aspx?year=2010&program=ceramics

**August 16–20** Water–Rock Interaction XIII Symposium, Guanajuato, Mexico. Web page: [wri13.cicese.mx](http://wri13.cicese.mx)

**August 21–27** 20<sup>th</sup> General Meeting of the International Mineralogical Association, Budapest, Hungary. Website: [www.ima2010.hu](http://www.ima2010.hu)

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

**August 27–30** 12<sup>th</sup> European Powder Diffraction Conference (EPDIC12), Darmstadt, Germany. E-mail: [epdic@conventus.de](mailto:epdic@conventus.de); web page: [www.conventus.de/epdic12](http://www.conventus.de/epdic12)

**August 27–30** Commission on Mathematical and Theoretical Crystallography Satellite Conference to the ECM, Darmstadt, Germany. E-mail: [Mathcryst.Commission@crm2.uhp-nancy.fr](mailto:Mathcryst.Commission@crm2.uhp-nancy.fr); web page: [www.crystallography.fr/mathcryst/darmstadt2010.php](http://www.crystallography.fr/mathcryst/darmstadt2010.php)

**August 29–September 2** 26<sup>th</sup> European Crystallographic Meeting (ECM), Darmstadt, Germany. E-mail: [ecm@conventus.de](mailto:ecm@conventus.de); web page: <http://ecm26.ecanews.org>

**September 1–4** International Symposium: Geology of Natural Systems - Geo Iasi 2010, Iasi, Romania. Web page: <http://geology.uaic.ro/symposium/index.php?act=inf>

**September 5–10** 11<sup>th</sup> Congress of the International Association for Engineering Geology and the Environment (IAEG2010), Auckland, New Zealand. E-mail: [iaeg2010@tcc.co.nz](mailto:iaeg2010@tcc.co.nz); web page: [www.iaeg2010.com](http://www.iaeg2010.com)

**September 11–15** The Society for Organic Petrology (TSOP) Annual Meeting, Denver, Colorado, USA. Web page: [www.tsop.org](http://www.tsop.org)

**September 19–22** Jahrestagung der Deutschen Mineralogischen Gesellschaft, Münster, Germany. Web page: [www.dmg-home.de/tagungskalender.html](http://www.dmg-home.de/tagungskalender.html)

**September 28–29** The Mineralogical Society's Annual Meeting: Nuclear Waste Management: Research Challenges for the Future, venue to be decided. Web page: [www.minersoc.org/pages/meetings/nuclear/nuclear.html](http://www.minersoc.org/pages/meetings/nuclear/nuclear.html)

**September 30–October 9** Society for Economic Geology 2010 Conference, Keystone, CO, USA. Web page: [www.seg2010.org](http://www.seg2010.org)

**October 4–8** Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences, GFZ Potsdam, Germany. Web page: [www.dmg-home.de/kursprogramm.html](http://www.dmg-home.de/kursprogramm.html)

**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](http://www.ceramics.org/meetings/index.aspx)

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

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

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

**November 29–December 3** 2010 Materials Research Society Fall Meeting, Boston, MA, USA. Web page: [www.mrs.org/s\\_mrs/index.asp](http://www.mrs.org/s_mrs/index.asp)

**December 2010** MSA and GS Short Course: Diffusion in Minerals and Melts. Details forthcoming. Web page: [www.minsocam.org/MSA/SC](http://www.minsocam.org/MSA/SC)

## 2011

**January 23–28** 35<sup>th</sup> International Conference and Exposition on Advanced Ceramics and Composites, Daytona Beach, FL, USA. Web page: [www.ceramics.org/meetings/index.aspx](http://www.ceramics.org/meetings/index.aspx)

**March 27–31** 241<sup>st</sup> American Chemical Society (ACS) National Meeting & Exposition, Anaheim, CA, USA. Web page: [www.acs.org](http://www.acs.org)

