Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology

Rare Earth Elements

ANTON R. CHAKHMOURADIAN and FRANCES WALL, Guest Editors
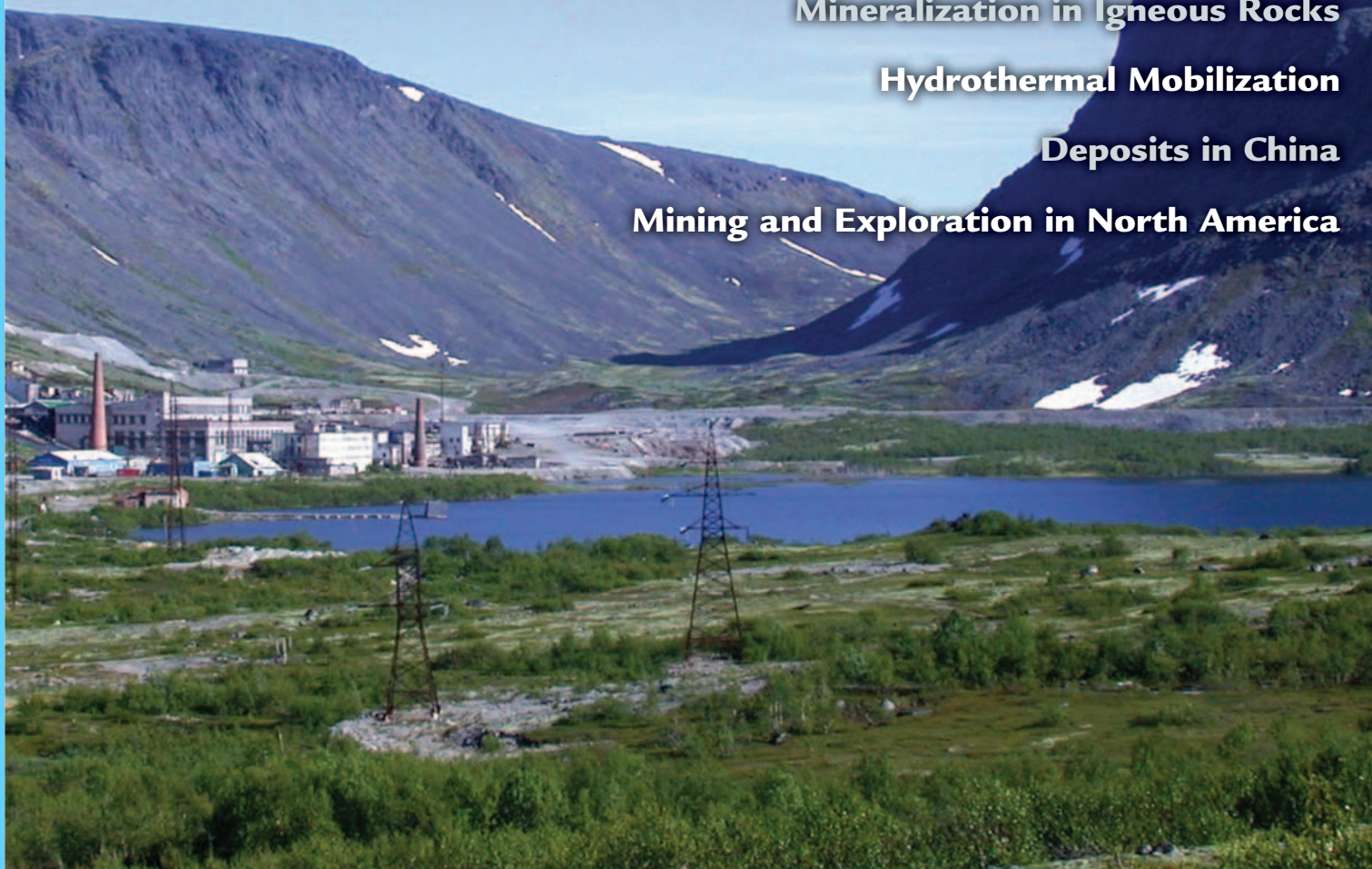
Minerals, Mines, and Magnets

Dynamics in the Global Market

Mineralization in Igneous Rocks

Hydrothermal Mobilization

Deposits in China

Mining and Exploration in North America

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Volume 8, Number 5 • October 2012

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The Mineralogical Society of America is composed of individuals interested in mineralogy, crystallography, petrology, and geochemistry. Founded in 1919, the Society promotes, through education and research, the understanding and application of mineralogy by industry, universities, government, and the public. Membership benefits include special subscription rates for *American Mineralogist* as well as other journals, a 25% discount on Reviews in Mineralogy & Geochemistry series and Monographs, *Elements*, reduced registration fees for MSA meetings and short courses, and participation in a society that supports the many facets of mineralogy.

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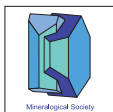
The Mineralogical Society of Great Britain and Ireland is an international society for all those working in the mineral sciences. The Society aims to advance the knowledge of the science of mineralogy and its application to other subjects, including crystallography, geochemistry, petrology, environmental science and economic geology. The Society furthers its aims through scientific meetings and the publication of scientific journals, books and monographs. The Society publishes *Mineralogical Magazine* and *Clay Minerals*. Students receive the first year of membership free of charge. All members receive *Elements*.

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

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The Clay Minerals Society (CMS) began as the Clay Minerals Committee of the US National Academy of Sciences – National Research Council in 1952. In 1962, the CMS was incorporated with the primary purpose of stimulating research and disseminating information relating to all aspects of clay science and technology. The CMS holds annual meetings, workshops, and field trips, and publishes *Clays and Clay Minerals* an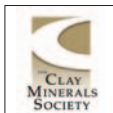d the CMS Workshop Lectures series. Membership benefits include reduced registration fees to the annual meeting, discounts on the CMS Workshop Lectures, and *Elements*.

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The Geochemical Society (GS) is an international organization founded in 1955 for students and scientists involved in the practice, study, and teaching of geochemistry. Our programs include co-hosting the annual Goldschmidt Conference™, editorial oversight of *Geochimica et Cosmochimica Acta* (*GCA*), supporting geochemical symposia through our Meeting Assistance Program, and supporting student development through our Student Travel Grant Program. GS annually recognizes excellence in geochemistry through its medals, lectures, and awards. Members receive a subscription to *Elements*, special member rates for *GCA* and *G-cubed*, and publication and conference discounts.

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

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

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The Société Française de Minéralogie et de Cristallographie, the French Mineralogy and Crystallography Society, was founded on March 21, 1878. The purpose of the Society is to promote mineralogy and crystallography. Membership benefits include the "bulletin de liaison" (in French), the *European Journal of Mineralogy*, *Elements*, and reduced registration fees for SFMC meetings.

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

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

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

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

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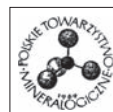
The Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), founded in 1969, draws together professionals and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The Society promotes links between mineralogical science and education and technology through annual conferences, field trips, invited lectures, and publishing. Membership benefits include subscriptions to *Mineralogia* and *Elements*.

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

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The Swiss Society of Mineralogy and Petrology was founded in 1924 by professionals from academia and industry and amateurs to promote knowledge in the fields of mineralogy, petrology, and geochemistry and to disseminate it to the scientific and public communities. The Society coorganizes the annual Swiss Geoscience Meeting and publishes the *Swiss Journal of Geosciences* jointly with the national geological and paleontological societies.

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The Meteoritical Society is an international organization founded in 1933 for scientists, collectors, and educators to advance the study of meteorites and other extraterrestrial materials and their parent asteroids, comets, and planets. Members receive our journal, *Meteoritics & Planetary Science*, reduced rates for *Geochimica et Cosmochimica Acta*, which we cosponsor, the *Meteoritical Bulletin*, and *Elements*. We organize annual meetings, workshops, and field trips, and support young planetary scientists worldwide. Through our medals and awards, we recognize excellence in meteoritics and allied fields.

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The Japan Association of Mineralogical Sciences (JAMS) was established in 2007 by merging the Mineralogical Society of Japan, founded in 1955, and the Japanese Association of Mineralogists, Petrologists, and Economic Geologists, established in 1928. JAMS covers the wide field of mineral sciences, geochemistry, and petrology. Membership benefits include receiving the *Journal of Mineralogical and Petrological Sciences* (*JMPS*), the *Ganseki-Koubutsukagaku* (*GKK*), and *Elements*.

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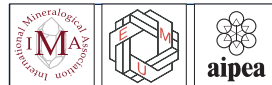
Affiliated Societies
The International Mineralogical Association, the European Mineralogical Union, and the International Association for the Study of Clays are affiliated societies of *Elements*. The affiliated status is reserved for those organizations that serve as an "umbrella" for other groups in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

TALES, TALES…

Georges Calas

The formation of ore deposits often appears to result from a "magic chain" made from a coherent succession of geological, geochemical, mineralogical, etc. processes that concentrate metallic elements. The efficiency of such element concentration is really extraordinary, as illustrated by elements such as gold, which is concentrated from the ppb level to nuggets weighing 70 kg. As a consequence, humankind has used for millennia these mineral resources, which have been central to technological progress since the Stone Age. And it is still the case. Rare earth elements do not take full advantage of this "magic chain." The most abundant rare earth elements are indeed similar in crustal abundance to transition elements such as chromium or nickel. Despite this, ore deposits of the former are much rarer than those of the latter. Scandium, a transition element usually classified with the rare earths due to its geochemical properties, forms fewer than 10 rare or very rare and unique minerals. A geochemical invariant during weathering processes, exploited only as a by-product, scandium is a typical element not involved in the "magic chain."

Rare earths minerals do not usually attract attention and are often put in a modest place in museum mineral collections. They are also sacrificed in mineralogy classes to leave time for more noble or "important" minerals. This reminds me of Andersen's *Ugly Duckling*, a tale beloved around the world that shows an apparent transformation for the better. Indeed, despite rare earths being of prime importance in geochemistry, rare earth minerals remained, in the past, of minor importance for most mineralogists. However, recent events have put the spotlight on them, placing the rare earth resource in the forefront of present-day concerns. Modern societies are anxious to obtain this resource needed for many technological developments: once extracted, rare earths are desirable, although, in the past, they never attracted such attention and fame. The *Ugly Duckling* is now a noble swan.

In most countries, politicians and the media frequently question Earth science departments and organizations about rare earths, as our disciplines have always been involved in the exploration, mining and mineral processing of metallic resources. They are eager to hear from us about

the future evolution of the resource of strategic metals; the development of applications has been much faster than that of knowledge about how the resource might be increased to match this expansion. The names of the rare earth elements, such as ytterbium and europium, have become familiar to the public, because they are frequently heard on the radio, TV, and Internet. There is an emerging collective fear that we will run out of this resource. This is perfectly depicted in the cartoon reproduced below and published in December 2010 by the French satirical magazine *Le Canard Enchaîné*.

The first issue of *Elements*, guest edited by Robert Bodnar, was on the theme "Fluids in Planetary Systems." Interestingly, the first article of the issue, written by Steve Kesler—and thus the first contributed article published in *Elements*—was entitled "Ore-Forming Fluids." Since, *Elements* has published several articles dealing with ore-forming processes. However, the present issue on rare earth minerals and deposits is devoted only to ore deposits. It perfectly illustrates how recent laboratory and field data provide clues to understanding the conditions of formation of rare earth deposits.

The "rare earth crisis" that occurred in 2010 underlined the importance of teaching ore deposits in the Earth science curriculum. This realization is affecting the positions and funding opportunities in many Earth science departments. For instance, Europe is creating a network on minerals resources, ERA-Min (www.era-min-eu.org), in order to strengthen a community that received less attention in the past. And new expertise will arrive in the field.

The *Beauty* was sleeping: it has been said that, during the emergence of China's rare earth supremacy, most Western countries did not realize the perilous situation they now find themselves in, as if they were sleepwalking. The *Sleeping Beauty* is awaking. It is our hope that the present revival of interest in ore deposits in general and in rare earth deposits in particular, integrating sustainable development concepts and an active environmental conscience in the exploitation and utilization of mineral resources, will continue to help us find answers about the workings of the "magic chain."

– What? A gram of dysprosium! You've gone overboard!
– We wanted to offer you lanthanum, but we didn't find any!
(Cabu, *Le Canard Enchaîné*, 15/12/2010 – © Le Canard Enchaîné)

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THIS ISSUE

This issue devoted to the rare earth elements is timely: these elements have become indispensable not only for producing the technological gadgets our society is consuming in exponentially increasing quantities, but also for meeting future energy challenges, while the resource is limited. The six articles assembled by Guest Editors Anton Chakhmouradian and Frances Wall therefore focus on the resource aspect, from the economic context to the distribution of deposits worldwide. I learned a lot working on this issue. I was surprised by the caption of Figure 1A in the Hatch paper stating that direct-drive wind turbines contain approximately 150–200 kg of Nd and 20–30 kg of Dy per megawatt of generating capacity. That seemed a lot, so I queried the author. His answer: "Now you know why everyone's making a big fuss about finding future supplies." Extracting rare earths from minerals is complex, and in many instances deposits will not become economic to exploit until we find new ways to extract these elements. Also I now understand why China is almost a monopoly producer.

Are thematic articles in *Elements* review articles? The question was debated at the last meeting of the Executive Committee. One former guest editor argued that he had instructed all authors in his issue to provide a snapshot of their field, and perhaps this is an appropriate way to describe *Elements*' thematic articles. Occasionally, original research results *are* published in *Elements*. This is what A. Williams-Jones answered to my query regarding Figure 5 in his manuscript: "The modeling was done for the purpose of this manuscript. I wanted to also add some original science. The discovery that fluorine could not be an agent of REE transport was also made during the preparation of this manuscript and led to a separate manuscript that is now in review."

For the first three years of *Elements*, Peter Heaney entertained and enlightened us with his beautifully crafted Triple Point articles. I was delighted that he accepted my invitation to write a 12th column. So all the Heaney fans out there, read about his sabbatical project and enjoy!

Elements Course Packs at MinPubs.org

It is now possible to take content from different issues of *Elements* and combine it with material from the *American Mineralogist* and the Reviews in Mineralogy and Geochemistry series, then assemble the articles in specially priced course packs that students can purchase on their own. The course packs can be provided in either paper or electronic form. It is also possible to purchase single *Elements* articles (from volume 1, number 1 to the present). Check www.minpubs.org (see also page 389).

If you wish to have a course pack assembled for your class, obtain an entire Reviews volume as a single electronic file, or if you are ordering 5 or more articles and would like a coupon code for a 25% discount on your order, or have other questions, contact jaspeer@minsocam.org.

Pierrette Tremblay, Managing Editor

ONLINE ACCESS

If you receive a print copy of *Elements*, you are also entitled to the electronic version, from volume 1, number 1—go to www.elementsmagazine.org/archives.htm.

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If your institution subscribes to GeoScienceWorld, we encourage you to access *Elements* at www.elements.geoscienceworld.org.

ERRATUM

In the article "Granitic Pegmatites: Scientific Wonders and Economic Bonanzas", published in the August issue (8: 257–261), the second sentence of the final paragraph on page 257 should read

A model now associated with Cameron et al. (1949) …

The word "David" was inadvertently added during the first round of corrections to the proofs, and the error was not picked up by the managing editor nor the authors. We apologize for any misunderstanding. This error has been corrected in the electronic version of the article.

# CELESTINE FOR STATE MINERAL! A SABBATICAL PROJECT

Peter Heaney

Fifteen years ago, a faculty colleague contemplated his upcoming sabbatical—and decided that he would vanish. He informed few people of his destination and made sure that every technological intrusion met with polite rebuff. To all but his closest associates, he simply disappeared one day and reappeared a year later—project completed.

The efficiency of his model was so absolute I decided to replicate it for my own sabbatical—with one exception. Can we shut off e-mail for an entire year and emerge professionally intact? In 1997 it was possible, but today? Reluctantly, I opened the gates to that one Trojan horse, but no other. I secured a corner office within the Department of Mineral Sciences at the US National Museum, whose entry demands multiple stations of identity confirmation. I pointed my chair away from the office door to dissuade the very friendly people in the department from being very friendly to me. Waves of e-mails washed across my computer screen without eliciting a response. Days passed without one ring from my office phone.

I was luxuriating in my isolation when one January morning a message appeared that raised the hairs on the back of my neck.
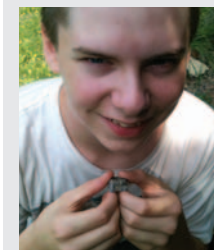
Royce holding a piece of celestine

Mr. Heaney,

I am a 6th grade student at Commonwealth Connections Academy. I did a science paper on what would I like to have as a state mineral, and I was excited to find that there was none already listed. So, I am on a journey to get celestine named as the Pennsylvania State Mineral. I am currently in the "lobbying" step. Would you be interested in helping me?

Royce Black, Geologist-in-Training

As Paul McCartney's lyrics to "Yesterday" played through my mind, I frantically began to consider my various avenues of plausible deniability. I could pretend that the e-mail was lost in my spam filter. It happens all the time! But Royce, whom I would come to admire as an indomitable force of nature, had blanketed the Pennsylvania mineralogical community with his request, and many of his recipients redirected their messages to me with copies to him. Rats! I could of course claim to be busy with more important matters. What, after all, are the public obligations of a professor whose governor has cut by 20% the state's contribution to the university budget?

In the end, it was "Geologist-in-Training"—the sign-off that would grace all of Royce's future e-mails to me—that I could not resist. Maybe, with the right encouragement at the right time, Royce would develop into a future Roebling medalist. Or, at least, maybe he will figure out how agates form. So I accepted my fate and began to turn two questions over in my mind: What claim does celestine hold on the title of Pennsylvania State Mineral? And what is the purpose of state objects anyway?

A few days' worth of Internet sleuthing settled the first question persuasively. MinDat.org cites a 1791 pamphlet in which the existence of a new "kind of barite" from central Pennsylvania is first recorded. Authored by Andreas Gotthelf Schütz in High German (with the Gothic type used in the masthead of the *New York Times*), the 16-page article is freely downloadable from the digital archive at the Bavarian State Library. Gerhard Franz of the Technical University of Berlin provided an annotated translation for us, and the hunt was on. We now know that Schütz (1771–1807) was a German naturalist trained at the famed Mining

Academy of Freiberg, and that he explored the Pennsylvania wilds in the late 1780s, collecting rocks and fossils for scientific study in his home country. Martin Klaproth (discoverer of Ti, Zr, and U) published the composition as strontium sulfate in 1797; a year later, Abraham Gottlob Werner gave celestine a formal physical description and its name, based on its lovely sky-blue color.

Does that legitimate the designation of celestine as the Pennsylvania State Mineral? You bet! Only about 300 different minerals are found in the Keystone State. Of those, eight represent the first discoveries worldwide of a new mineral species: celestine, sauconite, lansfordite, nesquehonite, downeyite, matulaite, laphamite, and eastonite. Given the scientific royalty associated with the first characterization of celestine, its historical precedence, and its beautiful blue color, wouldn't you choose it as state mineral?

Though they sometimes seem to exist only to provide answers for *Trivial Pursuit* and *Jeopardy*, state objects fundamentally are symbols of celebration—of a region's heritage, its natural resources, and its economic foundation. Surprisingly, only 20 of the 50 US states officially have designated state minerals (excluding state rocks and gems; see TABLE 1). Some states have opted for glitter (gold: Alaska, California, North Carolina); some favor stolid ores (galena: Missouri, Wisconsin); and other states are a bit quirky (bowenite of Rhode Island is a "jade-like" variety of serpentine).

TABLE 1 OFFICIAL US STATE MINERALS

US State	Mineral	US State	Mineral
Alabama	Hematite	Massachusetts	Babingtonite
Alaska	Gold	Missouri	Galena
Arkansas	Quartz	Nevada	Silver
California	Gold	New Hampshire	Beryl
Colorado	Rhodochrosite	North Carolina	Gold
Connecticut	Almandine garnet	Rhode Island	Bowenite
Delaware	Sillimanite	South Dakota	Rose quartz
Georgia	Staurolite	Utah	Copper
Illinois	Fluorite	Vermont	Talc
Kentucky	Coal	Wisconsin	Galena

Celestine is economically less prominent than some state minerals, but it was an actor in a major scientific drama that now is largely lost to history. Thanks to the likes of Lavoisier, Priestley, Davy, and Scheele, techniques in chemical analysis blossomed in the late 1700s. At that time, a budding natural philosopher could establish an international reputation through the discovery of a new element; such breakthroughs were accorded the public and professional acclaim that greets advances in fundamental particle research today. Unknown minerals were targeted as the most likely repositories of new elements, and naturalists like Schütz traveled to exotic localities across the world in hopes of finding them. Déodat de Dolomieu (of dolomite fame) had in fact reported celestine occurrences in Sicily in 1781, but he misinterpreted the mineral as barium sulfate—today's barite. Klaproth, a true genius of analytic chemistry, inferred that Schütz's material was insufficiently dense to be *barium* sulfate. Fortunately, strontium was discovered as a new element in the early 1790s (from a carbonate in Strontian, Scotland). It took a few years—but only a few—for Klaproth to identify celestine as the Sr-rich analogue of barite.

Unlike my former colleague, I cannot claim to have completed this sabbatical project. Royce has hand-delivered hundreds of letters to Pennsylvania state legislators, of whom a few have expressed strong support for his proposal. A hearing in the state capitol, however, has been postponed from the summer to an indefinite date in the fall, and Royce may be learning more than he wanted to know about the legislative process. Nevertheless, those assisting his mission have gained an unexpected appreciation for the impact that state minerals can wield in educating the next generation of Earth scientists. Maybe the 30 missing states will join the charge.

Peter J. Heaney
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ALLISON MACFARLANE TO HEAD THE NUCLEAR REGULATORY COMMISSION

Allison M. Macfarlane, designated by President Obama as chair of the Nuclear Regulatory Commission, was sworn in on July 9 as the 15th person to lead this agency charged with regulating the civilian use of nuclear materials. She will serve a term ending June 30, 2013. "The agency faces multiple challenges. I look forward to working collegially with my fellow commissioners and the excellent, dedicated staff at the NRC to address these issues," said Macfarlane, an expert in nuclear waste issues.

Allison Macfarlane holds a doctorate in geology from the Massachusetts Institute of Technology. Most recently she was an associate professor of environmental science and policy at George Mason University in Fairfax, Virginia. She has held fellowships at Radcliffe College, MIT, and Stanford and Harvard universities. From 1998 to 2000 she was a Social Science Research Fellow–MacArthur Foundation Fellow in International Peace and Security. She has served on National Academy of Sciences panels on nuclear energy and nuclear weapons issues.

From 2010 to 2012 she served on the Blue Ribbon Commission on America's Nuclear Future, created by the Obama Administration to make recommendations about a national strategy for dealing with the nation's high-level nuclear waste. Her research has focused on environmental policy and international security issues associated with nuclear energy, especially the back-end of the nuclear fuel cycle. In 2006 MIT Press published a book she coedited with Rod Ewing, *Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste*, which explored technical issues at the proposed waste-disposal facility at Yucca Mountain, Nevada.

Allison Macfarlane is the third woman to serve as chair of the commission, the 33rd member to serve on the panel, and the only individual with a background in geology to serve on the commission.

GORDON BROWN HONORED BY AGI

The Medal in Memory of Ian Campbell for Superlative Service to the Geosciences is the American Geosciences Institute's highest award, given in recognition of singular performance and contributions to the profession of geology. The 2012 Campbell medalist is Gordon E. Brown Jr., Dorrell William Kirby Professor of Earth Sciences at the Department of Geological and Environmental Sciences of Stanford University. Dr. Brown's stellar career as a professor and researcher in mineralogy and geochemistry is well known and amply justifies the award.

Dr. Brown received his BS in chemistry and geology from Millsaps College (1965) and his MS (1968) and PhD (1970) in mineralogy and crystallography from Virginia Polytechnic Institute & State University. He has served as president of the Mineralogical Society of America (1995–1996) and is a fellow of the Geological Society of America (1997), the Geochemical Society (1999), and the American Association for the Advancement of Science (2000). He has also received the Mineralogical Association of Canada's Hawley Medal (2007) and the Mineralogical Society of America's Roebling Medal (2007).

He has made major contributions to a broad range of fundamental and applied problems, at the interface between Earth science, environmental science, physics, and chemistry. His public service is reflected by the positions he has held and the more than 30 committees in which he has participated at various levels, including occupying key positions advising and providing research management for NSF- and DOE-supported centers. He is also known for the many students he has advised and the extensive effort he has made to get students involved in mineralogy. His research has been concerned with major societal issues, such as the remediation of polluted or contaminated sites, the sequestration of heavy metal/metalloid and organic pollutants/contaminants in ecosystems, the impact of certain minerals or the elements they contain (or release) on human health, and the disposal of waste (industrial, nuclear, etc.). He also helped popularize large user facilities and has contributed to increasing the visibility of the geosciences.

HONORARY DOCTORATES FOR DONALD DINGWELL

The University of Alberta awarded a DSc to Donald Bruce Dingwell on 6 June in Edmonton for his contributions to experimental geosciences, volcanology, and excellence in science. He delivered a convocation address—at the university where he obtained his PhD in 1984—entitled "Preparing for the Unexpected."

University College London also awarded a DSc to Dingwell on 5 September for his major achievements in experimental Earth sciences. Dean Catlow cited his important role in the scientific landscape of Europe and the world.

Renowned for establishing the experimental investigation of melts and magma as a vital component of Earth sciences, Don Dingwell holds the Chair of Mineralogy and Petrology at the Ludwig Maximilian University of Munich. He is serving as the secretary general of the European Research Council, a major position in the international granting system.

THE STARDUST COMET MISSION: STUDYING SEDIMENTS FROM THE SOLAR SYSTEM'S FROZEN ATTIC

Comets are ice-bearing bodies that eject solids and volatiles when they are sufficiently close to the Sun. The surviving inventory of these bodies is only a fraction of a vast population of ice-bearing planetesimals that once filled the cold regions of the early Solar System. The NASA Stardust mission collected thousands of solid particles during a close flyby of a 4.5 km diameter active comet and returned them to Earth in 2006. These samples of comet 81P/Wild 2 provided the first sample-based information on proven cometary materials. Detailed laboratory studies of these samples have provided "ground truth" insight into the origin of comets that could not have been obtained by either remote sensing or in situ methods.

Wild 2 is currently on an orbit that ranges from Jupiter to Mars but, like other Jupiter-family comets, it is believed to have spent nearly all of Solar System history beyond Neptune. Its depression-covered surface (FIG. 1) was probably shaped by sublimation, a process that may have eroded hundreds of meters off its original surface. Over 20 dust jets were observed during the flyby, and this ejection process allowed samples to be collected on a low-cost mission without landing. Dust particles impacted into low-density silica aerogel and aluminum foil at a speed of 6.1 km s^{-1} (FIG. 2). The aerogel capture process worked wonderfully for solids larger than a micron but it often degraded or melted smaller particles. Particles collected by Stardust are believed to be a sampling of solids that were at the edge of the Solar System at the time of its formation. They were packed in ice and do not appear to show evidence of parent-body thermal metamorphic alteration. The compositional range of adjacent olivine grains in dust particles and the preservation of moderate Cr abundances in olivine, along with other indicators used to gauge alteration levels in meteorites, imply that the comet is no more internally processed than the parent bodies of the most primitive meteorites.

The mission was named Stardust in part because it was commonly believed that the rocky portion of comets would be composed of presolar interstellar grains, the primary carriers of heavy elements involved in star and planet formation. This belief was partly based on the idea that comets formed in distant isolation from the inner regions of the Solar System where meteorite parent bodies formed and nebular processes destroyed nearly all presolar grains. The major surprise of the Stardust mission has been that all of the micron and larger grains that have been analyzed have isotopic compositions consistent with formation in the Solar System. Five submicron isotopically anomalous (inorganic) presolar grains have been identified, but their abundance is small. Due to capture degradation of submicron grains, the absolute abundance of presolar grains in the comet is difficult to determine, but the current best estimate is on the order of 1000 ppm (Leitner et al. 2010, 2012), a value that is small but higher than the ~100 ppm found in presolar grain–rich meteorites and micrometeorites and also higher than the typical ~375 ppm abundance in 10 μm interplanetary dust particles (IDPs). These findings imply that preserved isotopically anomalous interstellar grains are not a major component of this comet, and the fact that such grains do not dominate any IDP, which are likely of cometary origin, suggests that the early Solar System did not contain any refugia that preserved presolar solids with distinctive isotopic compositions. It is likely that the combination of nebular environments and migration processes destroyed nearly all of the initial solid materials from which the Solar System formed. These silicate-destroying processes should also have destroyed presolar organics. This finding casts doubt on the long-held notion that interstellar molecules played a significant role in making habitable planets in our Solar System and perhaps in any planetary system.
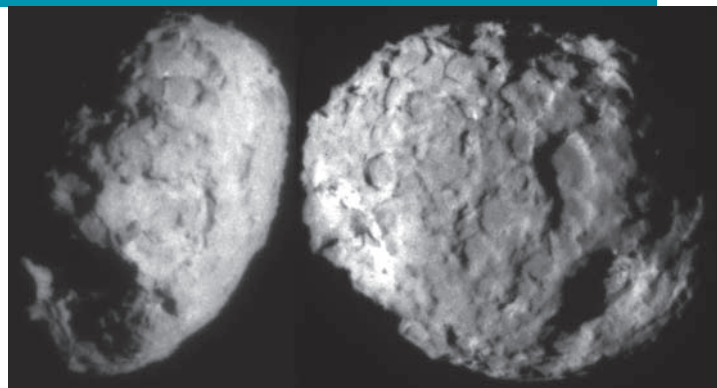
FIGURE 1 Orthogonal views of the surface of comet Wild 2. The complex surface of this and other imaged comets significantly differs from the impact-gardened surfaces of asteroids. IMAGE: NASA (HTTP://STARDUST.JPL.NASA.GOV/PHOTO/COMETWILD2.HTML)

A stunning outcome of the sample studies is that the majority of 1–100 μm grains in Wild 2 are familiar materials that are found in primitive meteorites. The ice and organics in the comet may have formed in cold regions, but the solids—most of the comet's mass—were formed by the same high-temperature nebular processes that made the bulk of solids that accreted to form meteorite parent bodies. If we think of asteroids and comets as collections of cosmic sediments, respectively accumulated in the inner and outer Solar System, it is astonishing that they contain similar rocky materials.

The most common large grains appear to be chondrule fragments, common meteoritic components that were pulse heated to 1700–2050 K (Hewins and Radomsky 1990) as freely orbiting nebular components. Wild 2 contains examples of a wide range of chondrule types, including Fe-rich, Fe-poor, and Al-rich. As seen in meteorite chondrules, ^{16}O-rich relict olivine grains have been found in these igneous objects that
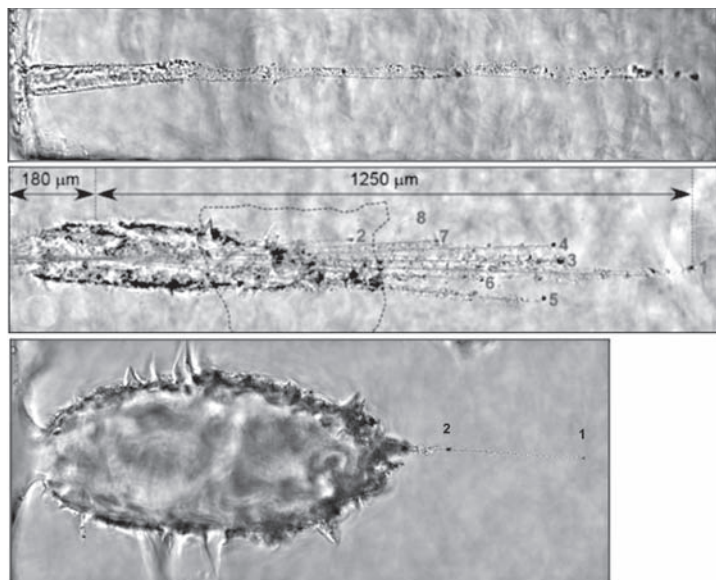
FIGURE 2 These three aerogel impact tracks illustrate dramatic structural differences between impacting Wild 2 particles, which traveled left to right in the images. The particle that made the top track (290 μm long; T58) was solid and did not experience fragmentation, while the center track (T113; Nakamura-Messenger et al. 2011) was made by a weakly bonded aggregate of solid particles that were each several microns in size. Most of the mass that produced the bottom track (1.4 mm long; T141) was composed of either very fine or thermally unstable components that stopped in the upper track portion, producing the large hollow, bulb lined with melted and compressed silica aerogel. The deepest penetrating particle, labeled 1, is a sulfide, and particle 2 is a CAI. A 0.4 μm, isotopically presolar SiC grain was found on the bulb wall. IMAGES: NASA (HTTP://STARDUST.JPL.NASA.GOV/PHOTO/COMETWILD2.HTM)

is that the comet's rocky components are inner Solar System materials that were transported to the edge of the solar nebula where they could accumulate low-temperature ice and organics. Supporting this notion is the observation that the comet appears to contain a wider diversity of materials than are found in specific chondrite groups. Chondrite groups have distinctive properties because much of their mass was made from local materials that in some cases have restricted ranges of properties, such as oxygen isotope composition and minor element composition of olivine. It appears that a major difference between asteroids and Wild 2 is that asteroids were largely constructed from locally made materials whose properties give meteorite groups distinctive characteristics, while comets like Wild 2 contain a broader mix of nebular materials.

The simplest interpretation of this finding is that comets represent the Solar System's frozen attic and that their rocky materials were transported and mixed over distances of tens of astronomical units. The abundance of high-temperature nebular solids at the edge of the Solar System is strong evidence for massive outward transport of inner Solar System materials by a variety of nebular processes (Shu et al. 2001; Bockelée-Morvan et al. 2002; Cuzzi et al. 2008; Ciesla 2010; Boss 2012). An alternative view is that the high-temperature components originated in the outer Solar System, perhaps inside transient Jupiter-mass objects that formed in the outer Solar System but were disrupted (Bridges et al. 2012).

The studies of Wild 2 samples have shown that the rocky fraction of this comet is a fabulous mix of fine- and coarse-grained materials that are remarkably similar to high-temperature components found in asteroidal meteorites. The samples do not show evidence for the appreciable thermal or aqueous alteration that has modified essentially all meteorite samples. The diverse set of minerals and rocks in the comet are inconsistent with astronomical predictions. If Wild 2 solids were nearly all derived from inner portions of the protosolar nebula, it is perhaps likely that the rocky contents of other comets have a similar origin. Comets differ in volatile contents but their rocky materials may all be the same. If this is correct, then it is also possible that Pluto, its similar-size neighbor Eris, Neptune's moon Triton, and perhaps tens of Earth masses of comet bodies that were ejected from the early Solar System were made from these materials. With this in mind, future comet sample returns, more ambitious than Stardust, could provide profoundly improved insight into the nature of the nebular dust and small rocks that played important roles in the formation of the Solar System.

More information about the Wild 2 samples can be found in the April 2012 *Meteoritics and Planetary Science* issue, which resulted from a meeting that was held at Timber Cove, California, and was dedicated to Frank Stadermann, a Stardust pioneer who, along with his wife Christine Floss, discovered the first presolar grain in a comet.

D. E. Brownlee, University of Washington

clearly predate the final melting of their host (Nakamura et al. 2008). In addition to chondrules, Wild 2 also contains calcium–aluminum-rich inclusion (CAI) fragments (Simon et al. 2008). CAIs, which are rich in rare earth elements, are the oldest solids formed in the nebula, and they are distinguished by their ^{16}O-rich compositions (similar to that of the Sun) and a host of refractory phases that condense above 1400 K. Although the origin of chondrules and CAIs is uncertain, it is clear that they formed at extremely high temperature. The Wild 2 samples include a rich diversity of anhydrous silicates, sulfides, and metal phases (FIG. 3). A remarkable finding is the presence of LIME (low-iron, high-manganese) forsterites that have ^{16}O-rich compositions and are likely to be condensates.

Even though the collected sample was limited in mass and largely made of grains smaller than 100 μm, it contains a remarkable mix of high-temperature nebular materials. The most direct conclusion from this

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Meet the Authors

Anton R. Chakhmouradian earned his master's (1993) and doctoral (1997) degrees in geology and mineralogy at St. Petersburg State University, Russia. Following postdoctoral studies at Lakehead University, he accepted an academic position at the University of Manitoba, Canada, where he has been teaching since 2001. His research is focused on the petrology, mineralogy, and geochemistry of carbonatites, alkaline rocks, and associated rare-metal deposits. He is an associate editor of *American Mineralogist* and *Mineralogy & Petrology*, and a recipient of the Young Scientist Award of the Mineralogical Association of Canada (2005) and the W. W. Hutchison Medal of the Geological Association of Canada (2011).

Gareth P. Hatch is a Founding Principal of Technology Metals Research and president of Innovation Metals Corp. His work and analysis cover the entire rare earth supply chain, from mineral exploration through to end-use applications. A two-time graduate of the University of Birmingham, UK, he has a BEng with Honours in materials science and technology, and a PhD in metallurgy and materials, focused on rare earth magnet alloys. He is based in the suburbs of Chicago, Illinois. For several years Gareth was director of technology at Dexter Magnetic Technologies. He holds five US patents on a variety of magnetic devices.

Jindrich Kynicky completed his graduate degree in mineralogy, petrology, and geochemistry at Masaryk University (Brno, Czech Republic) in 2003. For his doctoral degree (2006), he chose to work on carbonatites and associated rare earth deposits of central East Asia. In 2007, he was appointed associate professor of geology at Mendel University in Brno. During the past decade, he has organized and led many geological expeditions to Mongolia, China, and Siberia. In addition to his primary area of expertise in the evolution of carbonatites, alkaline rocks, and associated critical-metal deposits, he has contributed to environmental and soil science research.

Anthony N. Mariano and Anthony Mariano Jr. are mineral exploration geologists. They work as a team and specialize in the geology and mineralogy of rare elements on a world level. They have worked extensively in the field and in the laboratory for more than 50 years and in more than 50 countries. Their emphasis is on the economic evaluation and ranking of REE deposits and mineral processing evaluation in close collaboration with mineral processing specialists. The mineral marianoite was named after Anthony N. Mariano in recognition of his lifetime of contributions to mineralogy and mineral exploration.
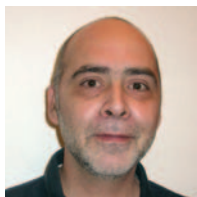
Artashes A. Migdisov is a research scientist at McGill University, Canada, where he runs the laboratory in experimental hydrothermal geochemistry. He received his PhD in geology and mineralogy in 1995 from Moscow State University, Russia, and then held a postdoctoral fellowship at McGill University. 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 gas mixtures. His current research activities are in the fields of the behavior of the REEs in hydrothermal systems and the vapor transport of metals.

Iain M. Samson is currently professor and head of the Department of Earth and Environmental Sciences at the University of Windsor and past president of the Mineralogical Association of Canada. He obtained BSc and PhD degrees from the University of Strathclyde in 1979 and 1983, respectively, and then spent three years as a postdoc at McGill University. His research interests are focused on the geochemistry of hydrothermal systems and the genesis of mineral deposits, and he has published on Irish-type Pb–Zn deposits; intrusion-related W–Sn–Mo, Cu, PGE–Cu, and rare-element deposits; diagenetic systems; and fluid inclusions.

Martin P. Smith is a principal lecturer in geology at the University of Brighton, UK, where he has worked since 2001. He gained his PhD from the University of Leeds in 1995 and carried out postdoctoral research there and at the Natural History Museum, London. His research interests include hydrothermal geochemistry, the origin of ore deposits, and hydrogeology. Alongside his work on the hydrothermal behavior of the REEs, he has worked on the genesis of IOCG mineralization and the impacts of unsaturated zone flow on groundwater chemistry.

Frances Wall is an associate professor of applied mineralogy and head of Camborne School of Mines, Exeter University, and scientific associate at the Natural History Museum, London. After a geochemistry degree at Queen Mary College London, she joined the Mineralogy Department at the Natural History Museum, London, earning a PhD from London University. She has a long-standing interest in carbonatites and ore deposits, editing books on rare earth minerals and carbonatites in 1996 and 2004. Frances moved to Camborne School of Mines in 2007 and now also works on responsible-mining topics. She is an officer of the International Mineralogical Association and a member of the Mineralogical Society of Great Britain and Ireland.

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, and then emigrated to Canada where he earned a PhD at Queen's University and worked for several years as an exploration geologist. His research, which combines field-based and experimental approaches, focuses on the behavior of metals in crustal fluids and the genesis of hydrothermal ore deposits. He is an associate editor of several journals and a fellow of the Royal Society of Canada.

Cheng Xu obtained his doctoral degree in 2004 from the Chinese Academy of Sciences. Between 2003 and 2010, he worked at the Institute of Geochemistry (Chinese Academy of Sciences). In 2010, he was appointed professor at the School of Earth and Space Sciences, Peking University. His primary areas of interest are igneous geochemistry, the petrogenesis of carbonatite–alkalic rock complexes, and the implications of magma evolution for metallogeny. His current research focuses on carbonatitic magmatism in East and Central Asia and associated rare-metal (REE, Nb, Mo) deposits.

Anatoly N. Zaitsev is a professor of mineralogy at St. Petersburg State University, Russia, and scientific associate at the Natural History Museum, London, UK. He received a diploma in geology, geochemistry, and mineralogy from Leningrad State University, and candidate of sciences (PhD) and doctor of sciences (habilitation) degrees from St. Petersburg State University. His past research focused on the mineralogy, geochemistry, and petrology of carbonatites and alkaline rocks from the Kola Peninsula, Russia. Recently, he has worked on volcanic rocks from the Gregory rift and Crater Highlands in Tanzania, including active carbonatite volcanism at Oldoinyo Lengai. He has been awarded the prestigious Alexander von Humboldt, Marie Curie, and Fulbright fellowships and the A. P. Karpinsky Medal.

Rare Earth Elements: Minerals, Mines, Magnets (and More)

Anton R. Chakhmouradian[1] and Frances Wall[2]

Exploration geologists searching for rare earth minerals in drill core at the Lofdal carbonatite complex, Namibia

The rare earth elements (REEs) are all around us, not only in nature but in our everyday lives. They are in every car, computer, smartphone, energy-efficient fluorescent lamp, and color TV, as well as in lasers, lenses, ceramics, and more. Scientific applications of these elements range from tracing the provenance of magmas and sediments to studying body structures with magnetic resonance imaging. The realization that we need rare earths for so many applications, but that their supply is effectively restricted to several mining districts in China, has brought these elements to the headlines and created a critical-metals agenda. Here we introduce the REE family: their properties, minerals, practical uses, and deposits. Potential sources of these elements are diverse and abundant if we can overcome the technical challenges of rare earth mining and extraction in an environmentally and socially responsible way.

KEYWORDS: rare earth elements, lanthanides, yttrium, rare earth deposits, critical metals

MEET THE RARE EARTHS

The "Great Element Hunt"

When Carl Axel Arrhenius (1757–1824), a thirty-year-old Swedish artillery officer and an amateur mineralogist, stumbled across heavy black masses of an unknown mineral on one of his rockhounding trips to the Ytterby feldspar mine on the tiny island of Resarö, just northeast of Stockholm (FIG. 1), little did he know that his discovery would keep chemists perplexed and busy for decades to come (APPENDIX 1 – SUPPLEMENTARY MATERIAL AVAILABLE ONLINE AT WWW.ELEMENTSMAGAZINE.ORG). It would take the Finnish chemist Johan Gadolin (1760–1852) only a few years to recognize that the new mineral, subsequently named *gadolinite* in his honor, contained a new "earth" and publish the results of his analytical experiments (Gadolin 1794). But it would take another 34 years before the first *rare earth element* (*yttrium*) was isolated from Gadolin's "earth" in a relatively pure form (Wöhler 1828) and eight more decades before the last terrestrially occurring member of the rare earth family (*lutetium*) was identified (Urbain 1908). The fact that the Ytterby material studied by Gadolin contains several thousand (!) parts per million of lutetium (i.e. about two orders of magnitude higher than the content of gallium in sphalerite, where the latter element was discovered around the same time) attests to the challenges facing nineteenth-century analysts attempting to separate individual rare earths from one another.

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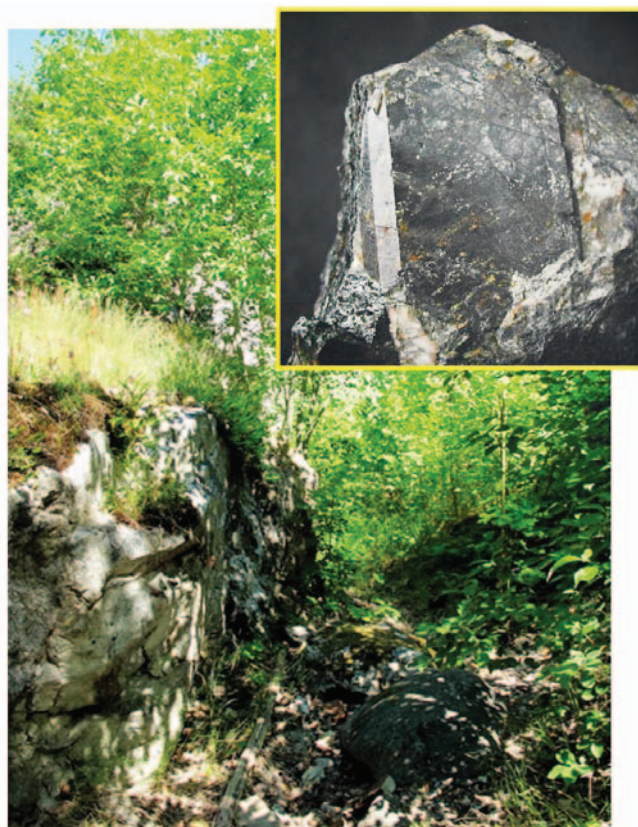
FIGURE 1 Entrance to the former Ytterby feldspar quarry in southern Sweden. This site is immortalized in the names of four rare earth elements discovered here: *yttrium*, *terbium*, *erbium* and *ytterbium*. PHOTO: COURTESY OF CLINT COX. The inset shows a 4 cm long crystal of gadolinite-(Y) from Ytterby, probably not unlike the one used by Gadolin to obtain a mixture of Y_2O_3 and oxides of associated rare earths. In addition to this mineral, Ytterby is the type locality for yttrotantalite (Y–Ta oxide) and tengerite (Y carbonate). INSET PHOTO: COURTESY OF BERTIL OTTER

The "Great Element Hunt" of the 1800s produced more rare earths than could be accommodated in the periodic table, but the majority of these "elements," sporting fanciful names like junonium and dämonium, were not supported by adequate analytical evidence and soon faded into obscurity (Spencer 1919). The final chapter in this great scientific quest was opened by Bohuslav Brauner, who not only found the right place for the rare earths in the periodic table but also predicted that an element was missing between neodymium and samarium (Brauner 1902), effectively launching the "Great Promethium Hunt" of the early 1900s. Today, the rare earth elements (REEs), also referred to as *terrae rarae* in some academic circles, are recognized as the largest group of elements showing a coherent behavior in Earth systems, so much so in fact that, in some geological materials, the concentration of any one of these elements can be estimated from those of other REEs by interpolation or extrapolation. Although this coherence makes the REEs an invaluable tracer of geochemical, biochemical, and planetary processes, it is ultimately responsible for their notorious inseparability, their high price—often disproportionate to their abundance (Fig. 2A)—and various methodological and instrumental difficulties involved in their detection, analysis, and commercial extraction. Although coherent and "inseparable," REEs actually do fractionate in many Earth processes, providing further insight into the physical and chemical parameters of the process.

FIGURE 2   Rare earth elements in a nutshell: (**A**) prices (from HEFA Rare Earth: www.baotou-rareearth.com), (**B**) abundances in the Earth's primitive mantle (McDonough and Sun 1995) and continental crust (Rudnick and Gao 2003), (**C**) effective ionic radii (in angstroms) of trivalent cations (purple diamonds), Ce^{4+}, and Eu^{2+}, all in an eight-fold coordination (Shannon 1976). Shown from left to right are: **Sc**andium, **Y**ttrium, **La**nthanum, **Ce**rium, **Pr**aseodymium, **N**eo**d**ymium, **P**ro**m**ethium, **S**a**m**arium, **Eu**ropium, **Gad**olinium, **T**er**b**ium, **Dy**sprosium, **Ho**lmium, **Er**bium, **T**huliu**m**, **Y**tter**b**ium, and **Lu**tetium. Selected data for silver (Ag) and tin (Sn) are given for comparison Z = atomic number

Rare Earth Family: What's in the Name?

According to recommendations by the International Union of Pure and Applied Chemistry (IUPAC), the rare earth family consists of 17 transition metals forming Group 3 (also referred to as IIIA in the old IUPAC classification) of the periodic table and comprising *scandium* (Sc), *yttrium* (Y), and the *lanthanide* (also called *lanthanoid*) *series* (La to Lu; Fig. 2). Earth scientists, however, have traditionally set Sc aside, grouping either Y plus the lanthanides or just the latter into the REE family. The reason for the exclusion of Sc is its small ionic radius (Fig. 2C); this element readily substitutes for Mg, Fe^{2+}, Zr, and Sn. This geochemical "mimicry" explains why the bulk of recent Sc production has come from large-scale mining operations in such diverse resource types as hydrothermal Sn–W ores (China, Russia, USA), igneous ilmenite and uraniferous alkali-metasomatites (Ukraine), bauxite (Russia), and biogenic phosphate deposits (Kazakhstan). A maverick among the REEs, Sc clearly deserves a thematic issue of *Elements* all its own. *Promethium* (Pm) does not form stable isotopes; out of the five radioactive nuclides with a reasonably long half-life, only ^{147}Pm is generated in natural fission processes in "appreciable" quantity, albeit still amounting to less than 600 g in the entire crust (Belli et al. 2007)! Such infinitesimal concentration levels make Pm virtually undetectable in, and impractical to extract from, geological materials.

The low–atomic number lanthanides (La–Eu) are conventionally termed *light REE*s (LREEs), whereas their heavier counterparts (Gd–Lu) are referred to as *heavy REE*s (HREEs). Yttrium is grouped with the HREEs because its ionic radius is nearly identical to that of Ho. These terms are somewhat arbitrary: some authors classify Eu as heavy, and the name *mid-REE* is sometimes applied to intermediate members of the series (e.g. Hatch 2012 this issue).

REEs IN NATURE

How Rare Are Rare Earths?

Experts delight in educating their audience that the term *rare earth elements* is a misnomer because these elements are not at all rare in the Earth's crust. Cerium and Y, for example, are the 25th and 30th most abundant elements by mass, respectively, far exceeding in concentration Sn, Hg, Mo, and all precious metals (Rudnick and Gao 2003). However, the crustal abundances of many other REEs, including those of great practical value, are exceedingly small, especially if recalculated to atomic concentrations. Atoms of terbium (Tb) and thulium (Tm), for instance, are two and five times (respectively) *less* abundant in the continental crust than Mo and two orders of magnitude rarer than Cu. It is also noteworthy that in the Solar System, most lanthanides with an odd atomic number are actually *lower* in abundance than 94% of the remaining elements, including Au, Pt, and other precious metals (Anders and Grevesse 1989), proving once and for good that rare earths *are* rare—certainly, on the cosmic scale!