**April 10–13** 2011 AAPG Annual Convention & Exhibition, Houston, TX, USA

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

**May 25–27** Geological Association of Canada /Mineralogical Association of Canada Annual Meeting, Ottawa, Canada. Web page: [www.gacmacottawa2011.ca](http://www.gacmacottawa2011.ca)

**June 20** The Mineralogical Society's Annual Meeting: Frontiers in Environmental Geoscience, University of Aberystwyth, Wales, UK. Details: N. Pearce, e-mail: [njp@aber.ac.uk](mailto:njp@aber.ac.uk); web page: [www.minersoc.org/pages/meetings/frontiers-2011/frontiers-2011.html](http://www.minersoc.org/pages/meetings/frontiers-2011/frontiers-2011.html)

**June 26–July 1** Euroclay 2011, Antalya, Turkey. Web page: [www.aiepa.org/downloads/EUROCLAY-2011%20flyer.pdf](http://www.aiepa.org/downloads/EUROCLAY-2011%20flyer.pdf)

**June 27–July 8** XXV<sup>th</sup> IUGG General Assembly, Melbourne, Australia. E-mail: [ray.cas@sci.monash.edu.au](mailto:ray.cas@sci.monash.edu.au); website: [www.iugg2011.com](http://www.iugg2011.com)

**July 10–20** EMU School – Bulk and Surface Structures of Layer Silicates and Oxides: Theoretical Aspects and Applications, Rome, Italy. Web page: [www.univie.ac.at/Mineralogie/EMU](http://www.univie.ac.at/Mineralogie/EMU)

**July 24–29** 10<sup>th</sup> International Conference on Mercury as a Global Pollutant, Halifax, Nova Scotia, Canada. Web page: [www.mercury2011.org](http://www.mercury2011.org)

**August 10<sup>th</sup>** ICAM International Congress for Applied Mineralogy, Strasbourg, France. Details: Maarten A.T.M. Broekmans, e-mail: [maarten.broekmans@ngu.no](mailto:maarten.broekmans@ngu.no); website: [www.icam2011.org](http://www.icam2011.org)

**August 7<sup>th</sup>** Annual Meeting of the Meteoritical Society, Greenwich, England. Details: Gretchen Benedix, e-mail: [greb@nhm.ac.uk](mailto:greb@nhm.ac.uk)

**August** MSA and GS Short Course: Applied Mineralogy of Cement and Concrete, Trondheim, Norway. Details: Maarten A.T.M. Broekmans, e-mail: [maarten.broekmans@ngu.no](mailto:maarten.broekmans@ngu.no); web page: [www.minsocam.org/MSA/SC](http://www.minsocam.org/MSA/SC)

**August 22–26** 25<sup>th</sup> International Applied Geochemistry Symposium (IAGS 2011), Rovaniemi, Finland. Web page: [www.iags2011.fi](http://www.iags2011.fi)

**August 22–29** XXII Congress of the International Union of Crystallography, Madrid. Web page: [www.ecanews.org/iucrs.php](http://www.ecanews.org/iucrs.php). and [www.iucr2011madrid.es](http://www.iucr2011madrid.es)

**August 28–September 1** 242<sup>nd</sup> American Chemical Society (ACS) National Meeting & Exposition, Denver, CO, USA. Web page: [www.acs.org](http://www.acs.org)

**September 4–7** 7<sup>th</sup> European Conference on Mineralogy and Spectroscopy (ECMS 2011), Potsdam, Germany. E-mail: [mkoch@gfz-potsdam.de](mailto:mkoch@gfz-potsdam.de)

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

**October 16–20** Materials Science & Technology 2011 Conference and Exhibition – MS&T '10 combined with the ACerS 113<sup>th</sup> Annual Meeting, Columbus, OH, USA. Details forthcoming

## 2012

**March 25–29** 243<sup>rd</sup> American Chemical Society (ACS) National Meeting & Exposition, San Diego, CA, USA. Web page: [www.acs.org](http://www.acs.org)