Rare Earth Distribution Patterns

The distribution of REEs in terrestrial and extraterrestrial materials follows a characteristic "jigsaw" pattern (Fig. 2B), which reflects the greater abundance of even-numbered elements relative to their odd-numbered neighbors. This principle, known as the Oddo-Harkins rule, is rooted in the different binding energies and, hence, relative stabilities of nuclei with paired and unpaired nucleons. "Jigsaw" patterns are difficult to use in comparative analysis, but they can be easily smoothed out by "normalizing" the measured concentrations of REEs to some reference REE
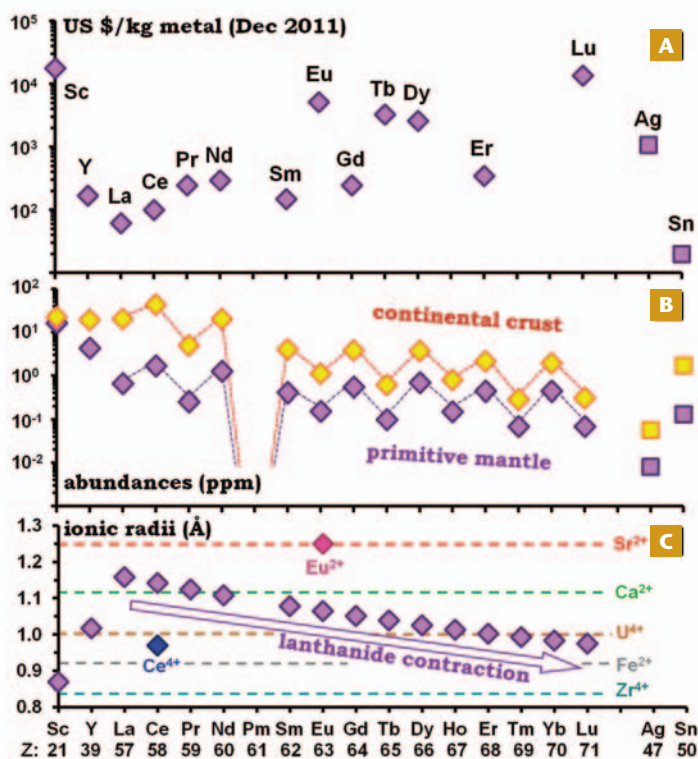
values (FIG. 3). What is chosen as the basis for normalization depends entirely on the scientific or practical task at hand. For example, evolutionary processes in mantle-derived magmas and their source characteristics can be tracked using REE abundances normalized to the primitive-mantle values of McDonough and Sun (1995). Other commonly used reference data sets represent CI chondritic meteorites, believed to approach the solar nebula in composition (Anders and Grevesse 1989); shales, used as a proxy for the upper continental crust (Taylor and McLennan 1985); and various seawater reservoirs (Nozaki et al. 1999). These graphs, normally plotted on a logarithmic scale, are used so routinely that care is now needed to ensure that they are indeed the most appropriate form of data presentation. The log scale can sometimes fail to reflect the true magnitude of variation among individual elements in REE-rich materials. It may be advantageous to normalize to a "custom" data set in certain cases, where relative variations in REE budget within a suite of genetically related samples need to be visualized (e.g. metasomatic rocks versus their protolith).
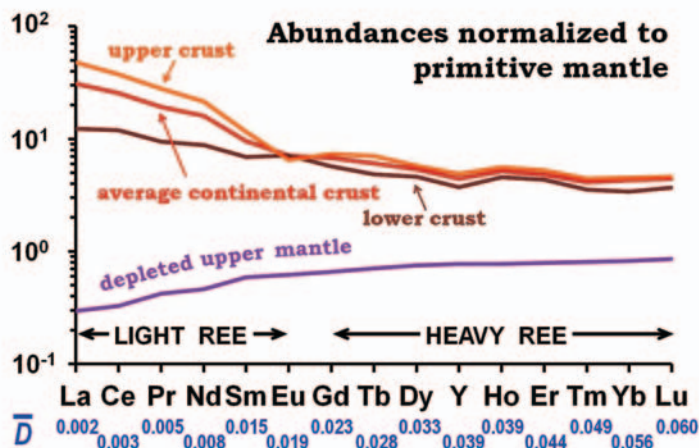
What Drives REE Fractionation in the Geological Environment?

As can be seen in FIGURE 2C, one notable characteristic of the REEs is a significant reduction in ionic radius from La to Lu (dubbed the "lanthanide contraction" by Goldschmidt 1925). This trend arises from the increasing attraction between the nuclei and $6s$ electrons of the lanthanides owing to the poor shielding properties of $4f$ electrons. Due to the lanthanide contraction, REEs exhibit systematic variations in partitioning between melts and crystals, coexisting liquids of different composition, and so on. For example, the tendency of REEs to partition into a melt under upper-mantle conditions decreases with decreasing ionic radius (i.e. the HREEs are generally more compatible with respect to mantle peridotite). The Earth's upper mantle, tapped by basaltic magmatism over billions of years, has developed a positively sloping normalized profile depleted in LREEs, whereas the continental crust shows complementary enrichment in these elements (FIG. 3).

In the geological environment, the REEs typically occur in the oxidation state 3+; however, a stable electron configuration can, in some cases, be attained with two or four electrons lost to ionization (e.g. s^2 in Eu^{2+} and $s^2d^1f^1$ in Ce^{4+}). Despite their similar radii, Y and Ho show different partitioning behavior in aqueous solutions, which has been attributed to the involvement of f or s electrons in metal–ligand bonding (i.e. greater covalency of Ho relative to Y; Choppin 2002) or to stereochemical changes during the transition from a solute to a solid (Tanaka et al. 2008). These differences in radius, oxidation state, and bonding drive fractionation of REEs in natural systems and enable their industrial separation. A few examples are decoupling of Y from Ho during precipitation of calcite from seawater (Tanaka et al. 2008), preferential removal of Eu^{2+} from low-f_{O2} melts by feldspars (Weill et al. 1974), and selective reduction of Eu in a chloride solution for industrial purposes (Gupta and Krishnamurthy 2005).

MINERALOGY OF THE RARE EARTHS

At the time of writing, ca 270 minerals (i.e. about 6% of the total number of valid species) are known to contain Y or lanthanides as an essential component of their crystal structure and chemical formula; five or six new REE minerals are typically discovered every year. Most common, both in terms of the number of species and the number of natural occurrences, are silicates (~43% of all REE minerals), followed by carbonates (23%), oxides (14%), and phosphates and related oxysalts (14%). Least common are sulfates, represented by the single species sejkoraite-(Y), not found outside its type locality. The parenthesized element symbols in the name of this and other minerals indicate the predominant REE in their composition (Levinson 1966). As can be expected from the abundances of these elements (FIG. 2), the rare earth budget of the overwhelming majority of REE minerals (96%) is dominated by Ce, Y, La, or Nd, and the few remaining species all have an even-numbered lanthanide in their Levinson modifier.

In addition to REE species *sensu stricto*, many minerals contain high levels of these elements substituting for other cations of comparable radius and charge (FIG. 2). For instance, mosandrite $[(Ca,Na)_{3-x}(Ca,REE)_4Ti(Si_2O_7)_2(OH,F,H_2O)_4 \cdot H_2O]$, apatite $[(Ca,REE,Sr,Na)_5(P,Si)_3O_{12}(F,OH,Cl)]$, ewaldite $[Ba(Ca,Na,REE)(CO_3)_2 \cdot nH_2O]$, and perovskite $[(Ca,Na,REE)(Ti,Nb,Fe)O_3]$ commonly incorporate $1–2 \times 10^5$ ppm REE in the Ca sites in their structure. Numerous other minerals may exhibit enrichment in REEs depending on their crystallization conditions; a few notable examples discussed further in this issue include titanite $(CaTiSiO_4O)$, zircon $(ZrSiO_4)$, eudialyte (Na–Ca–Mn–Fe–Zr cyclosilicate), pyrochlore $[(Ca,Na)_{2-x}(Nb,Ti)_2O_6(F,OH)]$, and members of the crandallite group $[(Ca,Sr,Ba,Pb)(Al,Fe)_3(PO_4)_2(OH)_5]$. Probably the most remarkable rare earth hosts are the so-called ion-adsorption (or "ionic") clays. In this material, up to 70% of the total REE content (0.05–0.2 wt%) is in the form of cations adsorbed to the surface of Al phyllosilicates (predominantly kaolinite and halloysite), but the mechanisms of ion–clay interaction are poorly understood.

Depending on various structural constraints (cation coordination, cation–ligand distances, etc.) and on the relative availability of specific REEs in the crystallization environment, different minerals and even samples of the same mineral from different rock types may exhibit significant variations in their REE distribution patterns (FIG. 4). Because the prices of REEs can vary by two orders of magnitude (FIG. 2), these variations have important economic implications. For example, fluorocarbonates may show relative enrichment in either LREEs or HREEs [cf synchysite-(Ce)
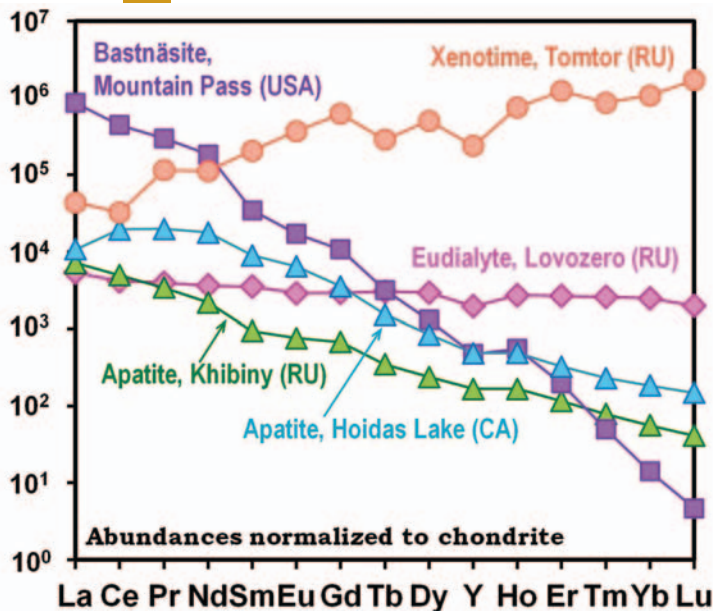
FIGURE 4 Chondrite-normalized REE profiles of selected minerals (Chakhmouradian and Reguir, unpublished data), including some typical constituents of REE ores and minerals that are currently investigated as potential industrial sources of rare earths (abbreviations as in TABLE 1; chondrite values from Anders and Grevesse 1989)

and synchysite-(Y)], and although the latter are far less common, they would generally be more valuable owing to a higher content of Y and other critical metals in their composition.

Although appreciable quantities of REEs are found in hundreds of minerals, only a few of these minerals are amenable to processing to yield a marketable product (e.g. oxides of individual elements) and occur in tonnages sufficient for mechanized mining. To date, rare earths have been produced from fewer than 20 minerals, and just several of them (bastnäsite, monazite, Al clays, xenotime, loparite, and parisite, listed approximately in order of decreasing importance) account for the bulk of historic production (TABLE 1). Cracking the rare earth "extraction code" for other minerals that form large-tonnage deposits (such as apatite or eudialyte) would revolutionize the resource market, and many companies around the world are investing heavily in this research. Meanwhile, the amenability of these alternative ore types to profitable extraction of REEs on a commercial scale remains to be demonstrated.

RARE EARTH DEPOSITS

A number of geological processes can lead to concentration of rare earth minerals in specific types of rock or sediment and to enrichment in either LREEs or HREEs by fractionation within the REE series (FIG. 5). The bulk of early production came from secondary deposits such as

TABLE 1 MAJOR RARE EARTH MINERALS

Mineral name[a] Formula	Relevant rare elements (range or max. value)	Major deposit type(s)[c]	Examples (past, present, and potential producers)[c]
Bastnäsite $REECO_3(F,OH)$	53–79 wt% $\sum REO$; ≤2.8 wt% ThO_2	CRB; HMD	Bastnäs, SW; Mountain Pass, USA; Maoniuping, Weishan, and Bayan Obo, CH; Karonge Gakara, Burundi
Parisite $CaREE_2(CO_3)_3(F,OH)_2$	58–63 wt% $\sum REO$; ≤4.0 wt% ThO_2	CRB; HMD	Mountain Pass, USA; Weishan and Bayan Obo, CH
Synchysite $CaREE(CO_3)_2(F,OH)$	48–52 wt% $\sum REO$; ≤5.0 wt% ThO_2	CRB; HMD associated with CRB and granites	Barra do Itapirapuã, BR; Lugiin Gol, MN; Kutessay, KR
Ba–REE fluorocarbonates[b] $Ba_xREE_y(CO_3)_{x+y}F_y$	22–40 wt% $\sum REO$; ≤0.7 wt% ThO_2	HMD; CRB	Bayan Obo, CH
Monazite $(REE,Th,Ca,Sr)(P,Si,S)O_4$ solid solution to cheralite $(Ca,Th,REE)PO_4$	38–71 wt% $\sum REO$; ≤27 wt% ThO_2; ≤0.8 wt% UO_2	CRB; HMD; granitic pegmatites; Fe oxide–phosphate rocks; laterites; placers	Kangankunde, ML; Bayan Obo, CH; Steenkampskraal, SA; Mt. Weld, AU; Tomtor, RU; Tamil Nadu and Kerala, IN; Buena, BR; Nolans Bore and Eneabba, AU; Perak, MA
Xenotime $(REE,Zr)(P,Si)O_4$	43–65 wt% $\sum REO$; ≤8.4 wt% ThO_2; ≤5.8 wt% UO_2	Granites and pegmatites; HMD associated with granites; laterites; placers; rarely CRB	Kutessay, KR; Pitinga, BR; Tomtor, RU; Mt. Weld, AU; Kinta and Selangor, MA Lofdal, Namibia
Churchite $REEPO_4•2H_2O$	43–56 wt% $\sum REO$; ≤0.3 wt% ThO_2	Laterites	Mt. Weld, AU; Chuktukon, RU
Fergusonite $REENbO_4$	43–52 wt% $\sum REO$; ≤8.0 wt% ThO_2; ≤2.4 wt% UO_2	Granites and pegmatites; HMD associated with peralkaline rocks	Bayan Obo, CH; Nechalacho, CA
Loparite $(Na,REE,Ca)(Ti,Nb)O_3$	28–38 wt% $\sum REO$; ≤1.6 wt% ThO_2	Peralkaline feldspathoidal rocks	Lovozero, RU

a   A number of other REE minerals have been mined on a small scale (typically, from pegmatites and other vein deposits) or proposed as potential ore minerals. However, their economic value at present is uncertain. Examples discussed further in the present issue include (listed alphabetically): aeschynite, $REE(Ti,Nb)_2O_6$; allanite, $CaREEAl_2Fe^{2+}(SiO_4)$ $(Si_2O_7)O(OH)$; ancylite, $(Sr,Ca)REE(CO_3)_2(OH)•H_2O$; britholite, $Ca_2REE_3(SiO_4)_3(F,OH)$; cerianite, CeO_2; cerite, $REE_9Fe^{3+}(SiO_4)_6(SiO_3OH)(OH)_3$; euxenite, $REE(Nb,Ta,Ti)_2O_6$; ferriallanite, $CaREEAlFe^{3+}Fe^{2+}(SiO_4)(Si_2O_7)O(OH)$; gadolinite, $REE_2Fe^{2+}Be_2Si_2O_{10}$; gagarinite, $NaCaREEF_6$; gerenite, $NaCaREE_3(Si_6O_{18})•2H_2O$; kainosite, $Ca_2REE_2(Si_4O_{12})$ $(CO_3)•H_2O$; nioboaeschynite, $REE(Nb,Ti)_2O_6$; shomiokite

$Na_3REE(CO_3)_3•3H_2O$. Some of the minerals listed here may predominantly contain either LREEs or HREEs (e.g. bastnäsite, fergusonite, allanite, gadolinite), while others show preference for a specific group (e.g. monazite, loparite, and cerite for LREEs; xenotime, churchite, and euxenite for HREEs).

b   Include huanghoite (x = y = 1), zhonghuacerite (x = 2, y = 1), and cebaite (x = 3, y = 2)

c   Abbreviations: CRB = carbonatites, HMD = hydrothermal-metasomatic deposits; AU = Australia, BR = Brazil, CA = Canada, CH = China, IN = India, KR = Kyrgyzstan, MA = Malaysia, ML = Malawi, MN = Mongolia, RU = Russia, SA = South Africa, SW = Sweden; REE = rare earth element(s), REO = rare earth oxide(s)
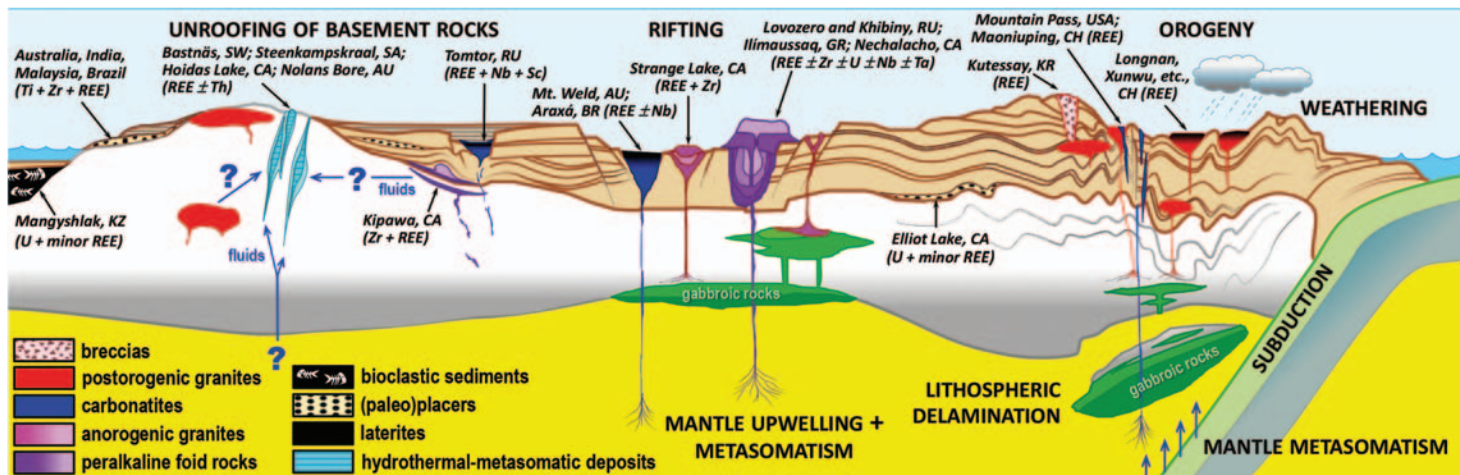
Major REE deposit types in a tectonic context. Rock types are given in the legend; processes are shown in capital letters; and past, present, and potential producers are in italics (KZ = Kazakhstan; for other abbreviations, see TABLE 1). Bayan Obo, although the world's largest REE deposit, is one of the least well understood (Kynicky et al. 2012) and is not indicated on this diagram.

monazite-bearing placers (see below). Although the *total* amount of REEs extracted prior to 1950 did not exceed 100 kt (kt = kilotonne = 1000 tonnes = 10^6 kg), i.e. less than what is produced *annually* today, there has recently been renewed exploration interest in placers and paleoplacers, particularly those enriched in xenotime and thus containing a higher proportion of valuable HREEs. The advantages of (paleo)placer deposits are their common proximity to waterways, ubiquitous association of REE minerals with other industrial minerals (e.g. zircon, ilmenite, rutile, cassiterite, U ores), and low start-up and processing costs because the need for crushing is reduced. However, because placer xenotime and monazite contain high levels of Th and U (TABLE 1), the commercial success of any of these projects will depend on their ability to solve the problem of safe handling and disposal of radioactive wastes. Rare earths were also extracted as by-products of uranium mining from conglomerates at Elliot Lake (Canada) and bioclastic phosphorites in Mangyshlak (Kazakhstan).

Igneous REE deposits are associated with carbonatites and peralkaline silicate rocks; subeconomic mineralization is also known from pegmatites associated with metaluminous granites and from Fe oxide–phosphate rocks (Chakhmouradian and Zaitsev 2012 this issue). In many of these deposits, high levels of REEs cannot be explained by magmatic processes alone and require a source enriched in incompatible elements and, in some cases, late-stage remobilization of these elements by fluids (Williams-Jones et al. 2012 this issue). Weathering is another powerful mechanism for concentrating REEs and other rare metals showing limited mobility in surface waters. Laterites developed at the expense of carbonatites and further affected by epigenetic reworking under reducing conditions show as much as an order of magnitude enrichment in REEs relative to the fresh rock (Kravchenko and Pokrovsky 1995). The discovery of spectacular deposits [>1 Mt of ore at 4–12 wt% total REE oxide (REO)] in weathered carbonatites at Araxá (Brazil), Tomtor (Russia), and Mt. Weld (Australia) has galvanized interest in this resource type. Mt. Weld is currently mined for REE phosphates that will be processed at a separation plant in Malaysia to yield 22 kt REO beginning in 2013.

Ion-adsorption clays formed by intense chemical weathering of granites coupled with a three- to fivefold enrichment of the laterite in REEs are another important type of surficial deposit, first recognized in southern China in the 1970s and since identified in Madagascar, Laos, and other (sub)tropical countries. Although these "ionic clays" have low grades (≤0.3 wt% REO), their amenability to open-cast mining and easy processing and the high proportion of valuable HREEs in their composition make this deposit type attractive to exploration. Looking further ahead, it may even be possible that future demand for REEs will justify harvesting seafloor mud enriched in REEs (500–2200 ppm) and constituting a virtually inexhaustible resource (Kato et al. 2011).

Many REE deposits, including several of industrial or historical significance (e.g. Bastnäs in Sweden, Steenkampskraal in South Africa, and Bayan Obo in China), owe their origin to fluids of uncertain provenance. These deposits range from simple injection or replacement veins to breccias and complexly zoned metasomatic bodies showing evidence of multiple mineralization stages. Typical ore minerals are monazite(–cheralite), apatite, allanite, bastnäsite, and other LREE fluorocarbonates. There seems little doubt that mineralizing fluids in these systems may have a multiplicity of sources (from proximal, unexposed intrusions to metasomatized mantle) and derive their metal potential from both their primary source and wall rocks encountered en route (FIG. 5). Although, in some cases, REE minerals are associated with Fe and Cu ores, the interpretation of Bastnäs and similar deposits as "IOCG-type" (iron oxide–copper–gold) is unwarranted.

RARE EARTH MINING AND PRODUCTION: A RETROSPECT

Historically, the mining and production of REEs have gone hand in hand with technological progress and developments in applied chemistry and physics. Prior to the 1890s, there was no commercial market for these elements. Small amounts of REE ore extracted principally from metasomatic rocks of the Bastnäs ore field in southern Sweden (Williams-Jones et al. 2012) served as a feedstock for numerous research laboratories. This situation changed when the Austrian chemist Carl Auer von Welsbach made a series of inventions that would light up the world (literally) and pave the way for the rare earth industry. Although his first patented invention, an incandescent mantle for street gas lights utilizing candoluminescence of La_2O_3 and Y_2O_3 (1885), found only limited use, his improved ThO_2–CeO_2 design patented six years later was an instant commercial success. The rapidly expanding gas-mantle business and

Welsbach's discovery of pyrophoric REE–Fe alloys ideal for flints and other sparking devices (1903) necessitated securing a cheap and plentiful source of Th and rare earths. Such a source was found in the mineral monazite, which occurs in many placer deposits around the world and is commonly enriched in Th (TABLE 1). By the time incandescent mantles finally gave way to electrical lighting in the 1930s, about 100 kt of monazite concentrate had been produced (Overstreet 1967), predominantly in Brazil (~70%, from mines in operation since the 1880s), India (~20%, since 1911), and the Carolinas, USA (~6%, 1887–1917). During this early period of REE mining, bedrock deposits did not contribute significantly to global production; the few known examples were all pegmatites associated with granitic and alkaline rocks.

The nuclear arms race in the 1940s and 1950s provided a powerful impetus for rare earth production and research. The chemistry of lanthanides was thought to be the key to the metallurgy of actinides, and the understanding of the nuclear properties of REEs was essential to harnessing the process of fission. Rare earth separation techniques developed in the 1800s (i.e. fractional crystallization and precipitation) were laborious and did not provide the degree of interelement partitioning required to produce large amounts of high-purity material relatively inexpensively and fast. For example, it took Charles James (1911) 15,000 experimental steps to obtain Tm devoid of any spectroscopically detectable impurities! The need for high-purity REEs and actinides stimulated the advent of ion exchange and solvent extraction techniques that almost immediately found practical application (Gupta and Krishnamurthy 2005).

Another important outcome of that early work was that by the 1960s, research-grade REEs were readily available in sufficient quantities and at reasonable prices to anyone studying the optical, magnetic, or other properties of these elements and their potential industrial applications. In the next few years, a great number of such applications were identified and commercialized. Many of those early, advanced technologies are still around today: just think of Sm–Co magnets used in various aerospace and communication devices, or Nd-doped $Y_3Al_5O_{12}$ lasers employed for trace element analysis, metal cutting, treatment of glaucoma, and other medical applications. To meet the growing demand for REEs, several new deposits were discovered and put into production. The opening of the Steenkampskraal mine in South Africa, Mountain Pass in California, and Karnasurt (Lovozero) in the Russian Arctic in the early 1950s heralded the beginning of a new era: rare earths were now valuable enough to move mining from placers into bedrock (see cover of this issue). The latter two deposits also reflect diversification of REE production into resource types other than monazite (bastnäsite and loparite, respectively).

From the mid-1960s to 1985, the carbonatite-hosted Mountain Pass deposit was the world's main source of REEs, producing over 20 kt REO at its zenith (Castor and Hedrick 2006). In the face of fierce competition from China and environmental problems, the mine closed down in 2002, but it has now been resurrected with new technology and is ramping up production (Mariano and Mariano 2012 this issue). The same factors (in addition to a slew of social and economic problems) contributed to a decline of the Russian production, from 26 kt of loparite concentrate (equivalent to ~8 kt REO) in 1990 to ≤9 kt in the 2000s.

Today, almost all (~97%, or 120–130 kt REO in 2006–2010; USGS 2012) of the world's REE supply comes from China, with 40–50% of this production contributed by the giant Fe–REE–Nb deposit at Bayan Obo (Kynicky et al. 2012 this issue). The other sources are minor and, in addition to the Mountain Pass bastnäsite and Russian loparite deposits, include placers, where monazite and xenotime are extracted as by-products from ilmenite–zircon sands (India, Brazil, Malaysia). Since 2003, none of these sources have contributed more than 3.5 kt REO (i.e. <3% of global output).

Maps and data presented elsewhere (British Geological Survey 2011; USGS 2012; articles in this issue) illustrate well the point that there could be a plentiful supply of REEs from a diversity of geographical and geological sources. In the past decade, numerous companies have been involved in rare earth exploration around the globe, pursuing >400 projects outside China. Their ultimate goals are to restore balance in the REE-supply market and to protect the high-tech industry from politically driven restrictions on the availability of these metals and, especially, critical REEs (Hatch 2012). Some of the manufacturing companies that rely on REEs are already buying into promising exploration projects in order to secure their future supplies.

INDUSTRIAL USES OF RARE EARTHS

The character of the rare earths in technological applications is rather similar to their geological distribution: small quantities of REEs are disseminated in products all around us, in every computer, smartphone, DVD player, TV set, etc. (FIG. 6). They are popularly viewed as "green metals" because a significant share of the REE market is taken up by magnets (~25%) used in wind turbines, hybrid electric vehicles, e-bikes and maglev trains; by automotive catalytic converters (~7%), which minimize toxic emissions into the atmosphere; and by phosphors (~6%), whose numerous applications include energy-efficient fluorescent lighting (Gibson and Parkinson 2011). An important difference between technology and nature is that, while nature tends to gently fractionate HREEs from LREEs, or vice versa, leaving almost all minerals with a mixture of both, many technological applications require that each element be isolated from the others before it can be put to practical use, as illustrated by the examples below (see also Hatch 2012).

FIGURE 6 A display in the Rare Earth Museum in Baotou (Inner Mongolia, China), showcasing some REE applications in alloys, ceramics, and glasses

The strongest permanent magnet ever made has the composition $Nd_2Fe_{14}B$ and was invented in the early 1980s. The magnetic properties of REE^{3+} compounds arise from a potentially large number of electrons with aligned spins in the $4f$ orbital and their localized nature; magnetic alloys similar to $Nd_2Fe_{14}B$ can be made with most of the other REEs, but none are as strongly magnetic as the Nd alloy (Kaltsoyannis and Scott 1999). "Neo" magnets, as they are known in the trade, enable miniaturization of electronic components and appliances, but their weakness is that they do not work well above about 200 ºC. Minor Dy and Tb are incorporated in $Nd_2Fe_{14}B$ magnets to expand their working range, but even these improved materials have to be replaced with more resilient Sm–Co alloys in high-T (300–550 ºC) applications. The development of a proof-of-concept refrigerator utilizing the giant magnetocaloric effect of Gd–Si–Ge alloys (Pecharsky and Gschneider 1999) may signal the arrival of a new era in commercial refrigeration, replacing the 150-year-old vapor-compression technology with more energy-efficient and environmentally friendly machinery.

The electronic configuration of REEs, with f electrons shielded from crystal-field effects by outer orbitals, also gives rise to the many valuable optical properties of these elements. The red color in your TV and computer screen, for example, comes from sharp emission lines at 610–630 nm in Eu^{3+} phosphors (substances that luminesce), whereas higher-frequency (450 nm) electron transitions in Eu^{2+} produce a blue radiance. The two forms are used together with Tb-activated green phosphors to give the white glow of a triband compact fluorescent tube. Euro banknotes have an antiforgery mark that will glow red in UV light—and what phosphor does it contain? Europium, of course!

SUPPLY VERSUS DEMAND

Critical and Strategic Metals Explained

Critical is a relatively new term referring to economically important resources subject to high supply risk. The European Union defined 14 critical materials and counted the entire REE family as one of these fourteen. The REEs are the exemplar of critical metals: they hit the headlines in 2010, when China drastically cut its export quota and the world realized that (1) these elements were essential for "all kinds of useful things" and (2) the supply of REEs was virtually monopolized by China. A plaque from 1992 in the REE-producing town of Baotou quotes China's legendary reformer Deng Xiaoping, "The Middle East has oil, China has rare earth." As the Chinese rare earth industry is working hard to keep these metals in the country by vertically integrating their business from bastnäsite and clay ore to "Neo" magnets and other value-added products, the rest of the world is scrambling to find alternative and secure supplies (e.g. Mariano and Mariano 2012). The term *critical rare earths* is used to specify the elements for which demand is most likely to exceed supply in the near future. Some analysts predict that even with new producers coming on stream in the next few years, the supply shortfall of Nd, Eu, Tb, Dy, and Y is likely to persist through at least 2014. The term s*trategic* is often used interchangeably with *critical* but has traditionally had a military connotation. Although the defence market for REEs is small (e.g. <10% of the domestic consumption in the US; Grasso 2011), REE-based materials have now become irreplaceable in such applications as precision-guided munitions and aircraft (magnets), dazzlers, targeting and mine-detection systems (lasers), radars, sonars, and radiation and chemical detectors (signal amplifiers).

REEcycling

It is estimated that <1% of used rare earths were recycled in 2010, but the rising prices and supply problems are encouraging more effort in this area. Some materials, like phosphor powders, are easier to "REEcycle," and some countries, like Japan, have been proactive in seeking commercially viable ways of doing so. Given that Japan alone has accumulated some 300 kt of REO in used electronics, recycling of these and other materials could be a worthwhile endeavor. However, its commercial success has so far been hampered by a number of issues, including the long lifetimes (≥10 years) of products incorporating significant quantities of REEs (e.g. hybrid cars and wind turbines), very low potential yield from REE components used in most other applications (e.g. <<0.1 wt% for mobile phones and other electronics), and the tendency of REEs to partition into the slag during conventional pyrometallurgical recovery of metals from automotive catalysts. A salient statistic is an estimate that 20–30% of Nd-magnet material is scrapped because it is not economic to reprocess (Moss et al. 2011). Clearly, the future of these programs depends on price dynamics (i.e. the economic feasibility of competing with virgin metal supply) and on the ability of governments to promote research and development in the field of "REEcycling" and provide financial incentives for up-and-coming producers.

ENVIRONMENTAL CONCERNS AND RESPONSIBLE SOURCING

The toxicity of the REEs is thought to be low, but some health problems have been documented (Wall 2013). For example, prolonged use of Ce polishing powder has been associated with lung pathologies, whereas ingestion of high levels of this element has been linked to heart problems in some monazite-producing areas of India. Although Ce is common in many products, the exposure from most applications, such as catalytic converters in cars and decolorizers in glass and dental porcelain, is low and there is no evidence of harmful effects. The use of Gd in magnetic resonance imaging led to small quantities of this metal finding their way into sewage, resulting in anomalously high Gd abundances in rivers flowing through heavily populated, industrialized areas in Europe (Bau and Dulski 1996). Again, these Gd anomalies have not been correlated with any adverse health effects. In China, REEs have long been used as additives in fertilizers and fed to livestock as a growth promoter. The long-term effects of such uncontrolled discharge of REE-based chemicals into the environment remain to be determined.

The main environmental concern regarding rare earth mining is not usually the REEs themselves but their common association with Th and U. These elements occur both in the structure of REE minerals and as discrete phases associated with the mineralization. The issue of by-product actinides has been increasingly on the public radar lately owing to some reports by the media and environmental groups that link high levels of radiation (i.e. >20 millisieverts per year) in areas of monazite mining and storage to various health problems among the population (e.g. Padmanabhan 2002). Epidemiological studies are inconclusive, and further work based on coordinated international efforts is desirable (Hendry et al. 2009).

Beyond radiation, the need for a wide array of processing chemicals creates many other problems around mine sites and REE-separation facilities in China and elsewhere. Practically every news agency has by now explored the not-so-friendly side of the "green metals," telling stories of toxic waste lakes, acrid air, and high cancer rates in the Bayan Obo area. The environmental impact of clay operations is also considered significant because chemicals used to liberate the adsorbed REEs have been allowed to escape into the surrounding countryside. It is a sobering thought that everyone who has benefited from REE-based technologies (and that must be all of us reading this issue) is using metals that come at such a high cost to the environment. The Chinese government has recently imposed much stricter regulations on the REE industry, suspending the issuance of new mining licenses, capping production, and clamping down on illegal operations and smuggling (Hatch 2012). Clearly, as new mines and processing facilities come on stream, both manufacturers and consumers of REE products need to make informed and responsible choices regarding the sourcing of REEs.

ACKNOWLEDGMENTS

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Dynamics in the Global Market for Rare Earths

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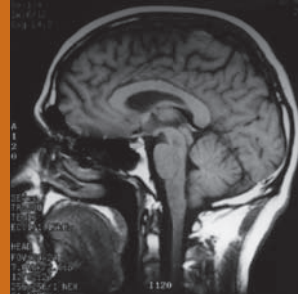
Magnetic resonance image of the brain, taken with the aid of Gd-based contrast agents. COURTESY OF BMJ PUBLISHING

The long-term growth of numerous industries will depend on the ability to secure stable and diverse sources of rare earths. Recent years have seen unprecedented volatility in this sector, with the rare earths being increasingly considered as strategic and critical to a wide range of technologies. During the next few years, demand for some of the rare earths is expected to exceed supply. Chinese export-quota policies have had a severe impact on the market. Worldwide exploration efforts are now leading to the deployment of a rare earth supply chain based outside China.

KEYWORDS: rare earths, rare earth oxide, neodymium, dysprosium, critical metals

INTRODUCTION

The rare earth elements (REEs) are a unique group of chemical elements that exhibit a range of special electronic, magnetic, optical, and catalytic properties. These elements are enablers: their use in components manufactured from a wide range of alloys and compounds can have a profound effect on the performance of complex engineered systems.

The REEs are usually defined as the 15 lanthanoid elements (lanthanum to lutetium), plus scandium and yttrium (Connelly et al. 2005). Promethium is radioactive and has no stable isotopes; it is thus present in the Earth's crust in vanishingly small quantities. Scandium exhibits a number of properties that are similar to those of other REEs, but is seldom found in the same minerals as the other REEs; it does not selectively combine with the common ore-forming anions (Hedrick 2000). It should be noted that the other REEs are chemically very similar to each other and tend to occur together within minerals in varying quantities. Their chemical similarities make them difficult to separate from each other, once liberated from the minerals in which they are found.

Flow-sheet designers and process engineers divide the REEs into three subgroups on the basis of initial segmentation during the separation process. Lanthanum (La), cerium (Ce), and neodymium (Nd) are the light REEs (LREEs); samarium (Sm), europium (Eu), and gadolinium (Gd) are the medium REEs (MREEs), and terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), and yttrium (Y) are the heavy REEs (HREEs) (see also Chakhmouradian and Wall 2012 this issue). HREEs are much rarer than LREEs or MREEs, partly due to their lower crustal abundances. They occur in small quantities within commercially processed LREE-rich minerals such as monazite and bastnäsite. HREE-enriched minerals and deposits that have been processed commercially include xenotime-(Y), ion-adsorption clays, and synchysite-(Y). New potential sources of HREEs outside China tend to be contained in minerals such as eudialyte, which have not been processed commercially before.

END USES OF RARE EARTHS

REEs have a variety of end uses (FIG. 1). Applications for REEs can be divided into two broad categories: process enablers and technology building blocks.

Rare Earths as Process Enablers

In a number of applications, REEs are used in the lifecycle of other materials and components but do not stay with the processed material. In general, simple REE compounds are utilized, such as rare earth oxides (REOs). Examples include:

- *Fluid-cracking catalysts* (FCCs). These are materials used in the petroleum-refining industry. La and Ce are added to the catalytic compounds (up to 8 wt%) to provide zeolite stability during the cracking process, which in turn yields high catalytic activity and process selectivity. This interaction aids in the transformation of crude oil into gasoline and other useful and valuable petroleum products.

- *Automotive catalytic converters*. Modern vehicles use catalytic converters to reduce the emission of pollutants that result from the internal combustion process. CeO_2 is the primary rare earth compound in such converters and is used in a wash coat in conjunction with zirconium (Zr) and platinum-group metals. The wash coat can contain up to 30 wt% CeO_2. The associated redox reaction aids in the conversion of NO_x, CO, and unburned hydrocarbons into less harmful compounds.

- *Polishing media*. Significant amounts of CeO_2 are utilized in the polishing of glass, mirrors, TV screens, computer displays, and the wafers used to produce silicon chips. When used in fine-powder form, the CeO_2 reacts with the surface of the glass to form a softer layer (the so-called "mechanochemical" effect), thus making it easier to polish the surface to a high-quality finish.

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FIGURE 1 (**A**) Direct-drive wind turbines contain approximately 150–200 kg of Nd and 20–30 kg of Dy per megawatt of generating capacity. IMAGE COURTESY OF SIEMENS AG

(**B**) Energy-efficient compact fluorescent lamps (CFLs) use phosphor materials containing critical REEs such as Eu, Tb, and Y.
IMAGE COURTESY OF GE LIGHTING

(**C**) Yttrium is an essential component of the thermal-barrier coatings used in jet engines. IMAGE COURTESY OF JOYANDJON.COM

Rare Earths as Technology Building Blocks

REEs can be incorporated into alloys and compounds for use in engineered components that, in turn, might be used to produce a complex engineered product or device. Relatively small amounts of REEs can be critical for the ultimate functionality of the end product. There are numerous such applications of REEs, for example:

- *Permanent magnets.* The use of REEs in magnetic alloys (containing 30–35 wt% REEs) has made it possible to produce magnet materials that generate very strong magnetic fields and that strongly resist being demagnetized. The LREEs present in these alloys—Nd, Pr, and Sm—effectively help to "channel" the inherent ferromagnetism of transition metals such as iron (Fe) and cobalt (Co). The addition of the HREEs Dy and Tb (typically totaling 2–4 wt%) further enhances the ability of Nd-based magnet materials to resist demagnetization caused by stray fields or increased temperatures.

These characteristics have revolutionized magnetics design in recent years, most notably in high-performance electric motors and generators. Such machines are used in, for example, Prius-class hybrid electric vehicles (HEVs) and in megawatt-scale, direct-drive wind turbines.

In addition to making electrical machines more efficient and to enhance performance, rare earth magnet materials have made it possible to miniaturize motors, loudspeakers, hard-disk drives, and other applications that use permanent magnets to operate. The magnetic field strength of rare earth magnets can be several times greater than that of ferrite magnets of the same shape and size, and the ability of these magnets to resist demagnetization can be an order of magnitude greater than that of ferrite magnets.

- *Energy storage.* Compounds of La and nickel (Ni) are used to produce battery cells for energy storage. The presence of La enables the absorption of hydrogen in the cell, and the ease of reversal of this electrochemical process makes La–Ni–H compounds particularly suitable for rechargeable-battery applications.

- *Phosphors.* Phosphor materials emit light after being exposed to electrons or ultraviolet (UV) radiation. Liquid crystal displays (LCDs), plasma screen displays, light-emitting diodes (LEDs), and compact fluorescent lamps (CFLs) all utilize such materials. Compounds containing Eu, Y, and Tb are frequently used to produce phosphors and are fine-tuned for particular color outputs. Since much more of the electrical energy is converted into light than in conventional light sources, phosphor materials are significantly more energy efficient than older technologies, requiring a lot less electricity to produce the same outputs. This energy efficiency is the key driver for government-mandated replacement of conventional incandescent light bulbs with CFLs in numerous jurisdictions around the world.

RARE EARTH DEMAND

In 2011, the estimated global demand was 105 kt of total REOs (TREOs) equivalent; this demand is expected to grow to 160 kt of TREOs by 2016 (Kingsnorth 2012). A hefty two-thirds of the demand in 2011 came from China alone, rising to 84% with Japan and Southeast Asia included (TABLE 1). Little change to this pattern is projected up to 2016 (TABLE 2).

Tables 1 and 2 also provide a breakdown of the estimated 2011 and projected 2016 demands, respectively, for TREOs used in a variety of end-use applications, in REO equivalents, by region (Kingsnorth 2012). The market demand is clearly dominated by permanent magnets and metal alloys.

RARE EARTH SUPPLY

In 2011, the estimated global TREO supply was approximately 113 kt; this amount is forecasted to grow to 195 kt of TREOs by 2016 (Kingsnorth 2012). At present over 95% of global supply originates from China. This is projected

TABLE 1 ESTIMATED GLOBAL RARE EARTH DEMAND IN 2011 (in tonnes of TREO ± 15%)

End Use	China	USA	Japan & SE Asia	Others	Total
Permanent magnets	16,500	500	3500	500	**21,000**
Metal alloys	15,000	1000	4000	1000	**21,000**
Catalysts	11,000	5000	2000	2000	**20,000**
Polishing powders	10,500	750	2000	750	**14,000**
Phosphors	5000	500	2000	500	**8000**
Glass additives	5500	750	1000	750	**8000**
Ceramics	3000	1500	2000	500	**7000**
Other	3500	500	1500	500	**6000**
Total demand	**70,000**	**10,500**	**18,000**	**6500**	**105,000**
Market share	**68%**	**10%**	**16%**	**6%**	**100%**

Source: Kingsnorth (2012)

to decrease to around two-thirds by 2016, as new non-Chinese sources of supply come on-stream. In 2011, the supply of REOs for rare earth magnets was broadly in line with demand.

Mining of Rare Earths in China

The Chinese Ministry of Land and Resources (MLR) allocates rare earth mining quotas to provinces and regions each year. Historically, the actual amount of rare earths mined has been significantly higher than the quotas allocated. In 2010, the estimated TREO production was 119 kt, compared to a mining quota of 89 kt; initial estimates for 2011 indicate production of 107 kt of TREOs, compared to a mining quota of 94 kt (Hatch 2011). In 2012, the MLR did not publish a list of allocations; instead, it issued the quota allocations in two tranches, giving themselves the freedom to potentially adjust the overall production for 2012 later in the year. Individual provinces and regions then acknowledged the receipt of a first batch of allocations, typically 50% of the total 2011 levels. Two of the nine REE-mining provinces, Sichuan and Shandong, did not make any such acknowledgments, though they may have received allocations from the MLR.

CHINESE RARE EARTH EXPORT QUOTAS

In recent years the Chinese Ministry of Commerce (MOC) has imposed restrictions on the export of rare earths from China. Reasons suggested by Western observers include the government's desire to encourage downstream users to relocate to China and recent initiatives to shut down and close inefficient and polluting mines in order to allow for environmental remediation. China also has ongoing issues relating to uncontrolled and illegal operations, which some observers estimate supply up to 15–20% of the world's REE demand. It should be noted that the export quotas do not apply to semifinished or finished goods, such as magnets or magnet alloys, produced in China. At present they apply only to the raw-material forms of REEs and simple REE-based compounds, along with some ferroalloys.

Effects of Rare Earth Export Quotas

Despite the imposition of export quotas over the past decade, until the past 18–24 months they presented few supply problems because REE demand was generally matched by supply. Significant end users also held substantial buffer stocks of materials, in some cases up to 24 months of inventory, to ensure continuity of supply. In

July 2010, the MOC announced a significant reduction in export quotas, bringing the total for 2010 to 30 kt. Representing a 40% reduction over 2009 levels, this measure caused considerable consternation in the rare earth industry and led to significant price increases for exported LREOs, in some cases by over 1500% in the space of just a few months!

The announcement at the end of December 2010 of an export quota of 15 kt for the first part of 2011 did little to quell concerns. However, the announcement for the second half of 2011 brought the quotas to around the same level as in 2010, and from their peak in July–August 2011, prices started to fall (as discussed below).

2012 Rare Earth Export Quotas

In December 2011, the MOC announced the first round of rare earth export quotas for 2012. The approach taken in this announcement was in contrast with previous years in three ways:

1 The MOC issued separate quota allocations for light rare earth and medium and heavy rare earth products (a range of compounds that include REE salts, oxides, metals, and some alloys), and not just for rare earths as a whole. While such an approach had been anticipated for some time, 2012 marked the first time that separate allocations were implemented, possibly in anticipation of the complaints ultimately filed at the World Trade Organization (WTO) in March 2012 (and discussed below).

2 In addition, for the first time, the MOC clearly telegraphed the intended total export quotas for the entire year, instead of waiting until the second half of 2012 to announce the final total for the year.

3 The MOC divided individual Chinese producing companies into two groups, based on progress towards the implementation of new pollution controls. Compliant companies received confirmed quota allocations, while the second group received only provisional allocations. Companies in the latter group would only have their quotas confirmed if they met the prescribed requirements by July 2012. Companies failing to meet the requirements would have their quotas reallocated to other companies. In May 2012, the MOC updated the list of companies in each group, reflecting the progress made by a number of these companies towards compliance with the new pollution controls (Hatch 2012a).

In August 2012, the MOC published the quota allocations for the remainder of 2012, with all but one of the companies that received provisional quotas passing the required inspections, thus receiving confirmed quotas. The final total of allocations for 2012 was 31 kt, slightly higher than for 2011 (Hatch 2012b).

RARE EARTH PRICING

Export-control policies from China have had a dramatic effect on prices for rare earths. The first important inflection point occurred in July 2010, following the announcement of second-half 2010 quota allocations that indicated a 40% reduction in quotas for 2010 compared to the previous year. This led to significant price increases for exported materials, particularly for LREEs and their oxides. The root cause of this was the imposition of an unofficial quota "surcharge" by traders and producers in China. This surcharge essentially assigned monetary value to each tonne of quota available, in addition to the value of the particular rare earth material itself, as a means of generating significant windfall profits for those involved.

TABLE 2 FORECASTED GLOBAL RARE EARTH DEMAND IN 2016 (in tonnes of TREO ± 20%)

End Use	China	USA	Japan & SE Asia	Others	Total
Permanent magnets	28,000	2000	4500	1500	**36,000**
Metal alloys	23,000	2000	3000	2000	**30,000**
Catalysts	15,500	5500	2500	1500	**25,000**
Polishing powders	13,000	2000	2000	1000	**18,000**
Phosphors	8500	750	2000	750	**12,000**
Glass additives	7000	1000	1000	1000	**10,000**
Ceramics	4000	2250	2500	1250	**10,000**
Other	5000	8000	4000	2000	**19,000**
Total demand	**104,000**	**23,500**	**21,500**	**11,000**	**160,000**
Market share	**65%**	**15%**	**14%**	**7%**	**100%**

Source: Kingsnorth (2012)

In the latter half of 2010, increases in this surcharge led to dramatic price increases for La-, Ce-, and other LREE-based compounds and to a disconnect between internal prices and those of exported materials. FIGURE 2 illustrates the impact of these measures on the pricing of Nd and Dy metals between June 2009 and June 2012.

September 2010 saw a diplomatic incident between China and Japan involving the collision of a Japanese patrol vessel with a Chinese fishing trawler near disputed islands in the East China Sea (Agence France-Presse 2010). Shortly after the arrest of the trawler captain, China was accused of imposing a rare earth embargo against Japan (Bradsher 2010). There was actually little conclusive evidence of such an embargo, despite the stories reported in the mainstream media at the time. Nevertheless, the incident created new impetus for the establishment of new sources of supply outside China, with security of supply now seen as of at least equal importance to pricing.

Price Peaks of 2011

Another key inflection point occurred around February 2011, when prices for rare earths used within China also started to increase. This was possibly the result of increased speculation and stockpiling of materials inside China. There is also some evidence to suggest an increase in the amount of materials being illegally siphoned off for export, as a means of capitalizing on the arbitrage between internal and external spot prices for these materials.

Prices for most rare earth materials peaked in mid-2011, and all rare earth prices have declined since then. The official export channels saw a significant reduction in volumes of materials shipped from China, indicating some degree of demand destruction, particularly for La- and Ce-based materials, which typically constitute 60–70% of export volumes.

Consequences on Producers and End Users of REE-Based Compounds

Confronted with escalating prices, some end users of REEs, such as those in the fluid-cracking catalyst and glass-polishing industries, made successful efforts to reduce or replace these elements, and this was reflected in reduced export volumes.

Producers and end users of rare earth magnets were impacted by the price increases of raw materials. This led to major efforts in 2011 and 2012 to reduce magnet usage, in electrical machines for example. Some design changes increased the complexity and cost of manufacturing, but these factors were more than offset by the cost savings realized by reducing the quantities of rare earth magnets required in each assembly.

Some magnetic-design engineers successfully replaced rare earth magnets with cheaper (though less powerful) ferrite magnets. Furthermore, for higher-performance grades of Nd–Fe–B magnet materials containing higher quantities of Dy and/or Tb, switching to usually more expensive Sm–Co magnets saved money too. Of course there are always trade-offs with such changes, most notably the increased size and mass of the devices containing the magnets. The alternative of retaining Nd–Fe–B magnets but using material grades with reduced Dy and/or Tb content was also adopted, through redesign efforts focused on coping with the lower maximum working temperature of the magnets made from these grades.

Other end users, such as phosphor producers, had little choice but to weather the price increases because of the lack of suitable substitutes or other options.