**May 28–30** Geological Association of Canada and Mineralogical Association of Canada Annual Meeting, St. John's, NL. Web page: [www.gac.ca/activities](http://www.gac.ca/activities)

**July 15–19** International Congress on Ceramics (ICC4), Chicago, IL, USA. Details forthcoming

**July 19–28** American Crystallographic Association (ACA) Annual Meeting, Boston, MA, USA. Web page: [www.AmerCrystalAssn.org](http://www.AmerCrystalAssn.org)

**August** Annual meeting of the Meteoritical Society, Cairns, Queensland, Australia. Details: Trevor Ireland; web page: [www.meteoriticalsociety.org](http://www.meteoriticalsociety.org)

**August 34<sup>th</sup>** International Geological Congress, Brisbane, Australia. Details forthcoming

**September 9–13** 244<sup>th</sup> American Chemical Society (ACS) National Meeting & Exposition, Philadelphia, PA, USA. Web page: [www.acs.org](http://www.acs.org)

**September 17–20** Geoanalysis 2012, Búzios, Brazil. Web page: [www.ige.unicamp.br/geoanalysis2012](http://www.ige.unicamp.br/geoanalysis2012)

**November 4–7** Geological Society of America (GSA) Annual Meeting, Charlotte, NC, USA. Web page: [www.geosociety.org/meetings](http://www.geosociety.org/meetings)

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/](mailto:Andrea.Koziol@notes.udayton.edu/).

# 20<sup>th</sup> IMA GENERAL MEETING

21–27 AUGUST 2010, BUDAPEST, HUNGARY



Rediscover a traditional region for the mineral sciences: you are invited by 10 central and southeastern European countries to the largest world conference on the mineral sciences, the 20<sup>th</sup> General Meeting of the International Mineralogical Association!

The scientific programme covers the fundamental topics of mineralogy, geochemistry, petrology and ore deposits, as well as applications in Earth and planetary science, materials science, and archaeological, environmental and life sciences. A large conference on a human scale.

The 30 pre-, mid- and post-conference field trips will open a window to the geology, history and culture of the central and southeastern part of the European Union. Detailed field trip descriptions are available on the conference homepage. Take advantage of very reasonable registration and accommodation costs in a safe region. A good conference in the holiday season? Why not combine the two?!

Visit us at [www.ima2010.hu](http://www.ima2010.hu).





## ARCHIBALD LIVERSIDGE (1847–1927) PIONEER GOLD GEOLOGIST AND GEOCHEMIST

The crystal cluster featured on the cover of this issue of *Elements* is informally named the “Liversidge nugget” after Archibald Liversidge, FRS, an important early protagonist for science in Australia (FIG. 1). A woodcut of the nugget (FIG. 2) appeared on the front cover and in Figure 1 of the 1888 edition of his *The Minerals of New South Wales*. He is pictured holding the nugget in his portrait (FIG. 1). He regarded this “beautiful group of crystals [as] perhaps one of the finest in existence”, describing them as “for the most part imperfect octahedral and elongated cubes; some have imperfectly developed faces of the rhombic dodecahedron, joined end to end in an arborescent form.” The nugget had been acquired by the Royal Museum of Science and Art in Edinburgh (now the National Museum of Scotland), but its provenance is uncertain, though probably New South Wales.

Archibald Liversidge was born in London and educated at the Royal School of Mines and at the University of Cambridge. In 1872, he was appointed Reader in Geology at the University of Sydney and two years later was promoted to Professor in Geology and Mineralogy. He was instrumental in the establishment not only of geology but also the teaching of all sciences at the university, countering the argument of the Principal and Classics Professor, Charles Badham, who dismissed the need for teaching science (chemistry, physics and geology) as they “are ornaments of the memory which may be acquired at any time of life”! He was made Dean of the Faculty of Science when it was established in 1879, a position he held until his retirement and return to England in 1907. In 1882, Liversidge was elected a Fellow of the Royal Society of London. He was one of the first to encourage women to enroll in university courses and was prominent in popularizing science through public lectures. He helped establish the Industrial, Technological and Sanitary Museum, Sydney, now the Powerhouse Museum, and revived the ailing Royal Society of New South Wales, of which he was president three times. He played a major role in the establishment of