Although current prices are significantly lower than the peak prices of 2011, many REE end users remain wary of relying on REE-based compounds and components for their devices and applications, given the volatility of raw-material prices. This means that demand projections for the next couple of years may not be as robust or as certain as once thought.

WTO RARE EARTH TRADE DISPUTE

In March 2012 the United States, the European Union, and Japan filed simultaneous complaints with the WTO against China, relating to restrictions on exports of REEs, tungsten, and molybdenum. The three complainants requested consultations with China on these matters. Materials covered under the complaints included rare earth ores, metals, oxides, carbonates, chlorides, fluorides, and other compounds, as well as phosphorescent powders, ferroalloys, and various magnetic powders and alloys that contain rare earths. The complainants alleged that China engaged in unfair treatment of foreign entities via export restrictions,
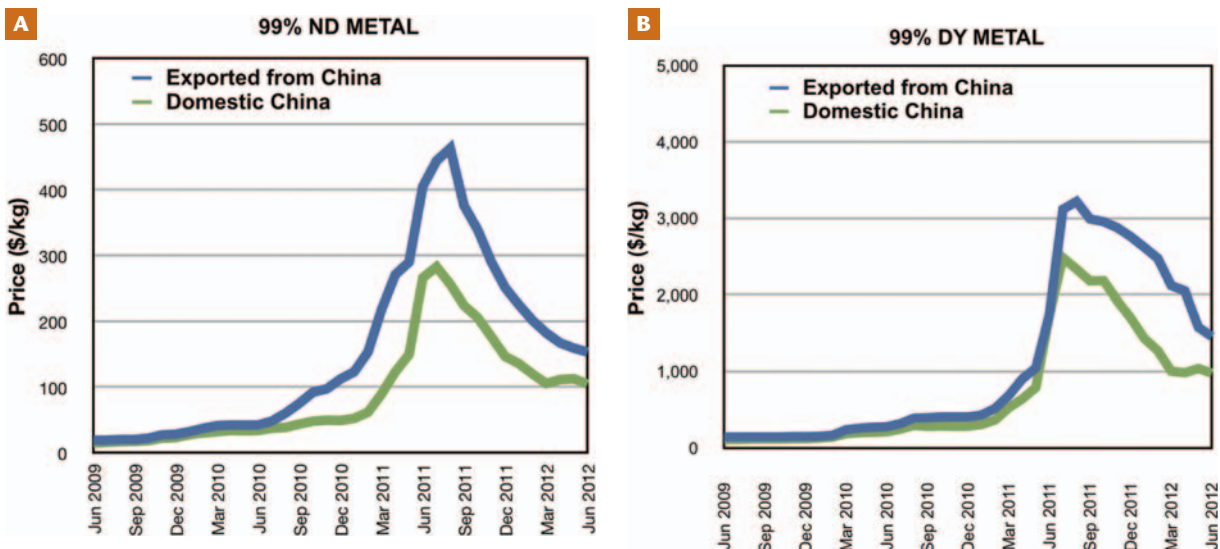
FIGURE 2   Spot prices (in US$) for Nd metal (**A**) and Dy metal (**B**). DATA FROM METAL-PAGES.COM

combined with discriminatory commercial operating rules within China. The complainants further alleged that the Chinese authorities set unofficial minimum export prices (artificially increasing the price of exported goods) and that there was an overall lack of transparency concerning the implementation of restrictive measures.

In June 2012 the Information Office of the State Council (equivalent to China's cabinet) published a wide-ranging white paper on the rare earth industry (China Daily 2012). While not officially linked to the WTO action, the paper related the Chinese government's concerns regarding pollution control, the protection of dwindling resources, and issues raised with respect to fair trade practices. The comments in this white paper might be interpreted in terms of allowable exceptions embodied within the General Agreement on Tariffs and Trade (GATT), which forms part of the WTO framework. Such exceptions to the normal rules are allowed under GATT, so long as they are not "*a disguised restriction on international trade*" (GATT 1947).

Potential Chinese Response

As strongly alluded to in the recent Chinese government white paper, China is likely to cite at least two exceptions in the GATT—specifically, measures "*necessary to protect human, animal or plant life or health*," and measures "*relating to the conservation of exhaustible natural resources if such measures are made effective in conjunction with restrictions on domestic production or consumption*" (GATT 1947). The first of these obviously relates to the ongoing issues of pollution control and mitigation in the Chinese rare earth sector.

With regard to the second exception, while the LREE deposits of northern China are commonly cited to have projected mine lives of hundreds of years (despite assertions to the contrary in the Chinese white paper), much has been made of projected mine lives of only 10–20 years for the HREE deposits in southern China. The second exception may well be deemed to apply to the HREEs in China, which could be a reason why the Chinese authorities split the export quotas in 2012, for the first time, between light and medium/heavy rare earths.

Potential Outcome of the Dispute

A similar case was recently settled at the WTO concerning export restrictions on bauxite, coke, and other materials from China. It was finally concluded in February 2012 after an appeal, and China lost the case (WTO 2012).

OTHER SUPPLY AND DEMAND ISSUES

Government Reports

The European Commission's Directorate-General for Enterprise and Industry published a study in June 2010 on raw materials critical to the European Union (European Commission 2010). Of the 41 metals and materials examined, REEs as a group were found to be exposed to the highest risk of disruption to supply.

In December 2010 the U.S. Department of Energy (DOE) released a report on its critical materials strategy; the report was updated in December 2011 (Bauer et al. 2011). DOE conducted a comprehensive analysis of several metals, including their criticality to clean technology. Criticality was defined in two ways: the first was the importance of a given metal to the functionality of particular technologies, such as electric vehicles, photovoltaic cells, wind turbines, and the like; the second measured the risk of disruption of supply for each of the metals. Five metals were deemed to be critical to clean technology on the basis of the two factors, in both the short and the long term; all

of them are REEs, specifically Nd, Eu, Tb, Dy, and Y. In August 2011, an analysis of REE supply and demand by Technology Metals Research (TMR) confirmed the five critical REEs as having the greatest exposure to potential supply issues (Hatch 2011).

Surpluses and Deficits

Unfortunately, the demand profile for REEs does not match their collective natural occurrence. For example, the typical ratio of Dy to (Nd + Pr) in Nd-based sintered rare earth magnets ranges from 1:50 to 1:2, whereas the same ratio in typical LREE-rich minerals is 1:100 to 1:50, and to date there has been negligible recovery of HREEs from them. This imbalance, coupled with new applications of HREEs in phosphors and energy-efficient lighting, is a driver in the pursuit of HREE-rich mineral deposits, despite the greater mineral-processing challenges. Because of the overall mismatch between demand and occurrence (closely linked to supply), and because even HREE-rich minerals contain significant quantities of La and Ce, some REEs will be in surplus while others will be in deficit (see TABLE 3).

TABLE 3	FORECASTED GLOBAL SUPPLY AND DEMAND FOR SELECTED RARE EARTHS IN 2016	
REO	**Demand @ 150–170 kt/y TREO**	**Supply @ 180–210 kt/y TREO**
CeO_2	60–70 kt	75–85 kt
Nd_2O_3	25–30 kt	30–35 kt
Eu_2O_3	625–725 t	450–550 t
Tb_4O_7	450–550 t	300–400 t
Dy_2O_3	1.5–1.8 kt	1.3–1.6 kt
Y_2O_3	12–14 kt	9–11 kt

Source: Kingsnorth (2012)

FUTURE SOURCES OF RARE EARTHS

The increased attention given to REEs over the past few years has caused an explosion of exploration activity for REE-bearing mineral deposits, particularly in North America and Australia. As of August 2012, 441 different exploration projects, run by 269 different companies in 37 different countries outside China, were active. Clearly not all projects are equal; some are being developed on the basis of initial grab samples whereas others have defined mineral resources and reserves. Most of these projects are in the early stages and are highly unlikely to succeed, as is the nature of the junior mining and exploration business.

TMR maintains a comparative index of REE projects with defined mineral resources, that is, resource estimates that comply with internationally recognized standards such as Canada's NI 43-101 or Australia's JORC code. As of August 2012, there were 43 such projects actively under development (Hatch 2012c). These and significant existing mines are shown in FIGURE 3. Canada and Australia are particularly well resourced with new rare earth projects in advanced stages of exploration and development.

Potential Bottlenecks

Accordingly, numerous potential new sources of REEs are on the horizon. A key issue is that many development companies plan to produce only an intermediate REE concentrate. End users require finished oxides, metals, and other REE products, and so the key challenge in progressing

beyond this stage will be to determine the logistics of separating the concentrates into finished REE-based compounds. Commercial-scale separation of this type is usually undertaken via solvent extraction (SX), a particularly intensive, time-consuming process. It is possible that technological advances to improve the separation of REEs via SX (such as the formulation and use of new reagents) will help to reduce costs and cycle times.

At present there are few rare earth separation facilities outside China, and those that do exist are not independent. Sending concentrates to China for processing would result in the finished REE-based compounds being subject to the export quotas and other restrictions mentioned earlier. There is also the additional challenge of handling the separation of HREEs, which require more intensive processing than LREEs. One solution to this issue is the creation of independent, centralized separation facilities designed to handle multiple sources of feedstocks, such as the facility being developed by Innovation Metals Corp. in Québec, Canada.

CONCLUDING REMARKS

In the medium and long term, it is highly likely that the world will successfully reduce its reliance on China as a source of REEs, thus increasing security of supply and reducing price volatility. This makes the use of REE-based compounds an attractive proposition for the growth of existing applications and the development of new ones. The ability of many end users to respond effectively to the 2011 price increases via technological innovation bodes well for the downstream portion of the supply chain, as the supply chain deals with the shorter-term uncertainty of supply and pricing.

ACKNOWLEDGMENTS

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Rare Earth Mineralization in Igneous Rocks: Sources and Processes

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Deposits of rare earth elements (REEs) in igneous rocks have played an instrumental role in meeting the growing industrial demand for these elements since the 1960s. Among the many different igneous rocks containing appreciable concentrations of REEs, carbonatites and peralkaline silicate rocks are the most important sources of these elements, both historically and for meeting the anticipated growth in REE demand. The contrasting geochemical and mineralogical characteristics of REE mineralization in carbonatites, peralkaline feldspathoid rocks, and peralkaline granites reflect different sources and evolutionary pathways of their parental magmas, as well as differences in the extent of postmagmatic reworking of primary REE minerals by hydrothermal fluids.

KEYWORDS: rare earth elements, lanthanides, yttrium, mineral deposits, carbonatites, nepheline syenites, granites

Mines at Khibiny (north-western Russia) have produced over 620 million tonnes of apatite concentrate since 1929. Historically, REEs have not been recovered from this concentrate, and 50,000–60,000 tonnes of REEs wind up in fertilizer-plant tailings annually. The current market situation has stimulated interest in the Russian mining industry to develop a commercially viable technology for extracting REEs from the Khibiny ore.

INTRODUCTION

Out of some 50 advanced rare earth exploration projects currently active outside China, 20 target carbonate igneous rocks (carbonatites) or their weathering products, whereas at least 13 other projects are focused on various alkaline silicate rocks. These statistics reflect the importance of igneous deposits in the economics of rare earth elements (REEs). Indeed, between the 1960s and 1995, these deposits accounted for over 50% of the global REE production. In the early 1990s, 30–35% of the total production of ca 50,000 tonnes of total rare earth oxides (REOs) came from the carbonatite-hosted Mountain Pass deposit in California, USA, 5–10% from Chinese carbonatites, and 10–15% from loparite mines in nepheline syenites at Lovozero, Russia. The present paper introduces the most significant types of igneous REE deposits and provides an overview of their sources, their evolution, and their geological, geochemical, and mineralogical characteristics.

Rare earth deposits in igneous rocks can be grouped into five distinct categories differing in the provenance and evolution of the magma and in the rock types hosting mineralization: (1) carbonatites, (2) peralkaline silica-undersaturated rocks, (3) peralkaline granites and pegmatites, (4) pegmatites associated with sub- to metaluminous granites, and (5) Fe oxide–phosphate deposits. We will place emphasis on the first three categories because they are far more important from a practical standpoint. To complement the information provided elsewhere in this issue by Kynicky et al. (2012), Mariano and Mariano (2012), and Williams-Jones et al. (2012), we will focus on localities outside China and North America.

TECTONIC SETTINGS, SOURCES, AND EVOLUTION OF REE-RICH MAGMAS

The majority of igneous REE deposits occur in intracontinental, anorogenic, extensional settings formed by pull-apart tectonics or asthenospheric upwelling. Here, thinning of the continental lithosphere facilitates decompressional melting of the mantle and emplacement of a wide spectrum of magmas, including alkali-rich, silica-undersaturated types relevant to the present discussion (carbonatite, nephelinite, and phonolite). These magmas often form extensive igneous provinces associated with rifts, grabens, crustal lineaments, and transcurrent fault systems (see Figure 5 in Chakhmouradian and Wall 2012 this issue). In some cases, these structures were activated episodically, giving rise to deposits of very different age within the same province; for example, the western branch of the East African Rift comprises carbonatite-hosted deposits of Mesoproterozoic, Ediacaran, and Cretaceous age (Woolley 2001).

Comparison with oceanic basalts (FIG. 1) shows that silica-undersaturated rocks from extensional settings are significantly enriched in light lanthanides and characterized by a greater degree of light REE (LREE)–heavy REE (HREE) fractionation [$(La/Yb)_N \geq 20$, as compared to ≤ 20 in basalts, where values are normalized to primitive mantle], implying that their parental magmas were derived by very low-degree (<1%) partial melting of the subcontinental upper mantle. Element-partitioning models show that the geochemical characteristics of anorogenic magmas require

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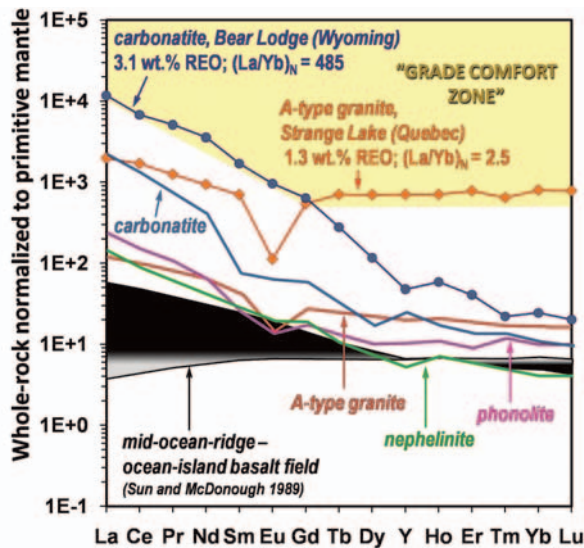E-mail: burbankite@gmail.com

FIGURE 1 Average compositions of various anorogenic magmas (see online supplementary data at www.elementsmagazine.org for data sources) compared with the data for oceanic basalts (normalized to the primitive mantle of McDonough and Sun 1995). To demarcate the "comfort zone" for desirable grades in igneous REE deposits (yellow field), we used the average compositions of ore (with a cutoff grade of 1 wt% REO) from Bear Lodge (Wyoming) and Strange Lake (Québec), both of which are North American deposits with recognized economic potential (Mariano and Mariano 2012). The data are derived from assessment reports posted at www.questrareminerals.com/strangelakeproject.php and www.rareelementresources.com/s/Home.asp. REO = rare earth oxide

elements will modify the rare earth budget of the derivative melt, causing changes in its normalized pattern; for example, the slope will increase if LREEs are fractionated from HREEs, and a negative Eu anomaly will appear if feldspars crystallize and are segregated out. This process of *fractional crystallization* can yield evolved melts showing a large increase in REE content relative to the original magma and capable of producing rare earth mineralization. The level of REE enrichment required for this to occur depends on the composition of the melt and physical parameters. For example, the solubility of monazite in silicic melts increases with decreasing alumina saturation index and increasing temperature (Wolf and London 1995), but remains low (<1 wt% LREE) in comparison with the solubility of $LREE(OH)_3$ in carbonate systems ($\geq 20\%$; Wyllie et al. 1996).

Separation of a homogeneous melt into two or more liquids of different composition, structure, and rheology can also contribute to the concentration of REEs in igneous systems. If one of the liquids (melt or fluid, L1) has a lower affinity for REEs than its conjugate phase, L2 (i.e. $^{L1/L2}D_{REE} < 1$), the REEs will concentrate in the latter. In *liquid immiscibility* experiments (Veksler et al. 2012), the partitioning behavior of REEs ranges from strongly in favor of the nonsilicate fraction in fluoride–silicate and phosphate–silicate systems ($^{L1/L2}D_{REE} \gg 1$ and > 100 for some elements) to completely the opposite in carbonate–silicate systems (FIG. 2). Carbonate–silicate immiscibility is also more effective in separating LREEs from HREEs because the latter are less compatible in the carbonate melt.
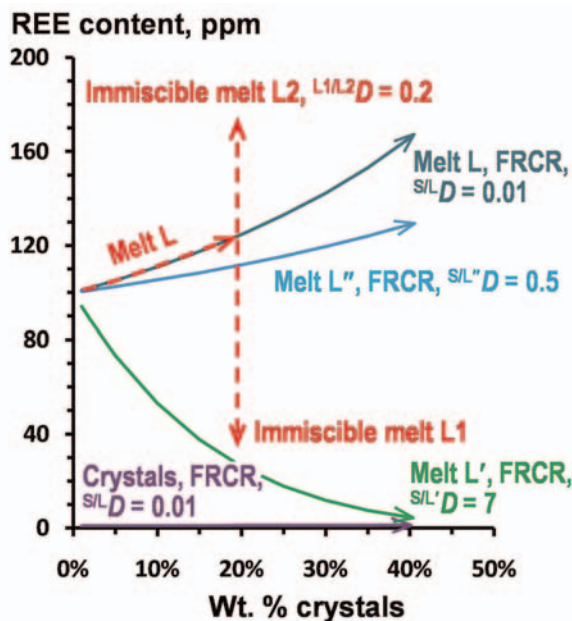
sources metasomatically enriched in incompatible elements (including REEs) relative to "run-of-the-mill" mantle peridotites that produce mid-ocean ridge basalt, for example (Arzamastsev et al. 2001). At present, it is not clear whether the REE budget of these enriched sources is controlled by such common silicate constituents of metasomatized mantle as amphibole (Arzamastsev et al. 2001) or by ephemeral phosphate and Ti oxide phases capable of incorporating high levels of incompatible elements (e.g. Ionov et al. 2006).

The origin of anorogenic (A-type, *sensu lato*) granitic rocks and their relation to geodynamics are a matter of considerable debate, which is reflected in the diverse terminology applied to these rocks by different authors. Their parental magmas may descend from a more primitive basaltic precursor, or they may form by partial melting of a subcrustal mafic underplate and deep crustal sources, possibly metasomatized by mantle-derived fluids (see Bonin 2007; Nardi and Bitencourt 2009 for discussion and references). Petrographically similar (but geochemically distinct) carbonate and silicate igneous rocks also occur in the (post)orogenic environment, where their emplacement is controlled by transtensional pull-apart tectonics. However, only carbonatites emplaced in such settings are known to host economic REE mineralization (Hou et al. 2009).

Regardless of their provenance, none of the magma types mentioned above are sufficiently rich in REEs to form a deposit if they reach the surface and erupt; some sort of evolutionary process is always required to generate the levels of enrichment observed in igneous REE deposits (FIG. 1). For example, precipitation of a mineral S with a lower REE content than its parental magma, L (i.e. $^{S/L}D_{REE} < 1$, where D is the partition coefficient), will drive the residual liquid toward enrichment in REEs (FIG. 2). Differences in partition coefficient among these

FIGURE 2 Effect of fractional crystallization and liquid immiscibility (for different partition coefficients) on REE abundances in magmas. Melt L becomes progressively enriched in REEs because it precipitates crystals with a very low $^{S/L}D$ value ($\approx D_{LREE}$ in clinopyroxenes and feldspathoids). Melt L″ undergoes depletion because $^{S/L}D$ is high ($\approx D_{Eu}$ in feldspars or D_{HREE} in garnet). Melt L represents an intermediate case ($\approx D_{HREE}$ in clinopyroxenes or amphiboles). If Melt L unmixes to produce two fractions, one of which (L1) has much lower affinity for REEs than the other (L2), the resulting trends would replicate the effect of carbonate–silicate immiscibility on most REEs (where L1 = carbonate and L2 = silicate). FRCR = fractional crystallization

FIGURE 3 Schematic maps of the Khibiny, Ozerny, and Lovozero REE deposits of Russia, showing their location, geology, and mineralization (neighboring countries with active REE exploration programs are indicated in capital letters). Hand-specimen photos show (in the order they are discussed): (**A**) primary burbankite (Brb) in calcite carbonatite, (**B**) complex carbocernaite–bastnäsite–calcite–monazite pseudomorphs after primary burbankite (Brb) in dolomite carbonatite, (**C**) loparite-bearing urtite, (**D**) eudialyte lujavrite (pink = eudialyte), (**E**) apatite (Ap)–nepheline (Ne) rock with titanite (Ttn), and (**F**) aggregate of shomiokite crystals (pinkish orange) from a low-temperature hydrothermal vein. Geological maps are from Bussen and Sakharov (1972), Epshtein et al. (1972), and Yakovenchuk et al. (2005). AR = Archean; PR = Proterozoic

REE MINERALIZATION IN IGNEOUS ROCKS: KEY EXAMPLES

Carbonatites

By definition, carbonatites are *igneous rocks* containing >50% of primary carbonate minerals. However, most carbonatites are actually *polygenetic* and show evidence of hydrothermal and metasomatic reworking; that is, they comprise early magmatic phases and products of crystallization from orthomagmatic and externally derived fluids. The most abundant carbonates in these rocks are calcite and dolomite, whereas ankerite, siderite, magnesite, and rhodochrosite are relatively rare. Other typical rock-forming constituents include apatite, magnetite, and ferromagnesian silicates.

The current view of carbonatite petrogenesis, supported by voluminous isotopic evidence, is that their parental magmas ultimately come from lithospheric and asthenospheric mantle sources. Relatively few carbonatites crystallize directly from mantle-derived melts generated by low-degree melting of metasomatized peridotite. The

majority of carbonatites occur in association with broadly coeval ultramafic and alkaline silicate rocks (FIG. 3), which is commonly interpreted to indicate a genetic relationship between them. Carbonate melts may evolve from alkali-rich carbonate–silicate magma of mantle provenance by either liquid immiscibility or fractional crystallization (Lee and Wyllie 1998), which has implications for the origin of REE mineralization (see below).

Carbonatites are characteristically enriched in REEs relative to other igneous rocks; about 90% of the published analyses fall in the 250–8000 ppm range (cf ≤1600 ppm in alkaline volcanics rocks; FIG. 1). However, these values can fluctuate wildly even within a single carbonatite intrusion (e.g. from <0.2 to 20.4 wt% REO at Khibiny, Kola; Zaitsev et al. 1998). Typically, carbonatites show strong enrichment in LREEs relative to HREEs (FIG. 1); the chondrite-normalized $(La/Yb)_{CN}$ ratio ranges from 20 to 1200, reaching 9500 at some localities (e.g. Sallanlatvi, Kola). Despite the highly fractionated nature of their parental magmas, a few carbonatites host minor HREE mineralization; examples include late-magmatic xenotime at Lofdal in Namibia (Wall et al. 2008) and carbohydrothermal parageneses with mckelveyite-group carbonates in Kola (Wall and Zaitsev 2004). A significant share of the rare earth budget of carbonatites is dispersed among their major constituent minerals (principally calcite, dolomite, apatite, and amphibole-group minerals; e.g. Reguir et al. 2012), whereas the remainder is incorporated in a plethora of REE-rich carbonate, phosphate, oxide, and silicate phases.