FIGURE 1 – Archibald Liversidge, 1909. Portrait by John Collier (1850–1934). Oil on canvas (detail). Commissioned by the University of Sydney. ©ART COLLECTION, UNIVERSITY OF SYDNEY

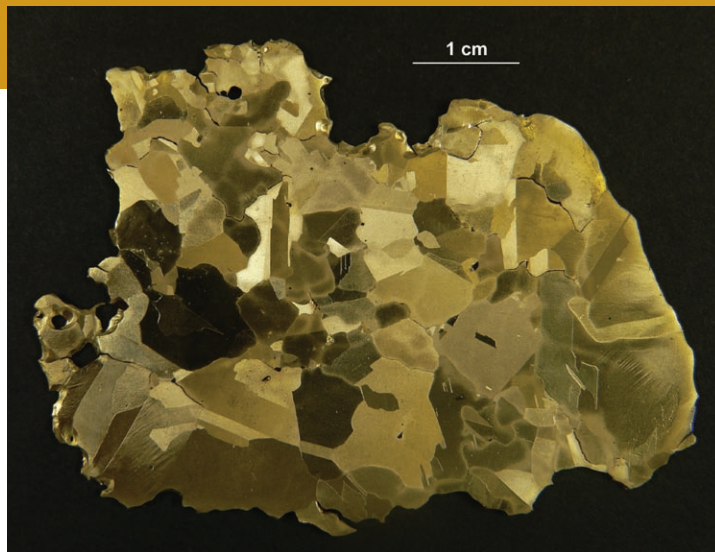


FIGURE 3 – Polished section of Liversidge's nugget from Coolgardie. COURTESY NATURAL HISTORY MUSEUM, LONDON (PHOTOGRAPH CRM BUTT, 2007)



FIGURE 2 – The Liversidge nugget, gold foil-stamped woodcut image from the front cover of *The Minerals of New South Wales*, Liversidge 1888

the Australasian Association for the Advancement of Science (later ANZAAS), which held its first congress in 1888, being its honorary secretary until 1909 and president in 1898. Liversidge was in some ways a typical Victorian polymath and published on a wide range of subjects, including analytical chemistry, agriculture, astronomy and anthropology, but his principal contributions were in mineralogy, chemistry and geology.

Liversidge's tenure at the University of Sydney corresponded with years when gold prospecting and mining were of major economic and cultural importance in Australia. He devoted considerable effort to the study of gold and, in particular, entered the debate concerning the origin of nuggets – were they formed in situ in placers or are they only detrital? He studied the composition and crystallography of numerous nuggets, many now archived in the Natural History

Museum, London (FIG. 3), noting their silver content and their polycrystalline structure. He also conducted many experiments on the mobility of gold relevant to the weathering environment, finding that gold was soluble in aqueous sulphide, organic and acid halide solutions and re-precipitated, *inter alia*, as octahedral crystals and hexagonal plates. He also noted that gold may be removed from solution and suspension by “fungoid growths”. He made one of the first estimates of the abundance of gold in sea water and found that gold is concentrated in some seaweeds. Nevertheless, despite showing the undoubted mobility of gold under Earth-surface conditions, Liversidge concluded that the majority of, if not all, nuggets are hypogene in origin. Over the next 100 years, his papers and conclusions were largely forgotten or ignored, and the perception that most nuggets are supergene returned to haunt another generation. Liversidge's work is echoed by three articles in this issue of *Elements* (Hough et al., Williams-Jones et al., Southam et al.), recognizing his status as a pioneer in the field.

**Acknowledgments:** Biographical information was obtained from Professor Roy McLeod and from published sources.

**Charles Butt**

CSIRO Exploration and Mining, Bentley, Australia

# BAYLOR UNIVERSITY

## STAFF POSITION IN MASS SPECTROMETRY

The Department of Geology at Baylor University is pleased to announce a search for a new staff position for hire beginning on or before January 1, 2010 as Instrumentation Specialist in Stable Isotope Mass Spectrometry. The Department currently consists of 15 geoscientists, including geologists, geophysicists and geographers (please see the Department website at: [www.baylor.edu/Geology/](http://www.baylor.edu/Geology/) for further information).

### • Instrumentation Specialist Position

The Department of Geology at Baylor University invites applications for a staff position managing the new stable isotope mass spectrometry laboratory at Baylor University, beginning as early as January 2010. A Ph.D. in Geology or Geochemistry is required at the time of appointment. The Department seeks an individual with a strong background in applications of stable isotope mass spectrometry to geological systems, who will manage a new laboratory containing a Thermo-Electron Delta V Advantage isotope ratio mass spectrometer with the following peripherals: Gas Bench II, combustion EA, TCEA, and a dual inlet. The instrumentation specialist is expected to support ongoing research programs that include geology, biology and environmental sciences. The position carries appointment as 90% staff and 10% research scientist, and we especially encourage collaboration with Geology faculty and students currently engaged in research focusing on terrestrial paleoclimatology. The successful candidate should also be capable of managing use of the instrument by faculty and students, be able to instruct new users, and conduct routine maintenance and repairs, assisted by a Baylor Sciences Building instrumentation Specialist. Baylor University also supports an annual service contract for the instrument.

Send letter of application, including statement of research interests, curriculum vitae, transcripts, and the names and contact information for three references to: Dr. Stephen I. Dworkin, Instrumentation Specialist Search Committee Chair, Department of Geology, Baylor University, One Bear Place #97354, Waco, TX 76798-7354 (Tel: 254-710-2361; [Steve\\_Dworkin@baylor.edu](mailto:Steve_Dworkin@baylor.edu)). The review of applications will begin October 1, 2009 and applications will be accepted until the position is filled. To ensure full consideration, application must be completed by December 1, 2009. Baylor is a Baptist university affiliated with the Baptist General Convention of Texas. As an Affirmative Action/Equal Opportunity employer, Baylor encourages minorities, women, veterans and persons with disabilities to apply.

## TENURE-TRACK FACULTY POSITION

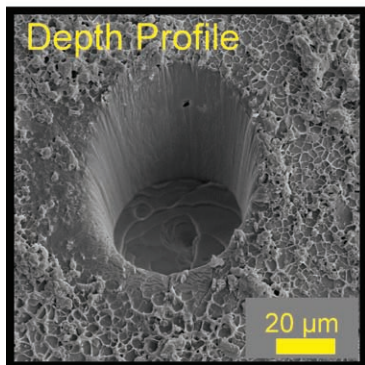
The Department of Geology at Baylor University is pleased to announce a search for a new faculty position for hire beginning in August of 2010 in Organic Geochemistry or Paleoclimatology. The Department currently consists of 15 geoscientists, including geologists, geophysicists and geographers (please see the Department website at: [www.baylor.edu/Geology/](http://www.baylor.edu/Geology/) for further information).