Carbonatites with appreciable REE mineralization have been reported at Khibiny and Vuoriyarvi (Kola, Russia), Ozerny and Arshan (Siberia, Russia), Fen (Norway), Khanneshin (Afghanistan), Amba Dongar (India), Barra
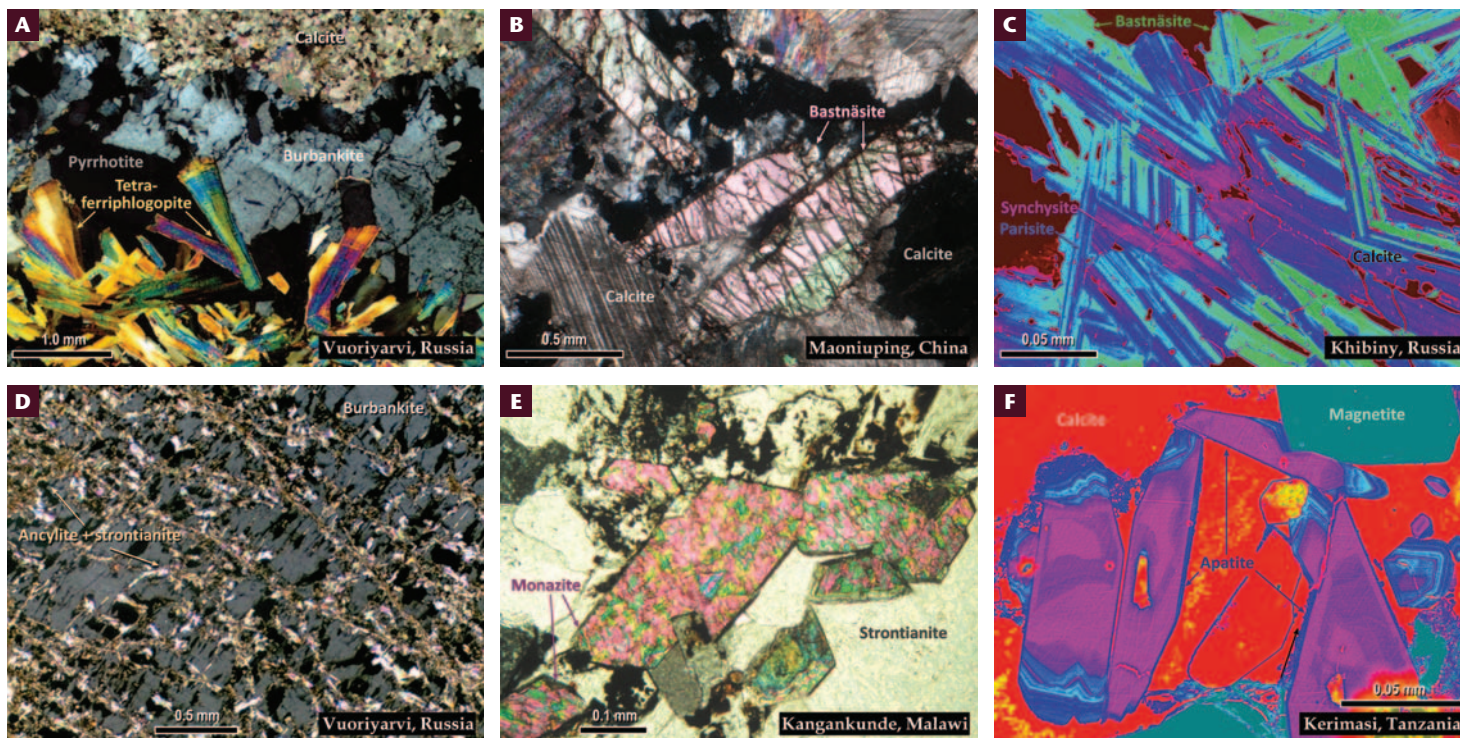
FIGURE 4 Typical REE host phases in carbonatites. (**A**) Primary burbankite decorating a contact between clinopyrox-enite and calcite carbonatite, (**B**) prismatic bastnäsite in calcite carbonatite, (**C**) syntactic intergrowths of REE fluorocarbonates, (**D**) partial replacement of primary burbankite by ancylite and strontianite, (**E**) monazite-rich hydrothermal paragenesis, (**F**) zoned apatite in calcite carbonatite, with strong REE enrichment (up to 8.5 wt% REO) in the oscillatory-zoned rim. (**A**), (**B**), (**D**), and (**E**) = micrographs (crossed polars); (**C**) and (**F**) = false-color back-scattered electron images. PHOTO E COURTESY OF HARALD DILL

do Itapirapuã (Brazil), Tundulu and Kangankunde (Malawi), and Wigu Hill (Tanzania), among many others. The most important REE hosts at these localities are carbonates and phosphates (FIG. 4), some containing very high levels of REEs and readily amenable to processing (TABLE 1 in Chakhmouradian and Wall 2012).

Three distinct assemblages of REE minerals have been recognized in carbonatites: (1) primary magmatic, (2) subsolidus hydrothermal–metasomatic, and (3) supergene. Where present, magmatic mineralization may constitute a viable resource (e.g. Mountain Pass; Mariano and Mariano 2012). The earliest phases to crystallize are Na–Ca–Sr–Ba–REE carbonates of the burbankite group, forming crystals up to several centimeters in size (FIGS. 3, 4A) and small drop-like inclusions in rock-forming carbonates, and REE(±Ca) fluorocarbonates, occurring as single crystals and syntactic intergrowths (FIG. 4B, C). Isotopic data (Zaitsev et al. 2002) indicate that the primary REE minerals and their host rocks are cogenetic and derived from the same mantle sources. Burbankite-group phases are commonly replaced by complex intergrowths of REE, Sr, and Ba minerals, such as carbocernaite, ancylite, synchysite, bastnäsite, strontianite, and barite (FIGS. 3, 4D). These pseudomorphs result from hydrothermal and metasomatic reworking involving low- to medium-temperature fluids of different provenance and chemistry (Wall and Mariano 1996; Wall and Zaitsev 2004). Although hydrothermally overprinted carbonatites are very common, they rarely host REE mineralization of potential economic interest (FIG. 4E). During intense chemical weathering, rare earths are concentrated to weight-percent levels in thick saprolitic and lateritic profiles developed at the expense of plutonic carbonatites (e.g. Tomtor and Chuktukon in Siberia, Mt. Weld in Australia). However, the market competitiveness of supergene ores, which comprise a very fine-grained mixture of clays and secondary REE phosphates (monazite, xenotime, churchite, rhabdophane, and crandallite-group minerals), remains to be demonstrated.

Assuming carbonatitic magmas originate in the same enriched parts of the mantle as other undersaturated silicate rocks shown in FIGURE 1, how can we explain the extraordinary geochemical signature of carbonatites? In the context of the preceding discussion, is it plausible that their REE enrichment results from immiscible separation of hybrid carbonate–silicate melts tapping metasomatized peridotites? Or do these rocks represent highly evolved melts derived by fractional crystallization? Experimental evidence (FIG. 2) argues against liquid immiscibility as the driving force behind the REE enrichment (Veksler et al. 2012). However, D_{REE} values are very high in systems involving salt melts rich in P and F. The highest partition coefficients (215 for La and 94 for Lu) were observed for a fluoride–silicate system, implying that an immiscible carbonate melt strongly enriched in F, for example, may be capable of scavenging REEs from its source magma. A more straightforward mechanism of REE enrichment is fractional crystallization of REE-poor oxide and silicate minerals (forsterite, phlogopite, diopside, magnetite, and ilmenite); this mechanism is supported by the common association of carbonatites with cumulate clinopyroxene–magnetite and olivine–magnetite rocks. The flip side to fractional crystallization is that at high activities of F and P_2O_5, carbonatitic magma will precipitate copious amounts of apatite, which has a gargantuan appetite for REEs (FIG. 4F), but no demonstrated practical value as a source of these elements (e.g. Xu et al. 2010).

Peralkaline Undersaturated Rocks

These rocks are undoubtedly the most mineralogically exotic and challenging to study among all products of anorogenic magmatism. For example, Yakovenchuk et al. (2005) list 45 (!) rare earth minerals (not including those
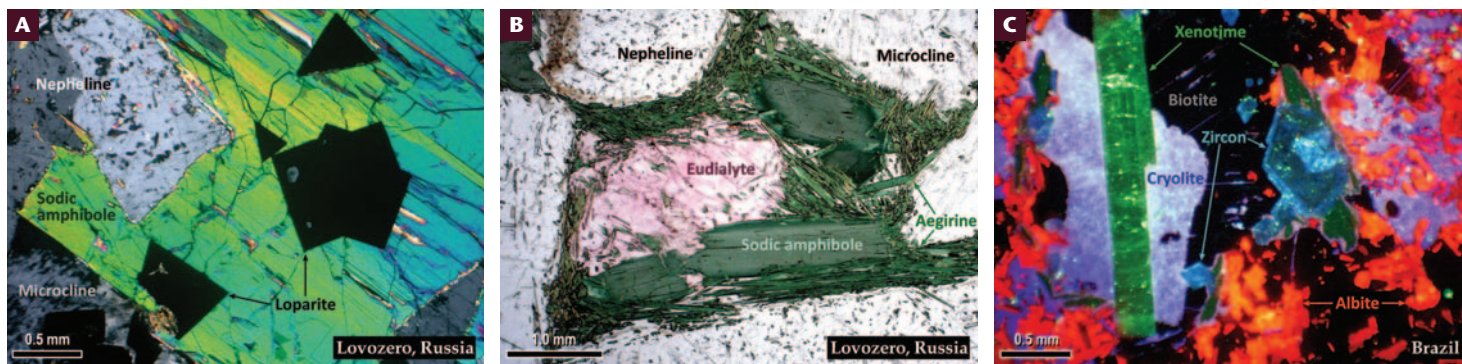
FIGURE 5 Selected REE host minerals in peralkaline rocks. (**A**) Loparite in nepheline syenite (crossed polars), (**B**) eudialyte in eudialyte lujavrite (plane polarized light), (**C**) cathodo-luminescence image of xenotime and associated minerals in peralkaline granite. PHOTO C COURTESY OF ANTHONY N. MARIANO

where REEs substitute for other cations) distributed throughout some 40 different rock types in the Khibiny alkaline complex (FIG. 3). Anyone interested in working with these unusual rocks will first need to learn a new language, because names like lujavrite, melteigite, and ijolite would probably perplex even a seasoned petrographer (and their correct pronunciation, an experienced linguist!). Khibiny, Lovozero (FIG. 3), and similar large composite plutons are products of the protracted evolution of alkali-rich and silica-undersaturated basic melts tapping a colossal volume of metasomatized mantle (e.g. on the order of several million cubic kilometers beneath Kola; Arzamastsev et al. 2001).

The structural and petrologic complexity of these complexes owes much to the differentiation of several compositionally distinct batches of magma emplaced in spatial and temporal proximity to one another (e.g. 377–362 Ma for Khibiny; Kramm and Sindern 2004). Some intrusions (e.g. Ilímaussaq in Greenland) offer compelling geochemical and geophysical evidence for a transient, deep-seated magma chamber where initial differentiation occurred (Sørensen 2006), whereas in other cases (e.g. Lovozero), geochemical data are at odds with geophysical models (cf Arzamastsev et al. 2001; Féménias et al. 2005). Plutonic feldspathoid syenites and their (sub)volcanic counterparts, phonolites, are the most voluminous products of magma evolution. Depending on the volatile content of the parental magma and the magma's ability to retain it, the predominant feldspathoid constituent may be nepheline or, less commonly, sodalite-group minerals. Abundant sodic clinopyroxenes and amphiboles (FIG. 5A, B) reflect the *peralkalinity* of these rocks, i.e. a surplus of Na + K over Al (in atomic terms) in their composition. Common "by-products" of the crystallization of such magmas are feldspar-poor rocks composed essentially of nepheline and ferromagnesian silicates; these rocks are typically referred to as the melteigite–ijolite–urtite series (with urtites being the most nepheline-rich members of the series).

There is a great deal of variation in the relative volumetric contribution and emplacement mode of individual rock types. The Khibiny pluton, for example, is a ring complex consisting predominantly (~60% by volume) of modally and texturally diverse nepheline syenites, some of which contain xenoliths of older alkali-ultramafic rocks. The syenite core and outer "ring" (FIG. 3) are separated by melteigite–ijolite–urtite series rocks whose temporal and structural relations with respect to the other units are a subject

of much debate (Arzamastsev et al. 2001; Yakovenchuk et al. 2005). The urtites host economically important apatite deposits (FIG. 3; see below).

In contrast to Khibiny, the smaller Lovozero complex is a layered intrusion whose lower part (~80% of the estimated volume) consists of a rhythmic sequence of nepheline (± sodalite) syenite, subordinate urtite, and modally transitional layers of variable thickness. Here, meso- to melanocratic trachytoid nepheline syenite (lujavrite) is the most volumetrically significant (~36%) rock type. The upper part of the Lovozero pluton is a crudely stratified package of eudialyte lujavrites reaching a thickness of 700 m and covering 44% of the pluton's exposed area (Bussen and Sakharov 1972).

In contrast to carbonatites, primary magmatic parageneses in peralkaline feldspathoid rocks lack monazite or REE carbonates (but see below). The bulk of their rare earth content is distributed between apatite-group phosphates and accessory zircono- and titanosilicates (e.g. eudialyte- and rinkite-group minerals); early crystallizing perovskite- and pyrochlore-group phases are much less common (Veksler and Teptelev 1990; Chakhmouradian and Mitchell 2002). Cumulate rocks containing large concentrations of REE-rich minerals form by gravity settling from extremely evolved magmas probably derived by fractional crystallization of feldspathoids, feldspars, and other minerals characterized by low $^{S/L}D_{REE}$ (e.g. Dawson et al. 2008). For example, the Na–REE–Ti–Nb oxide loparite (FIG. 5A) is a characteristic accessory constituent of many of the Lovozero rocks, but it is concentrated (2–4 vol%) in urtites and feldspar-bearing rocks transitional to lujavrites (Kogarko et al. 2002). Several of these loparite-rich units have been mined by underground methods since 1951 (FIG. 3 and cover of this issue). Loparite was the major source of LREE, Nb, and Ta for Soviet industry but is currently facing fierce competition from cheaper and easier-to-process ore types available in the global market. A potential alternative to loparite is the REE-bearing zirconosilicate eudialyte, which makes up >10 vol% (locally, up to 80 vol%) of eudialyte lujavrites and related rocks at Lovozero (FIGS. 3, 5B). Although the REE content of this eudialyte (~2.0–2.5 wt% REO) is lower than at some North American localities (Mariano and Mariano 2012), the Lovozero deposit is far superior to its potential rivals in tonnage and accessibility.

Other notable examples of REE-rich products of the protracted differentiation of peralkaline undersaturated magma include steenstrupine-bearing amphibole lujavrite at Ilímaussaq (Sørensen et al. 2011) and apatite–nepheline rocks at Khibiny (Kogarko et al. 1984). The apatite, mined for phosphate since 1929 (FIG. 3), contains ca 0.9 wt% REO with an appreciable proportion of HREEs (Samonov 2008). If these elements were extracted, the currently active mines could supply about 40% of the global rare earth demand.

Although some of the Russian apatite producers have expressed their interest in developing a REE separation technology at their chemical plants, it remains to be seen whether these efforts will materialize into a marketable and competitive product (see photo on p. 347).

Peralkaline feldspathoid rocks are commonly subjected to hydrothermal reworking and autometasomatism, whose effects are most conspicuous in pegmatites (e.g. Yakovenchuk et al. 2005). Such late-stage parageneses have been reported to contain HREE carbonate mineralization (e.g. shomiokite, mckelveyite, and related minerals; FIG. 3) arising from the decomposition of eudialyte and other primary minerals in extremely Na-rich carbothermal fluids (Pekov 2002). Although a mere mineralogical curiosity at present, this type of mineralization could be of practical interest if found in sufficient tonnages.

Peralkaline Granites

Granitic rocks differing in alumina, alkali, and Ca contents contain distinct, albeit overlapping, assemblages of accessory REE minerals, which account for 70–80% of the whole-rock rare earth budget in amphibole-rich metaluminous granites and >90% in peraluminous and peralkaline types (Bea 1996). The highest concentrations of REEs (commonly, in the 300–800 ppm range) are found in anorogenic peralkaline granites and associated pegmatites; there does not appear to be any consistent correlation between the REE geochemistry of these rocks and their different proposed modes of origin (see above). Extremely evolved systems attain much higher levels of enrichment through a combination of fractional crystallization and concentration of REEs in F-rich residual melts (e.g. Strange Lake, Canada; Boily and Williams-Jones 1994). One remarkable characteristic of peralkaline granites, which makes them an attractive exploration target, is their enrichment in HREEs relative to other igneous rocks (FIG. 1); for example, $(La/Yb)_N = 2–10$ and $Y/Nd \geq 1$. This peculiar element distribution is usually interpreted in terms of the low solubility of monazite in silicic melts (see above), resulting either in retention of LREEs in their monazite-bearing crustal source or in early removal of LREEs from the magma. The HREE enrichment of evolved granites is likely enhanced by fractional crystallization of feldspars ($^{S/L}D_{LREE} \gg \, ^{S/L}D_{HREE}$; e.g. Dawson et al. 2008), which is also responsible for the conspicuous negative Eu anomaly ($Eu/Eu^* \leq 0.6$) in their normalized patterns (FIG. 1).* It is not surprising, therefore, that in addition to monazite and allanite, which are typical LREE hosts in most granitoids, peralkaline varieties contain such HREE minerals as xenotime (FIG. 5C), fergusonite, samarskite, and gagarinite (Bea 1996; Bastos Neto et al. 2009). Other notable rare earth hosts include primary zirconosilicates (ranging from zircon to eudialyte and elpidite, depending on the activity of Na and silica in the system) and pyrochlore. Hydrothermally modified deposits also contain an assortment of exotic silicate, fluorocarbonate, and mixed-radical phases whose precipitation is controlled by the relative mobility of REEs in fluids of different chemistry and by fluid–rock interactions (Williams-Jones et al. 2012). If proven competitive relative to low-cost "ionic clay" operations in China (Kynicky et al. 2012), REE recovery from the mineralogically complex Strange Lake ore and from xenotime-bearing tailings of the Pitinga Sn–Nb–Ta mine in Brazil will hopefully pave the way for the development of other granite-based polymetallic projects.

Granitic Pegmatites

In addition to peralkaline granites (see above), their sub- to metaluminous counterparts in post- or anorogenic settings may be associated with pegmatites containing appreciable LREE (allanite–monazite subtype) or HREE (gadolinite subtype) mineralization (Černý 1997). Although pegmatites were the first bedrock source of REEs exploited in the first half of the 1900s to meet an increasing demand for Ce, Y, and actinides, these operations were small and short-lived. Apart from small tonnages, another handicap of these deposits is their "difficult" mineralogy, which incorporates a spectacular variety of REE hosts but is characterized by fairly low concentrations of minerals amenable to easy metal recovery. Interested readers are referred to Linnen et al. (2012) for further information.

Iron Oxide–Phosphate Deposits

Iron oxide–phosphate (± Ti) deposits are associated with a wide spectrum of igneous rocks (including anorthosites, gabbroids, felsic volcanics, alkaline-ultramafic intrusions, and carbonatites) and undoubtedly have a multiplicity of origins. Their REE budget is dominated by apatite (typically, ≤1 wt% REOs, but rarely up to 10 wt%) and, at some localities, small (10–150 μm) inclusions of monazite and xenotime formed during postmagmatic reequilibration of the apatite with a fluid (Harlov et al. 2002). With the possible exception of Mineville in the USA (Mariano and Mariano 2012), these deposits are not economic to develop exclusively for their rare earth content but may serve as a source of by-product REEs in large-scale iron ore or apatite mining operations.

PARTING THOUGHTS

Our current understanding of REE deposits is too fragmentary and too "crustal" (i.e. lacking in depth) for the development of an integrated metallogenic model in any foreseeable future. We are just beginning to appreciate the scale and significance of the mantle processes responsible for rare-element transport and enrichment in parts of the lower continental crust and subcontinental lithosphere. Another highly speculative area is the behavior of rare earths in those natural systems whose complexity has thus far thwarted all experimental and thermodynamic attempts at modeling their evolutionary pathways. For example, we still know next to nothing about the relative stability of different REE–Nb–Ta oxides in silicate magmas and REE partitioning between carbonate minerals and melts. Equally obscure (and underappreciated) is the fate of Y and lanthanides in synemplacement contact metasomatism, postmagmatic deformation, and metamorphism. Needless to say, work in any of these or other knowledge-gap areas will offer great intellectual rewards to researchers willing to embrace the challenge.

ACKNOWLEDGMENTS

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* The Eu/Eu* ratio stands for the normalized Eu concentration divided by the value interpolated from the abundances of its neighboring elements; i.e., $Eu/Eu^* = Eu_N/(0.5Sm_N + 0.5Gd_N)$.

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The image shows synchysite/parisite (blue), barite (yellow-green), quartz (pink) and iron and manganese oxides/carbonates (black and purple) replacing bastnäsite-(Ce) (orange) in a rare earth ore from Mountain Pass, California, USA.

Hydrothermal Mobilisation of the Rare Earth Elements – a Tale of "Ceria" and "Yttria"

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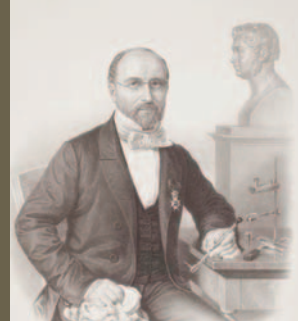
Carl Gustaf Mosander holding a blow-torch next to a bust of his mentor Jöns Berzelius. COURTESY OF THE SWEDISH MUSEUM OF NATURAL HISTORY

Although the rare earth elements have been thought by many to be immobile in hydrothermal fluids, we have known since the first attempts to separate them in the early nineteenth century that they are soluble in aqueous solutions. Driven by a need to isolate individual REEs for industrial applications, and more recently to explore for them, we have started to develop an understanding of their solubility and speciation in hydrothermal fluids. This knowledge is allowing us to understand the processes that promote their transport in the Earth's crust, their concentration, and their fractionation.

KEYWORDS: REE, hydrothermal, solubility, speciation, ore formation

INTRODUCTION

Our story of the hydrothermal mobility of the rare earth elements (REEs) has its origins in the 650-year-old Bastnäs base metal mining district of Sweden, where a dense reddish mineral, referred to as Bastnäs tungsten (heavy stone), was found in the 1740s. Nothing came of this discovery, however, until 1794 when an unusual black mineral (later named gadolinite), found some years earlier in a feldspar mine at Ytterby, near Stockholm, was shown by the Finnish chemist Johan Gadolin to contain 38% by mass of a new "earth". This prompted Wilhelm Hisinger, a wealthy foundry proprietor, to speculate over whether the same earth might also be present in Bastnäs tungsten, which he had seen, and been intrigued by, as a teenager. By 1804, he and Jöns Berzelius, the famous Swedish chemist, had demonstrated that this earth and a second new earth were, indeed, present in the Bastnäs mineral (later named cerite to celebrate the discovery of the dwarf planet Ceres; FIG. 1). The two earths became known as "yttria" and "ceria". During the next 100 years, through careful and painstaking separation techniques, they would be shown to be mixtures of oxides and, between them, to contain 16 of the 17 REEs, with the heavy REEs (corresponding to europium and lanthanides of higher atomic number, plus yttrium and scandium; HREEs) concentrated mainly in "yttria" and the light REEs (LREEs) in "ceria".

"These elements [the rare earths] perplex us in our researches, baffle us in our speculations and haunt us in our very dreams. They stretch like an unknown sea before us, mocking, mystifying and murmuring strange revelations and possibilities."

—Sir William Crookes, in an address to the British Association, February 16, 1887

Significantly for our story, the REEs at Bastnäs owe their concentration to hydrothermal processes. They are restricted to a narrow zone of dolomitic marble in which the carbonate has been replaced by magnetite, tremolite, talc, and the REE minerals cerite-(Ce) and ferri-allanite-(Ce) (Holtstam and Andersson 2007). In contrast to Bastnäs, the REE mineralisation at Ytterby occurs in a granitic pegmatite as gadolinite-(Y), fergusonite-(Y), allanite-(Ce) and xenotime-(Y). In another contrast to Bastnäs, except for allanite-(Ce), these are all HREE-rich minerals.

THE AQUEOUS SEPARATION OF THE REEs

The first indication that understanding the behaviour of the REEs in water would be important came in 1839 when Carl Mosander (a student of Berzelius) established that the "ceria" separated by Hisinger and Berzelius from Bastnäs tungsten was actually a mixture. Mosander observed that "nitric acid diluted with 75 to 100 parts of water...leaves the greater part of the red-brown oxide ('ceria') undissolved, and from the solution thus obtained, the oxide of lanthanum was derived"; he precipitated it using potassium hydroxide (Mosander 1843). Mosander had discovered that lanthanum (Greek, to lie hidden) oxide is more soluble in dilute acids than cerium oxide. A year later, Mosander realised that even his lanthanum oxide was not pure, and, using the same differential solubility of the lanthanum oxide in dilute acids that he had seen with cerium oxide, he was able to separate a new, more soluble, earth, which he named didymium oxide (twinned with lanthanum). Didymium oxide also turned out to be a mixture, and was eventually separated into oxides of samarium (1879), praseodymium (1885), neodymium (1885) and europium (1896).

Having shown that "ceria" was a mixture of rare earths, Mosander turned his attention to "yttria" and, using the same approach as he had with "ceria", separated "yttria" into yttrium, erbium and terbium oxides; he did this by fractionally precipitating them from a hydrochloric acid solution using ammonium hydroxide. In so doing, he showed yttrium to be the most soluble of these earths, followed by erbium and terbium (Mosander 1843). As with

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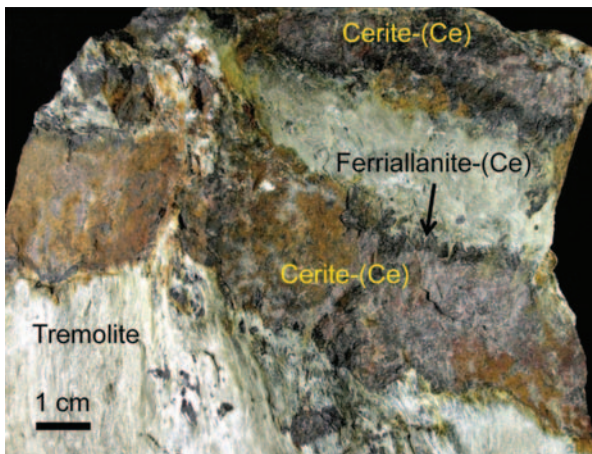
FIGURE 1 Layers of Bastnäs tungsten (red), later named cerite-(Ce), bounded by black ferriallanite-(Ce) in tremolite from the Sankt Göransgruvan mine, Bastnäs, Sweden. PHOTO BY DAN HOLTSTAM

"ceria", his "erbium" and "terbium" proved to be mixtures, and it took other chemists until the beginning of the 20th century to isolate the remaining six naturally occurring rare earths.