### • Organic Geochemistry/ Paleoclimatology

The Department of Geology at Baylor University invites applications for a tenure-track Assistant or Associate Professor in the general areas of organic geochemistry and/or paleoclimatology, beginning August 2010. A Ph.D. in Geology, Geochemistry or related field is required at the time of appointment. The Geology Department seeks an individual with a strong research agenda that possibly includes compound-specific organic geochemistry, paleoclimate modeling, or palynology applied to field and laboratory studies of terrestrial climate records archived within fluvial (river and floodplain), eolian (loess and sand dune), lacustrine (lake), and coastal systems. The individual must be able to communicate and collaborate with a subset of six Geology faculty members that are currently engaged in studies in the general area of paleoclimatology, and to carry out a vigorous externally funded research program that involves both undergraduate and graduate students. A strong commitment to excellence in teaching is essential, with both undergraduate and graduate courses that might include organic geochemistry, paleoclimate modeling or palynology, as well as other courses in his/her area of specialization. Research space for terrestrial paleoclimatology is available in the five-year-old, 500,000 ft<sup>2</sup> "state-of-the-art" Baylor Sciences Building, and startup funds associated with this position are highly competitive. Construction of a new stable isotope laboratory was completed in the spring of 2009, which currently includes a new 600 ft<sup>2</sup> laboratory containing a Thermo-Electron Delta V Advantage isotope ratio mass spectrometer with the following peripherals: Gas Bench II, combustion EA, TCEA, and a dual inlet, supporting ongoing research programs that include geology, biology and environmental sciences. The laboratory will be managed by a dedicated instrumentation specialist.

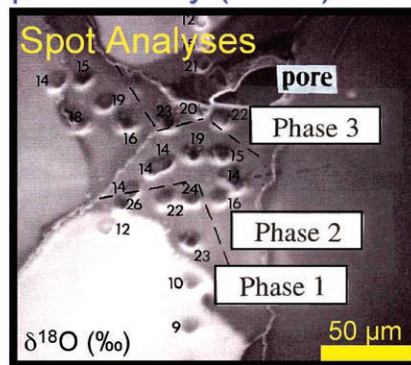
Send letter of application, including statement of teaching and research interests, curriculum vitae, transcripts, and the names and contact information for three references to: Dr. Steven G. Driese, Paleoclimatology Search Committee Chair, Department of Geology, Baylor University, One Bear Place #97354, Waco, TX 76798-7354 (Tel: 254-710-2361; applications sent by e-mail to: [Steven\\_Driese@baylor.edu](mailto:Steven_Driese@baylor.edu)). The review of applications will begin December 1, 2009 and applications will be accepted until the position is filled. To ensure full consideration, application must be completed by December 15, 2009. Baylor is a Baptist university affiliated with the Baptist General Convention of Texas. As an Affirmative Action/Equal Opportunity employer, Baylor encourages minorities, women, veterans and persons with disabilities to apply.

## FREE WORKSHOP on Secondary Ion Mass Spectrometry (SIMS)



Arizona State University  
January 6 – 8, 2010  
Tempe, Arizona, USA

**For information/registration**  
Contact: [Lynda.Williams@asu.edu](mailto:Lynda.Williams@asu.edu)  
by Dec. 12, 2009 (Limit 25)  
Limited travel grants available  
Get hands-on experience with  
Prof. Richard L. Hervig  
<http://sims.asu.edu>



### ADVERTISERS IN THIS ISSUE

Activation Laboratories (ActLabs)	276
Australian Scientific Instruments (ASI)	273
Earth Magazine	287
Excalibur	276
International Center for Diffraction Data (ICDD)	280
GeoScienceWorld	275
Goldschmidt 2010	314
ioGlobal	Inside back cover
RockWare	Back cover
Savillex	Inside front cover
SIMS workshop (Arizona State University)	336
Smart Elements	276
Society of Economic Geologists	280
Springer	296
Thermo	271

- ▶ You have a position to fill at your department or lab? Advertise it in *Elements* or on the *Elements* website.
- ▶ Looking for a job?

Check our website  
[www.elementmagazine.org](http://www.elementmagazine.org)

### PARTING QUOTE

THE MOST INCOMPREHENSIBLE THING ABOUT  
THE WORLD IS THAT IT IS COMPREHENSIBLE

ALBERT EINSTEIN

### JOB POSTINGS

Baylor University	336
See <a href="http://www.elementsmagazine.org/jobpostings">www.elementsmagazine.org/jobpostings</a>	

## Targeted Solutions from the Global Leaders in Applied Geochemistry

### Geochemical data compilations and appraisals

We can compile attributed geochemical data sets (in any format), merge and level multi generation data and assess the quality and usefulness of historical company/government data sets, be it on a project or continental scale. Visit our website today to download example geochemical maps:

[www.ioglobal.net](http://www.ioglobal.net)

### Target Generation

Robust target generation requires integration of multiple data sets including assay data, hyperspectral data, regolith mapping, radiometrics, geology, etc. Using industry leading exploratory data handling and analysis techniques, ioGeochemistry will extract the maximum information from your data to aid in target generation, ground selection and drill-site prioritisation.

### Technical Geochemical Project Management

ioGeochemistry can manage your geochemical programs including planning, analysis, data management, QAQC, interpretation, imaging, target identification and costs. Whether you are sending your samples to a lab for assay or you are using a portable XRF unit, whether you are in Africa sampling termite mounds or India sampling village wells, ioGeochemistry has the experience to maximise the effectiveness of your program.

### Geometallurgy

ioGeochemistry can utilise multi-element assay data to identify mineralogical controls related to key metallurgical processing parameters. ioGeochemistry can also assist with phase-specific assaying, where extraction of commodity elements is highly dependent on controlling mineral phases.

### QAQC Auditing Services

From laboratories to on-site sampling procedures, ioGeochemistry can audit your QAQC practices and QC sample data to ensure compliance with internal and external requirements such as NI43-101. Use of the ioQA™ Reporter facilitates rapid report production so that QC performance may be documented and evaluated.



### Quality Control Program Design and Monitoring

We can design and monitor programs to ensure sampling, sub-sampling, sample preparation, CRM manufacture and use, and the quality and appropriateness of assay and laboratory procedures meet your company and stock exchange reporting requirements.

### Geochemical Innovation and Knowledge Transfer

ioGeochemistry maintains strong links with research groups around the world developing innovative new geochemical approaches. ioGeochemistry can act as your conduit to these researchers, transferring research concepts into robust exploration techniques. A key activity in this space is the design and execution of fit for purpose orientation studies.

### Training

ioGeochemistry training courses are designed to be generic, however they can be tailored to a geological region, commodity or specific problem. For maximum benefit from the courses, ioGeochemistry incorporates the client's own data-sets to ensure that value-added products and worked through examples are taken back into the client's work environment. ioGeochemistry can also train our client's field staff in QAQC compliant field practices.

Contact us to discuss your project today: [info@ioglobal.net](mailto:info@ioglobal.net)

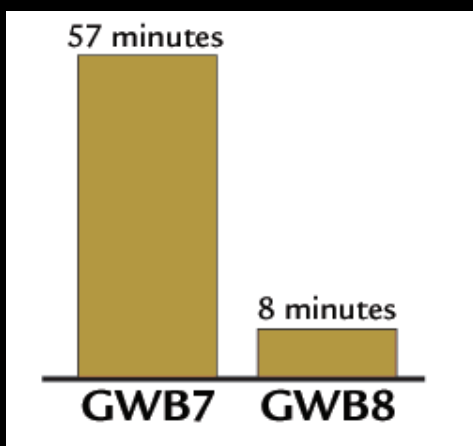


Perth • Melbourne • Brisbane • Vancouver

Head Office: 369 Newcastle Street Northbridge WA 6003 AUSTRALIA T: +61 8 6555 6510 F: +61 8 6314 6600

[info@ioglobal.net](mailto:info@ioglobal.net)

# Built for Speed



Simulation time for 1600-node 2-D reactive transport model tracking surface complexation of heavy metals. Run on twin 2 GHz quad-core Xeon processors under Windows XP. GWB7 is single-threaded and GWB8 ran on 8 parallel threads.

## GWB Professional 8

Now with multi-threading/parallel processing for multi-core computers.

**\$7,999**  
**(\$2,599 upgrade)**



## The Geochemist's Workbench®

It's fast. **VERY** fast.



# RockWare®

Since 1983

303.278.3534 • 800.775.6745

[gwb.com](http://gwb.com)