Although Mosander had demonstrated that the rare earths vary in their solubility in aqueous fluids, it was not until nearly 60 years later that the first quantitative experiments investigating this solubility were conducted. These experiments, which involved dissolving REE oxides in an aqueous ammonium oxalate solution, showed that solubility increased in the sequence La_2O_3, Pr_2O_3, Nd_2O_3, Ce_2O_3, Y_2O_3 and that the solubility of Y_2O_3 is an order of magnitude greater than that of the next most soluble rare earth oxide, Ce_2O_3 (Brauner 1898). By the mid-1920s, the serial behaviour of the REEs had been established, driven by the need to separate them for industrial applications. The solubility of the lanthanides had been shown to increase with atomic number [trivalent cerium salts were found to have lower solubility than measured by Brauner (1898), that is, their solubility was between that of the salts of lanthanum and praseodymium], and the salts of yttrium were shown to have a solubility between that of the salts of dysprosium and holmium, corresponding to the position of yttrium in the REE series based on ionic radius (Williams et al. 1925). At this time, researchers were also observing that the solubility of the REEs varied considerably with the nature of the salt. Thus, consistent with Pearson's rules (see below), Crew et al. (1925) observed that YCl_3 is more soluble in water than YBr_3, and that $Y(NO_3)_3$ is more soluble in water than both these salts. They had, in effect, demonstrated that the stability of complexes involving yttrium increases with the nature of the ligand, in the sequence Br, Cl and NO_3.

AQUEOUS COMPLEXATION OF THE REEs AT AMBIENT TEMPERATURE

Investigations of the stability of aqueous REE complexes date back to the early part of the 20th century (e.g. Noyes and Johnston 1909), but it was not until the 1950s that the thermodynamic properties needed to quantitatively evaluate this stability were measured (e.g. Izatt et al. 1955). Since then, a large number of studies, employing a variety of methods, have determined these properties at ambient temperature for all the REEs, except promethium, with the ligands commonly found in nature. However, until recently, there has been little agreement on the stability of the

different complexes as measured by their formation constants, and very few of the research groups publishing these studies have investigated the REEs systematically as a group or considered multiple ligands (Wood 1990a).

Important insight into the stability of aqueous REE complexes can be gained using Pearson's rules (Pearson 1963), which state that hard (not polarisable) cations will bond preferentially with hard anions (ionically) and soft (polarisable) cations will bond preferentially with soft anions (covalently). Because REE ions have a preferred charge of +3 (Ce and Eu can also be quadrivalent and divalent, respectively) and their ionic radii are relatively small, they are hard cations. Thus, if we restrict the list to inorganic ligands, the order of monovalent ligands with which the REEs should form their most stable aqueous complexes is $F^- > OH^- > NO_3^- > Cl^- > Br^-$ (Pearson 1963). For complexes involving divalent ligands, the order should be $CO_3^{2-} > SO_4^{2-} > P_2O_5^{2-}$. Although, as noted above, all the REEs are hard, Ce^{4+} is the hardest, with a charge/radius ratio in octahedral coordination of 3.96, and Eu^{2+} is the softest, with a charge/radius ratio of 1.53. The charge/radius ratios of the trivalent lanthanides increase with atomic number, from 2.56 for La^{3+} to 3.00 for Lu^{3+}; Y^{3+} has a charge/radius ratio of 2.88, almost identical to that of Ho^{3+}, and Sc^{3+} has a charge/radius ratio of 3.39. Thus, based on Pearson's rules, the stability of complexes of the trivalent REEs involving a hard ligand like F^- or CO_3^{2-} is predicted to increase systematically along the lanthanide series from La to Lu, with Y occupying a place between Ho and Er and Sc situated beyond Lu.

Since the mid-1990s, research groups led by R. Byrne and J. Schijf at the University of Florida and F. Millero and Y. Luo at the University of Miami have investigated the aqueous speciation of the REEs systematically for a large number of ligands. We consider the data reported by these groups to be the most consistent and accurate available on the stability of the REEs at ambient temperature. Moreover, the order of stability of the complexes is consistent with the predictions of Pearson's rules. The stability of REE complexes with hard ligands such as F^- and CO_3^{2-} is an order of magnitude greater than with ligands of intermediate hardness, like Cl^-, and the stability for a particular ligand increases with the hardness of the REE (Schijf and Byrne 1999; Luo and Byrne 2001). Significantly, however, the stability of complexes of the REEs with SO_4^{2-}, which ranks behind F^- and CO_3^{2-} in terms of hardness, varies little with the hardness of the corresponding REE, and complexes with the borderline ligand Cl^- decrease in stability with increasing REE hardness (Luo and Byrne 2001).

BEHAVIOUR OF THE REEs AT HIGH TEMPERATURE AND PRESSURE

Despite a long history of experimental investigations showing that the rare earth elements form stable aqueous complexes with a variety of ligands at ambient temperature, geochemists were long divided over whether the REEs are mobile or immobile during fluid–rock interaction. Indeed, REE abundance patterns have been used routinely to characterise geological processes related to the formation of igneous and sedimentary rocks, even where such rocks have been subjected to hydrothermal alteration (e.g. Herrmann et al. 1974). The occurrence of REE deposits of indisputable hydrothermal origin, however, including the giant Bayan Obo REE deposit in China (Chao et al. 1992; Smith and Henderson 2000), leaves little doubt that, at least in some geological environments, the REEs are highly mobile.

Information on the stability of REE complexes at high temperature and pressure was initially limited to theoretical estimates based on extrapolations of thermodynamic data available at 25 °C (Wood 1990b; Haas et al. 1995). These estimates reproduced the stability relationships discussed above for REE species at ambient temperature, predicting that the REEs will form their strongest bonds with ligands like F⁻ and that complexes of the HREEs will be more stable than those of the LREEs. They also served as a source of data with which to model the hydrothermal behaviour of the REEs in ore-forming environments and, among other things, they led to the conclusion that in environments in which the REEs are concentrated to economic or potentially economic levels, they are invariably transported as REE fluoride complexes.

During the past 15 years, a research group at McGill University, led by Migdisov and Williams-Jones, has systematically investigated the speciation of the REEs experimentally in fluoride- and chloride-bearing aqueous solutions at temperatures up to 300 °C and pressures up to 100 bar. Some experimental data have also been gathered for REE sulfate species, but none for REE carbonate or REE phosphate species, which are predicted to be relatively stable. These studies have shown that the high-temperature behaviour of the REEs differs in important respects from that inferred from theoretical models.

The theoretical models significantly overestimate the stability of REE fluoride species at elevated temperature, and this difference increases with increasing temperature. Moreover, the difference is much greater for the HREEs than the LREEs (Fig. 2A). Thus, contrary to the theoretical models (e.g. Haas et al. 1995), which conform with the hard–soft predictions of Pearson's rules, experimental determinations show that LREEF²⁺ species are more stable than HREEF²⁺ species at elevated temperature (Migdisov et al. 2009). This change in the relative stability of LREEF²⁺ and HREEF²⁺, from that at ambient temperature, occurs at approximately 150 °C.

Experimental determinations of the formation constants of REE chloride species show that they behave similarly to REE fluoride species, that is, above 150 °C their stability decreases along the lanthanide series from Ce to Lu (there are no data for yttrium chloride species), and this effect increases with increasing temperature (Fig. 2B). Consistent with the classification of Cl⁻ as a borderline base, the data of Haas et al. (1995) predict relatively little variation in stability from LREE to HREE. Consequently, they underestimate the stability of the LREEs and overestimate the stability of the HREEs (Migdisov et al. 2009). Experimentally determined stability data for REE sulfate complexes are limited to Nd, Sm and Er. These data show, in contrast to the data for REE fluoride and REE chloride complexes, that all the REE sulfate complexes have relatively similar stability, in agreement with theoretical predictions (Migdisov and Williams-Jones 2008). However, the formation constants are somewhat lower than predicted theoretically.

The reason that the stability of REE complexes involving halogens is opposite to that predicted by Pearson's rules is the very large decrease in the dielectric constant of water with temperature. Under ambient conditions, the high dielectric constant and resulting hydrogen bonding lead to strong shielding of aqueous ions and inhibition of electron transfer. At higher temperature, however, the decrease in the dielectric constant reduces resistance to electron transfer, promoting "softening" of ions (Cárdenas et al. 2011). The overall hardness of the REEs therefore decreases with increasing temperature, but their relative hardness is unaffected. By contrast, the "softening" of the ligands does affect the relative stability of the corresponding REE complexes. As discussed earlier, the stability of REE species involving the hard anion F⁻ increases with the hardness of the REEs at 25 °C (from LREEs to HREEs), consistent with the "hard cation prefers hard anion" Pearson's rule, whereas the stability of REE complexes involving the borderline chloride ion decreases with increasing REE hardness. At higher temperature, the chloride ion is softer than at 25 °C, and therefore the decrease in REE chloride stability with increasing REE hardness should be even greater than at 25 °C. This is precisely what is observed experimentally. Similarly, the increase in REE fluoride stability with increasing REE hardness should be smaller or even reversed at higher temperature. The latter is observed experimentally. Unfortunately, we cannot explain why the stability of REE sulfate species is independent of REE hardness at both low and high temperature, but we suspect that the answer lies in the more complex nature of the sulfate species and a different behaviour in the presence of water than that of simple anions.

REE ORE DEPOSITS

Our best insights into the hydrothermal mobility of the REEs come from ore deposits that have been affected by hydrothermal processes or are of hydrothermal origin. These deposits are genetically associated with carbonatites and peralkaline silicate rocks, and typically contain the REEs in weight percent concentrations. Commonly they contain fluid inclusions, and in many cases, the inclusions are solid-bearing. Some even contain REE minerals (Fig. 3).
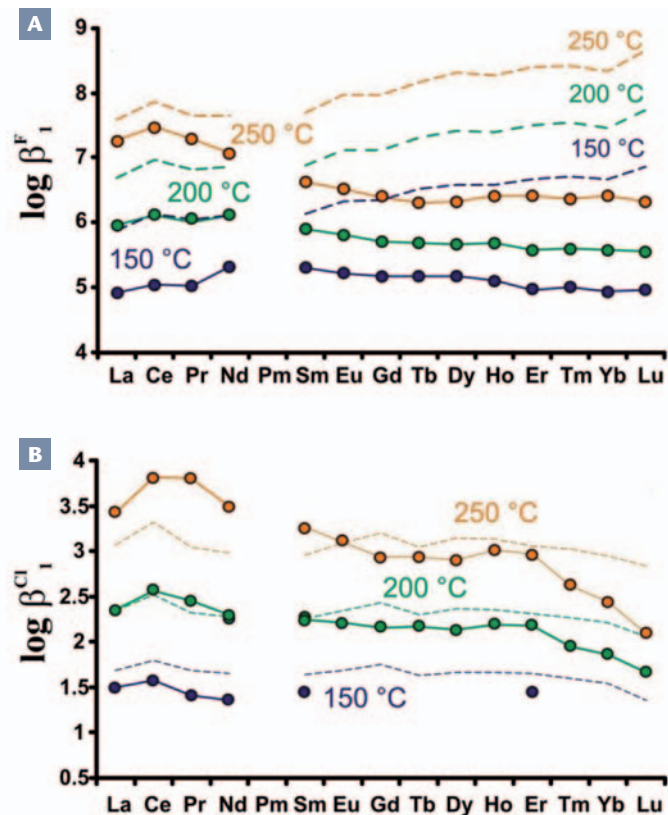
FIGURE 2 Values of the first formation (stability) constant, $\log \beta_1$, of REE fluoride complexes (**A**) and REE chloride complexes (**B**) at various temperatures. The solid lines represent experimental data from Migdisov et al. (2009) and the dashed lines theoretical estimates from Haas et al. (1995).
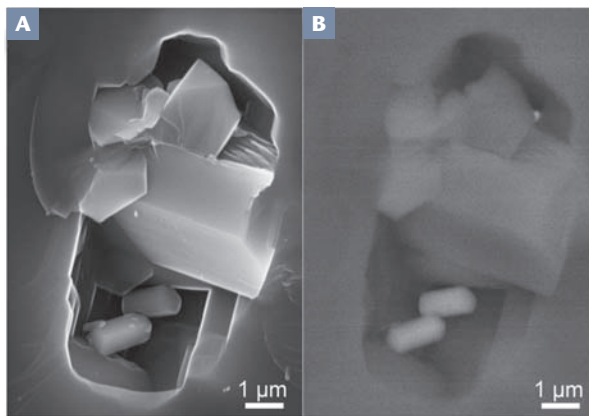
The largest of these deposits is Bayan Obo, China, which is currently responsible for 45% of global REE production and has reserves of 135 million tonnes grading 6 wt% REE_2O_3. The REE mineralisation is hosted by a dolomitic unit (most agree that this unit is sedimentary), and is LREE-enriched, epigenetic, and hydrothermal in origin. There are two principal orebodies, Main and East. These comprise: (1) an early, marginal disseminated monazite-(Ce) stringer facies containing 3 to 6 wt% REE_2O_3; (2) an inner, layered facies containing 6 to 12 wt% REE_2O_3, in which dolomite was replaced by monazite-(Ce), bastnäsite-(Ce), fluorite, apatite, aegirine, magnetite and hematite; and (3) a massive central iron oxide facies containing <3 wt% REE_2O_3 (Chao et al. 1992). Based on minimum trapping temperatures of fluid inclusions, the ores are interpreted to have formed between 300 and 400 °C from brines containing 7 to 10 wt% NaCl equivalent (Smith and Henderson 2000). Other examples of REE deposits that are of indisputable hydrothermal origin are the Gallinas Mountains deposit, New Mexico, in which a fluorite–bastnäsite-(Ce) assemblage cemented quartz syenite and sandstone breccias (Williams-Jones et al. 2000), and the Karonge deposits in Burundi, which occur as centimetre- to decimetre-thick bastnäsite-(Ce) veins and stockworks in granitic gneiss (Lehmann et al. 1994). The Gallinas Mountains deposit is interpreted to have formed between 300 and 400 °C from brines containing 12 to 18 wt% NaCl equivalent, and preliminary data for the Karonge deposits suggest that they formed at >420 °C from a brine containing >25 wt% NaCl equivalent. The hydrothermal REE deposits described above and others of which we are aware are all LREE-enriched.

Major deposits in which the REEs were concentrated by a combination of magmatic and hydrothermal processes include the Nechalacho deposit, Northwest Territories, Canada, with an indicated resource of 88 million tonnes grading 1.53 wt% REE_2O_3, and the Strange Lake deposit in Québec-Labrador, Canada, with an indicated resource of 66 million tonnes grading 1.52 wt% REE_2O_3. Both deposits are characterised by high proportions of HREEs. The Nechalacho deposit is hosted by a layered, silica-undersaturated alkaline complex in which the primary magmatic REE mineralisation formed as a result of gravity settling of eudialyte (a complex zirconosilicate containing ~7 wt% REE_2O_3) and zircon (containing ~3 wt% REE_2O_3) (Sheard et al. 2012). Hydrothermal fluids subsequently dissolved these minerals and reprecipitated the REEs as fergusonite-(Y),

secondary zircon, allanite-(Ce), bastnäsite-(Ce) and monazite-(Ce). The HREEs were deposited proximal to the precursor minerals, whereas the LREEs were mobilised on a scale of metres and perhaps tens of metres. At Strange Lake, the REE mineralisation is hosted by rare-metal pegmatites in a peralkaline granite pluton and was the product of end-stage crystallisation of a fluorine-rich magma that was highly enriched in incompatible elements, including the REEs. Hydrothermal fluids remobilised REEs contained in primary pyrochlore, zircon (~4 wt% REE_2O_3) and monazite-(Ce), and redeposited them largely within the confines of the pegmatites as allanite-(Ce), gadolinite-(Y) and kainosite-(Y). Fluid inclusion analyses indicate that the remobilisation took place at temperatures ranging from 350 °C to <150 °C and involved interaction of sodic magmatic brines with lower-temperature calcic brines (Salvi and Williams-Jones 1996). For some other descriptions of the hydrothermal mobility of the REEs in ore systems or systems that may be potentially ore-forming, readers are referred to Ngwenya (1994), Gieré (1996), Oliver et al. (1999) and Rankin (2005).

HYDROTHERMAL TRANSPORT AND DEPOSITION OF REE MINERALS

In the preceding sections, we established that the REEs are readily concentrated by hydrothermal processes, that the LREEs are more mobile hydrothermally than the HREEs, that the REEs form stable complexes with fluoride and chloride ions at high temperature (and likely sulfate, carbonate and phosphate), and that the LREE complexes with these ligands are more stable than their HREE counterparts. Our review of REE deposits, above, showed that the fluids involved in REE transport and deposition commonly have a high chloride and possibly fluoride activity (there is commonly a close association between hydrothermal REE mineralisation and fluorite).

We begin our analysis of hydrothermal REE transport and deposition by using the available thermodynamic data for REE fluoride and REE chloride complexes to evaluate the speciation of the REEs as a function of pH and temperature. Unfortunately, although the chlorinity of REE-depositing hydrothermal systems is well known, the fluorinity is poorly known. The only measurements of the concentration of fluorine in hydrothermal fluids that have precipitated REE minerals are those of Banks et al. (1994) for magmatic–hydrothermal fluid inclusions from veins in the Capitan Pluton, New Mexico. This study also analysed the REE content of the fluid. If we assume that the ore fluid contained 10 wt% NaCl (see above), 500 ppm F and 200 ppm Nd (Banks et al. 1994) and is undersaturated with respect to solids, the data of Migdisov et al. (2009) predict that at 200 °C, NdF^{2+} is the dominant dissolved species for pH values above 3 and that $NdCl^{2+}$ becomes important at this pH at higher temperature. At 400 °C, $NdCl^{2+}$ is the dominant species for pH values below 7. From this analysis, it might appear that both fluoride and chloride species play a role in REE transport, depending on the temperature and pH. However, whereas REE chloride minerals are relatively soluble at ambient and higher temperature, REE fluorides are extremely insoluble even at high temperature, which places an upper limit on the amount of REEs that can be transported as REE fluoride complexes. At a pH of 3 and a temperature of 400 °C, the concentration of dissolved Nd is 200 ppm, mainly as $NdCl^{2+}$ (FIG. 4A). Increasing the pH to 5, however, reduces the solubility to <1ppm, because of HF dissociation and resultant NdF_3 [fluocerite-(Nd)] saturation; more fluoride ions are available to bind with the REEs and precipitate fluocerite. Decreasing temperature has the same effect: HF dissociates, reducing NdF_3 solubility

(Fig. 4B). Thus, although the high stability of REE fluoride complexes has led many to assume that these species control the transport of REEs in ore-forming hydrothermal systems, this is unlikely to be the case. Instead, fluoride acts a binding ligand that promotes precipitation of REE minerals such as fluocerite-(Ce) and, more importantly, bastnäsite-(Ce), the main REE ore mineral. The very low solubility of monazite-(Ce) allows the same conclusions to be drawn for phosphate. It thus seems probable that chloride species transport the REEs in most hydrothermal systems.

The deposition of the REEs as bastnäsite-(Ce) can be described by the reaction:

$$REECl^{2+} + HF + HCO_3^- = REECO_3F + 2H^+ + Cl^-,$$
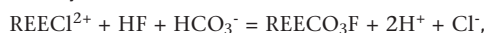
where $REECO_3F$ is bastnäsite-(Ce), and thus any mechanism that leads to an increase in pH and/or HCO_3^- activity or a decrease in Cl^- activity will lead to deposition of bastnäsite-(Ce). At Bayan Obo, the host for the REE mineralisation is a dolomite. Reaction of the ore fluid with this lithology provides a very effective mechanism for ore deposition because of the reaction:

$$2H^+ + CaMg(CO_3)_2 = Ca^{2+} + Mg^{2+} + 2HCO_3^-,$$
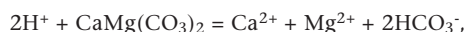
which leads to sharp increases in both pH and HCO_3^- activity. The mechanism also elegantly explains the intimate association of bastnäsite-(Ce) with fluorite in the deposit and in other deposits similar to it. Like the REE fluoride and fluorocarbonate minerals, fluorite is extremely insoluble, and thus any free fluoride will deposit as fluorite

when brought into contact with a source of calcium. Hydrothermal REE deposits do not, however, form invariably through reaction with dolomite and limestone, and for hosts with low Ca content, it is attractive to call on mixing of the ore fluid with formational waters of higher pH, lower temperature and elevated activity of calcium (and bicarbonate ions in the case of bastnäsite) to explain coincident fluorite and REE-mineral deposition, for example, at Gallinas Mountains.

Although it is important to provide depositional models that satisfactorily explain the formation of deposits like Bayan Obo, which we have argued are hydrothermal in origin, it is equally important to explain the hydrothermal mobilisation of the REEs in deposits like Nechalacho, which formed initially through magmatic concentration. A feature of these deposits, which was commented upon above, is that the LREEs were preferentially mobilised to significantly greater distances from their magmatic source than the HREEs. We have modelled this scenario using a system in which aliquots of REE-bearing fluid (equal proportions of each REE) pass through and react with a phosphorus-bearing (100 ppm P) nepheline syenite, depositing monazite. The NaCl content of the fluid was assumed to be 10 wt% NaCl and the pH 4.5. Thermodynamic data for monazite were taken from Popa et al. (2007) and for the REE species from Migdisov et al. (2009). The fluid was assumed to cool from 400 to 200 °C at 500 bar (Fig. 5A).

At the start of the reaction, monazite, containing equal proportions of each REE, precipitated. With progressive fluid–rock interaction, the pH buffering capacity of the rock decreased. Consequently, the LREEs were leached and reprecipitated farther along the unit at lower temperature (Fig. 5B). Early monazite was thus replaced by monazite containing progressively heavier REEs, and the REEs were
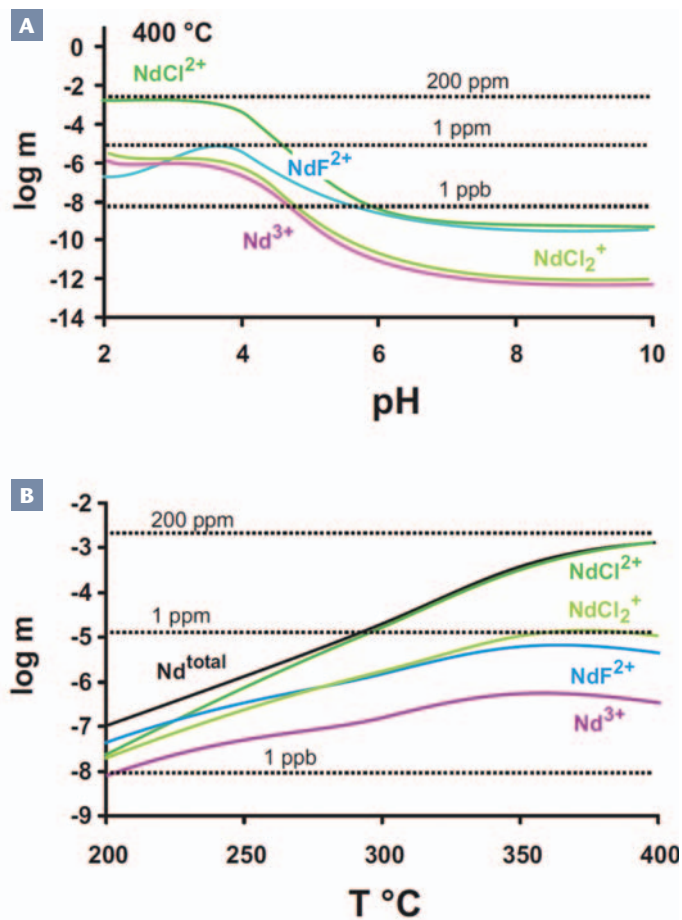
FIGURE 4 Concentration of aqueous Nd species (log molality), as a function of pH at a temperature of 400 °C (A), and as a function of temperature at a pH of 3 (B). The fluid contained 10 wt% NaCl, 500 ppm fluorine and 200 ppm Nd.
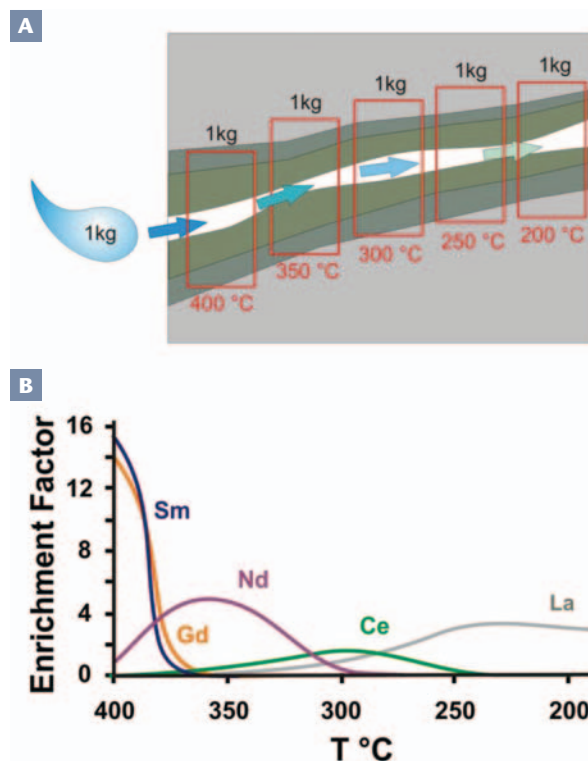
FIGURE 5 (A) Progressive interaction of 1 kg of nepheline syenite containing 100 ppm phosphorus with successive 1 kg aliquots of fluid containing 10 wt% NaCl, 500 ppm F and 50 ppm each of La, Ce, Nd, Sm and Gd. The initial pH was 4.5 and the fluid cooled from 400 to 200 °C at 500 bar. (B) Fractionation of the REEs after interaction of the rock with five aliquots of fluid. The enrichment factor is defined as $(REE/\Sigma REE)_{Rock}/(REE/\Sigma REE)_{Initial\ solution}$.

gradually fractionated along the fluid path; HREEs were restricted to the high-temperature input zone, and LREEs migrated from it. The model demonstrates convincingly that interaction of a flux of saline hydrothermal fluid with primary magmatic REE mineralisation will lead to the preferential mobilisation of LREEs and their transport to locations distal from that mineralisation.

CONCLUDING REMARKS

Although the rare earth elements continue to "perplex us in our researches," as they did Sir William Crookes over 125 years ago, they have also continued "murmuring strange revelations and possibilities." If we are interpreting them correctly, they have started to show us how the REEs are mobilised by hydrothermal processes and concentrated to exploitable levels. We have learned that the REEs form stable aqueous fluoride and chloride complexes, and probably also carbonate, sulfate and phosphate complexes. However, it seems that only chloride complexes can mobilise the REEs in appreciable quantities. We therefore conclude that hydrothermal concentration of REEs occurs mainly when fluids containing these complexes interact with cooler, pH-neutralising rocks, or mix with cooler, pH-neutralising fluids. In so doing, these processes have helped create strategic resources for a society increasingly dependent on new technologies.

ACKNOWLEDGMENTS

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Diversity of Rare Earth Deposits: The Key Example of China

Banded ore of the Bayan Obo deposit

Jindrich Kynicky[1], Martin P. Smith[2] and Cheng Xu[3]

As a source of strategic commodities for high technologies, the deposits of rare earth elements (REEs) in China are a world-class phenomenon. The combination of the world's largest accumulation of REEs in the Bayan Obo deposit and the low cost of mining the extremely valuable heavy REEs from residual deposits makes China almost a monopoly producer. Research on a range of Chinese deposits shows that not only hypogene but also secondary processes create economic REE deposits. These deposits have characteristic REE distribution patterns, which range from primary light REE enrichment in carbonatites from the Himalayan Mianning–Dechang orogenic belt and in metamorphosed carbonatite and polyphase mineralization at Bayan Obo, through unusual flat REE patterns in carbonatites from the Qinling orogenic belt, to strong secondary heavy REE enrichment in residual clays from southern China.

KEYWORDS: rare earth deposits, Bayan Obo, ion-adsorption clays, carbonatites, China

INTRODUCTION

Since the mid-1980s, China has been the dominant producer of rare earth elements (REEs). It currently accounts for over 90% of the world's output and hosts approximately 50% of the known global reserves (Tse 2011). This dominance of the global market is related to the discovery, in 1927, of the Bayan Obo deposit in Inner Mongolia. Other significant deposits occur associated with carbonatites in the Himalayan Mianning–Dechang belt and the Qinling orogenic belt; still others are associated with lateritic ion-adsorption clay deposits in southern China (TABLE 1). The lateritic deposits are important because of their higher relative proportions of the heavy REEs (HREEs), which are industrially and economically the most significant. Thirty years of weakly regulated REE mining in China have also left a legacy of environmentally damaging accidents and contamination, which are currently being addressed through significantly tightened environmental standards in mining and ore processing. In this paper, we review the main REE deposit types in China (TABLE 1; FIG. 1) and document the geological reasons for China's impressive REE endowment.

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DIVERSITY OF REE DEPOSITS IN CHINA

Rare earth deposits in China show a wide spatial distribution and are associated with rocks of carbonatitic affinity or with weathered granitic rocks (FIG. 1). Current mining activities are focused on three main deposit types:

1 Proterozoic dolomitic marbles affected by fluids of carbonatitic affinity (Bayan Obo) in northern China

2 Deeply weathered residual deposits (ion-adsorption clays) in southern China

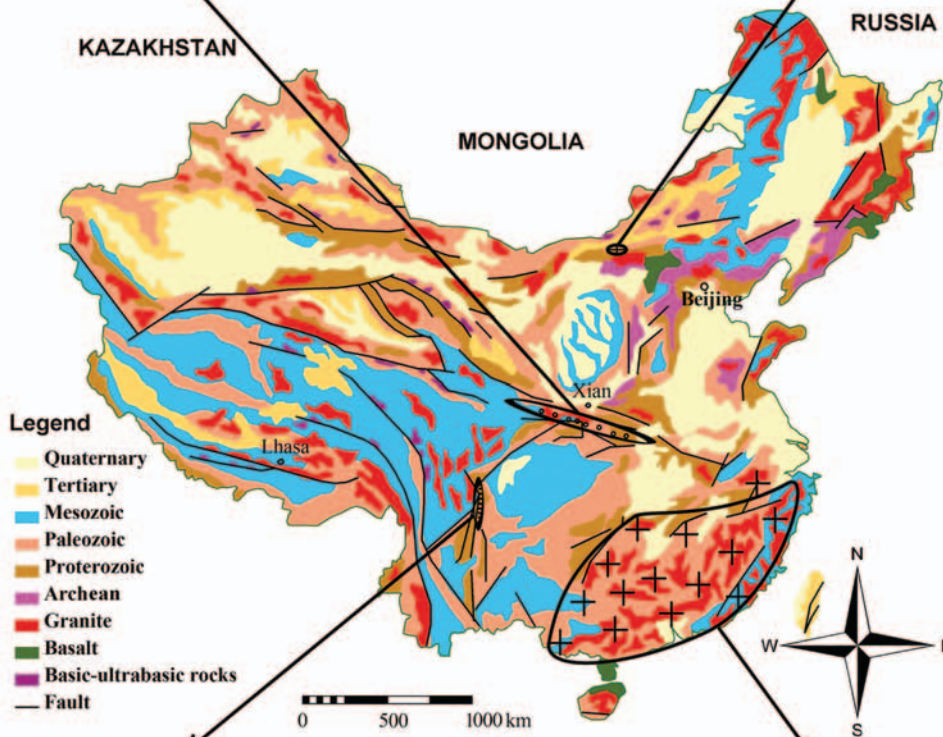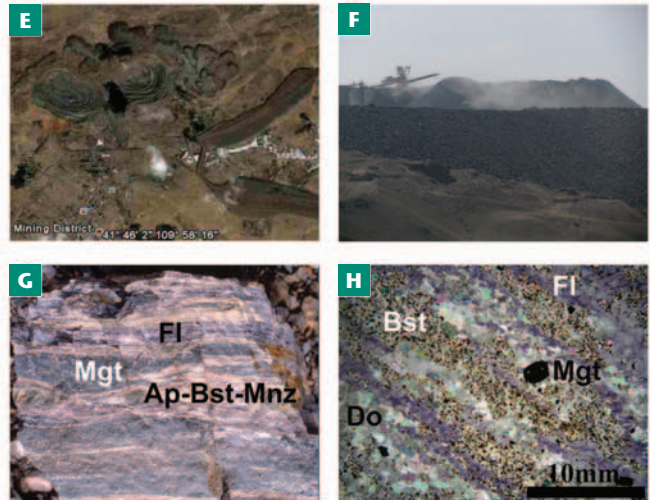**3** Carbonatites in the Mianning–Dechang and Qinling orogenic belts

The distribution of these deposits is controlled by the large-scale tectonic structure of southeastern Asia, as well as by the distribution of climatic zones in the case of the ion-adsorption deposits. Bayan Obo is situated in the northern margin of the Proterozoic North China craton, close to a zone marking the inferred site of Caledonian subduction (Chao et al. 1997). The carbonatites of the Qinling orogenic belt in central China are associated with Late Mesozoic rift basins, modified by Cenozoic thrusting. The ion-adsorption deposits are associated with weathered rocks (mainly granites) in a range of geological settings across southern China and other regions of Southeast Asia.

The REE contents of the Bayan Obo rocks and the majority of carbonatites are comparable to global averages for carbonatites. However, the unusually sulfide-rich deposits at Huanglongpu and Huayangchuan in the Qinling belt (FIG. 1A–D) are significantly enriched in HREEs and Y relative to typical carbonatites (FIG. 2A). The bulk composition of the deeply weathered residual (lateritic) ores is essentially that of their granitic protoliths, but the REE content of the clays has been modified by the weathering process, leading to relative enrichment in the HREEs and the development of anomalously low Ce levels (FIG. 2B). Today, REEs are being mined at Bayan Obo and a number of small- to medium-sized lateritic deposits in southern China. Extraction of REEs as a by-product of Nb–Ta mining is planned for the near future at the Miaoya deposit in the Qinling belt. The deposits of the Mianning–Dechang REE belt were mined in the past, and those deposits are currently of strategic significance.
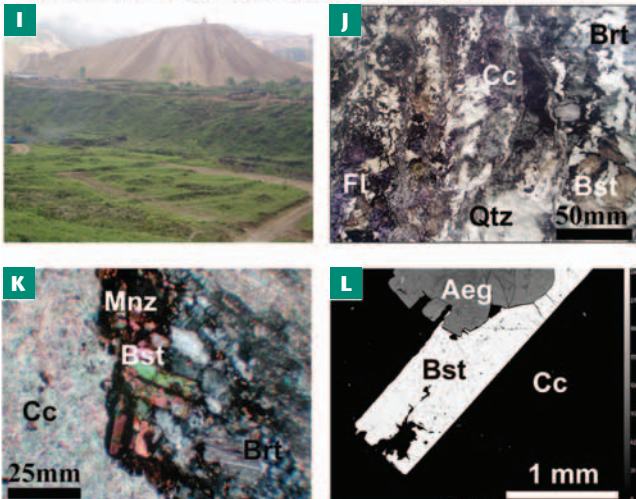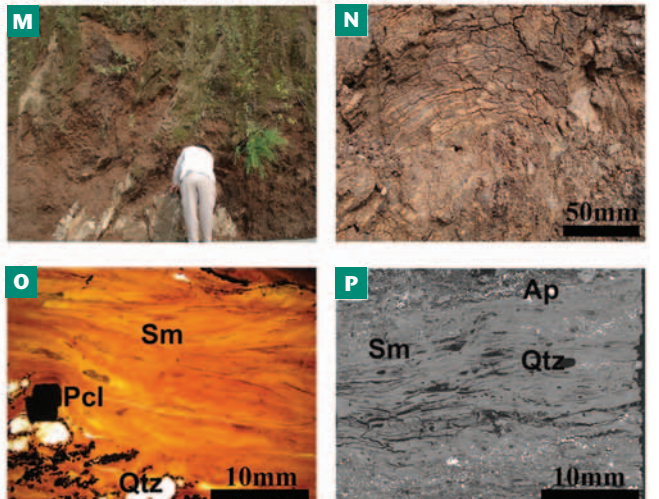
HUANGLONGPU - QINLING BELT

A **B** **C** **D**

All Bst
Xnt-Mnz-Mo
0.2mm

All
Xnt-Mnz-Mo
Y-Mg
Cc
0.2 mm

BAYAN OBO - INNER MONGOLIA

E **F** **G** **H**

Fl
Mgt
Ap-Bst-Mnz

Fl
Bst
Do
Mgt
10mm

KAZAKHSTAN

RUSSIA

MONGOLIA

Beijing

Xian

Lhasa

Legend
- Quaternary
- Tertiary
- Mesozoic
- Paleozoic
- Proterozoic
- Archean
- Granite
- Basalt
- Basic-ultrabasic rocks
— Fault

0   500   1000 km

N
W — E
S
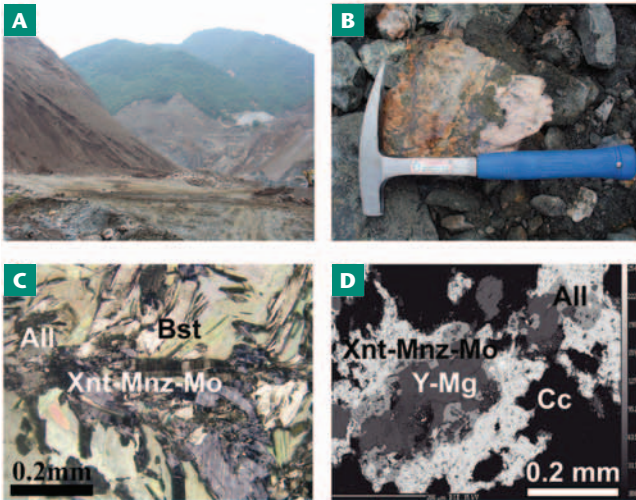
MAONIUPING - MIANNING-DECHANG BELT

I **J** **K** **L**

Brt
Cc
FL
Qtz
Bst
50mm

Mnz
Bst
Cc
Brt
25mm

Aeg
Bst
Cc
1 mm

REE ION-ADSORPTION CLAYS - SOUTH CHINA

M **N** **O** **P**

50mm

Sm
Pcl
Qtz
10mm

Ap
Sm
Qtz
10mm
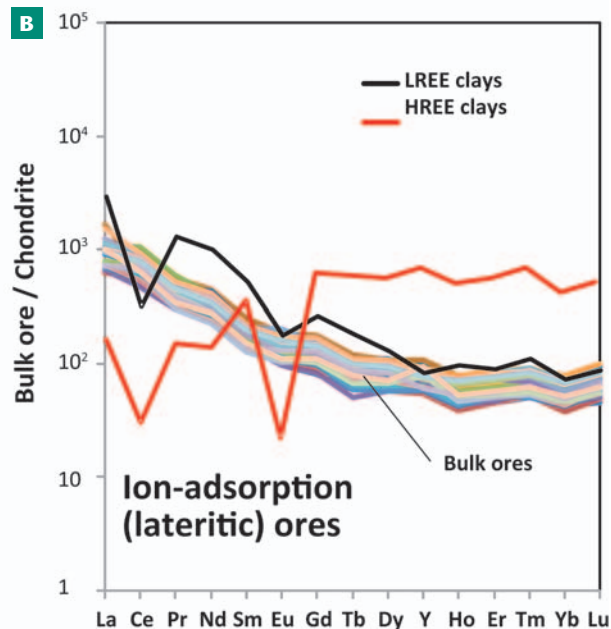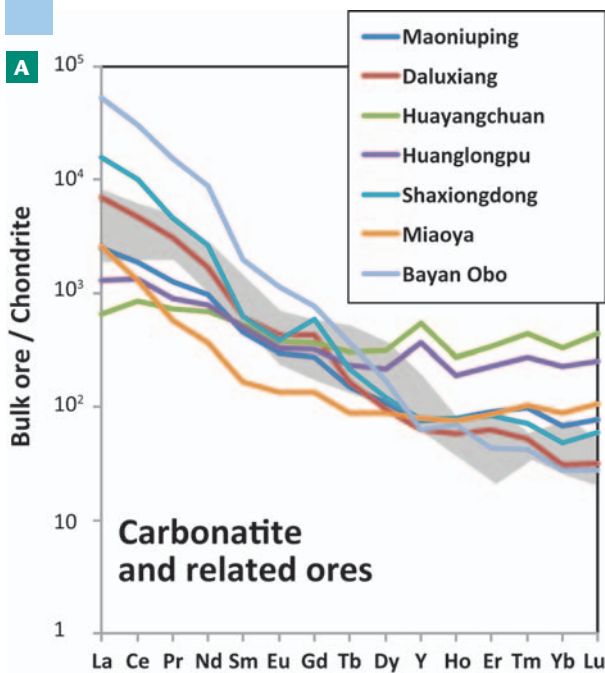
FIGURE 2 Representative chondrite-normalized plots showing the distribution of REEs in the deposits discussed in the text. Yttrium is plotted as a pseudo-lanthanide between Dy and Ho. (**A**) Bulk-rock composition of carbonatites and related ores. The grey field shows the global range for carbonatites, from Woolley and Kempe (1989). (**B**) Bulk-rock and mineralogical composition of ion-adsorption (lateritic) ores

BAYAN OBO – THE WORLD'S LARGEST REE DEPOSIT

Geology

The Bayan Obo deposit (FIG. 1E, F) contains world-class reserves of Fe and REEs associated with a low-grade reserve of Nb, which is extracted as a by-product (TABLE 1). This deposit is largely responsible for China's preeminence in the global REE market. The deposit is hosted in dolomitic marble, which forms part of a sequence of Proterozoic metasedimentary rocks (the Bayan Obo Group) dominated by sandstones and slates. The deposit is composed of three main ore bodies, which are situated at the contact with overlying slate in the core of a synform. Numerous smaller bodies and disseminated mineralization occur throughout the marble unit. The REE resource is dominated by light REEs (LREEs) (FIG. 2A), which are primarily hosted in bastnäsite and monazite, with lesser amounts of Ca–REE and Ba–REE fluorocarbonates; Nb is hosted in disseminated rutile, columbite, aeschynite, and pyrochlore.

The genesis of the deposit is complex, comprising at least eleven stages. These began with carbonate deposition and proceeded through metamorphism and mineralization to the intrusion of Hercynian granitoids to the south of the ore bodies (Chao et al. 1997). The complex evolution of the ores is clearly marked by metasomatic banding enhanced by deformation, centimeter- to decimeter-scale folding, boudinage and cross-cutting undeformed veins. Massive pods of sodic pyroxene and amphibole also show

later vug fills of calcite, fluorite, barite, and Nb–Ti and REE phases. The multistage evolution is also reflected in microscale textures (FIGS. 1G, H AND 3). Geochemically, these rocks are comparable to carbonatites (FIG. 2A), and true carbonatites do occur in the area (Tao et al. 1998) as dikes crosscutting the Archaean Wu Tai gneiss to the north of the ore bodies, as well as the Bayan Obo Group rocks.

Origin of the Bayan Obo Ores

The ores were unequivocally formed by hydrothermal replacement, producing an alteration assemblage that is both alkali- and F-rich (Chao et al. 1997; Smith and Henderson 2000). Despite the apparent affinity with carbonatites, the origin of both the host dolomite and the ore bodies is controversial due to conflicting geochronological and isotopic evidence (Wang et al. 1994). Thorium–Pb isotope analyses of monazite gave ages dominantly in the range of 430–420 Ma, and initial Nd isotope ratios at this time indicate crustal sources for the REEs (FIG. 4). However, other radiometric techniques yielded Proterozoic formation ages, and Ar–Ar analyses of amphibole from the deposit and host rocks gave ages ranging from 1260 Ma to 343 Ma, with the youngest age of 225 ± 7 Ma coming from K–Ar dating of K-feldspar from pegmatite dykes crosscutting biotite schists in the Bayan Obo Group sediments (Chao et al. 1997). SHRIMP dating of single zircon crystals from coarse-grained dolomitic marble in the main marble unit indicated Proterozoic ages (1370–1257 Ma) for igneous-derived zircon cores and Caledonian ages (455 Ma) for metamorphic or hydrothermal rims (Campbell et al. 2000).

< FIGURE 1 Simplified geological map of China showing the locations of key REE-producing areas, images of selected deposits, and photomicrographs and backscattered electron (BSE) images illustrating characteristic microtextures. (A–D) Huanglongpu: (**A**) Huanglongpu Dashigou open pit; (**B**) representative specimen of carbonatite rich in sulfide–fluorocarbonate mineralization; (**C**) photomicrograph of a typical Mo–REE mineral association; (**D**) BSE image of molybdenite–HREE mineralization. (E–H) Bayan Obo: (**E**) satellite image of the Bayan Obo open pits; (**F**) the newly mined western orebody and associated waste piles; (**G**) banded ore, highly deformed but economically the most important ore type; (**H**) photomicrograph of banded ore under partially crossed polarizers. (I–L) Maoniuping: (**I**) Maoniuping deposit and waste pile; (**J**) representative specimen of fluorite-, quartz- and aegirine-

bearing carbonatite; (**K**) photomicrograph of typical coarse-grained bastnäsite- and monazite-bearing carbonatite; (**L**) BSE image of large bastnäsite-(Ce) crystal associated with aegirine. (M–P) Residual REE-clays: (**M**) the most productive second unit of residual REE-clays; (**N**) detailed image of clay with a few relict quartz grains, from the second unit; (**O**) photomicrograph of clay minerals and relict quartz bands with pyrochlore; (**P**) BSE image of clay minerals in bands, with relict quartz and apatite, and newly formed crandallite-group phosphate minerals.

Abbreviations: Aeg = aegirine; All = Allanite; Ap = apatite; Bst = bastnäsite; Brt = barite; Cc = calcite; Dol = dolomite; Fl = fluorite; Mgt = magnetite; Mo = molybdenite; Mnz = monazite; Pcl = pyrochlore; Qtz = quartz; Sm = smectite; Y–Mg = unidentified Y–Mg silicate; Xnt = xenotime.

TABLE 1 GENERAL INFORMATION ON THE MOST IMPORTANT REE DEPOSITS IN CHINA
(listed from LREE enriched to HREE enriched)

DEPOSIT AND LOCATION	RESERVES (× 10⁶ tonnes)	GRADE (wt%)	AGE (Ma)	KEY REE MINERALS
Bayan Obo (Inner Mongolia)	REE_2O_3: 48 Nb_2O_5: 2.2	6 0.13	Multistage origin, main stages: 1370–1200, 430–420, 343–225 (Wang et al. 1994; Chao et al. 1997)	REE fluorocarbonates (bastnäsite, parisite, etc.), monazite
Maoniuping (Himalayan Mianning–Dechang REE belt)	1.45	0.5–8.16	40–30 (Yuan et al. 1995)	Bastnäsite, monazite
Daluxiang (Himalayan Mianning–Dechang REE belt)	0.76	5	15–10 (Yang et al. 1998)	Bastnäsite
Miaoya (Qinling orogenic belt)	1.21	1.72	235 (Xu et al., unpublished data)	Bastnäsite, synchysite, monazite
Huanglongpu (Qinling orogenic belt)	Unavailable	?	220 (Du et al. 2004)	Bastnäsite, synchysite, monazite, xenotime
Huayangchuan (Qinling orogenic belt)	Unavailable	?	181 (Yu 1992)	Bastnäsite, synchysite, xenotime, allanite
Ion-adsorption clays (southern China)	Ambiguous (up to 10)	0.05–0.2	195–130 (granitic rock) 2–0 (weathered crust)	Clay minerals, weathered primary minerals (e.g. xenotime)

The carbonatite dikes show a similar age spectrum (Ren et al. 1994; Zhang et al. 1994; Fig. 4). The simplest model that accounts for the isotopic data and textural characteristics of the ore is intrusion of carbonatites into metasedimentary marbles during the Proterozoic, and subsequent development of REE mineralization with Nd isotope ratios comparable to enriched mantle (Fig. 4). The deposit was subsequently metamorphosed between 555 and 420 Ma, and again from 343 Ma to 225 Ma, resulting in the current nature of the ore and the resetting of the various isotope systems, including Ar loss from amphiboles, micas and feldspars. This model is still oversimplified because alkali- and F-rich fluids infiltrated the ore bodies both before and after deformation. Fluids post-dating the main deformation stage may have been derived from subduction-related granitoids or may indicate a further phase of alkaline magmatism. It is this extended history of magmatism, metamorphism, and fluid flow that has resulted in the accumulation of the enormous REE reserves of the Bayan Obo area.
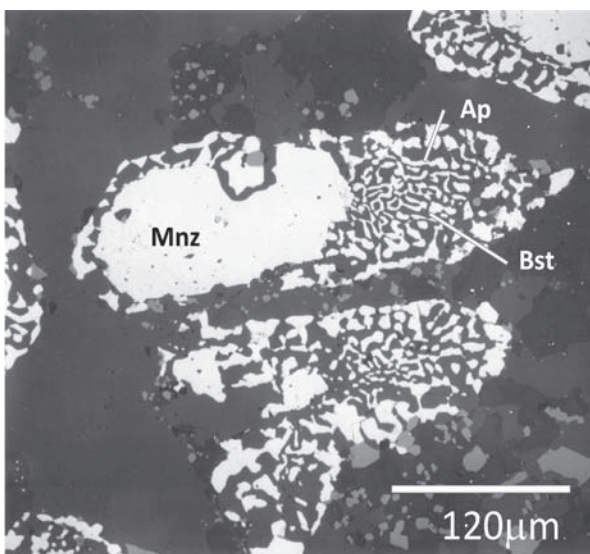
FIGURE 3 Textural evidence for multiple stages of fluid flow, mineralization and metamorphism abounds at Bayan Obo. In this BSE image, euhedral monazite (Mnz) is replaced by a corona of symplectitic basnäsite (Bst) and apatite (Ap) (Smith et al. 1999).

DEEPLY WEATHERED RESIDUAL DEPOSITS

Ion-Adsorption Clays: The Key Role of Weathering

These deposits, also known as residual REE-clays or South China clays, have been mined since the early 1970s and represent the world's most important source of HREEs. The largest of these deposits are located in the southern Chinese provinces of Jiangxi, Hunan, Fujian, Guangdong and Guangxi (Fig. 1). The currently mined deposits have combined estimated resources of at least 1 million tonnes (1 Mt) and possibly more than 10 Mt (Chi and Tian 2008). The clays (Fig. 1M, N) formed by lateritic weathering of predominantly felsic rocks containing accessory REE minerals (Kanazawa and Kamitani 2006). The weathering process resulted in alteration of the primary REE hosts and the complete disintegration of most rock-forming minerals, with the exception of quartz and some stable accessory minerals (Fig. 1O, P). Although similar climatic conditions are prevalent across Southeast Asia, residual REE-clays developed only in morphologically predisposed areas, where erosion is minimal. The protolith must also contain a significant proportion of accessory REE minerals susceptible to chemical weathering, such as REE fluorocarbonates (bastnäsite, parisite and synchysite), phosphates (monazite, apatite and, rarely, xenotime), oxides (pyrochlore, aeschynite and other Nb–Ti phases), and members of the epidote group (especially allanite). Many of these minerals partially outlast the extreme weathering and are found as discrete irregular and weathered grains or as bands associated with clay minerals and relict quartz (Chi and Tian 2008).

In addition to the formation of secondary REE phases (fluorocarbonates or crandallite-type phosphates, depending on the acidity and nature of the weathering environment), significant amounts of the released REEs are adsorbed onto clay mineral surfaces (Fig. 2B). The two most important adsorption phenomena in clays are cation exchange on the layer surfaces and chemisorption of anions at the layer edges. The REEs adsorbed on clay minerals are fractionated and enriched during adsorption–desorption processes. Adsorption processes are key to the concentration of the HREEs because cations with higher charge/size ratios are preferentially sorbed (Bau 1991). Exchangeable REE cations
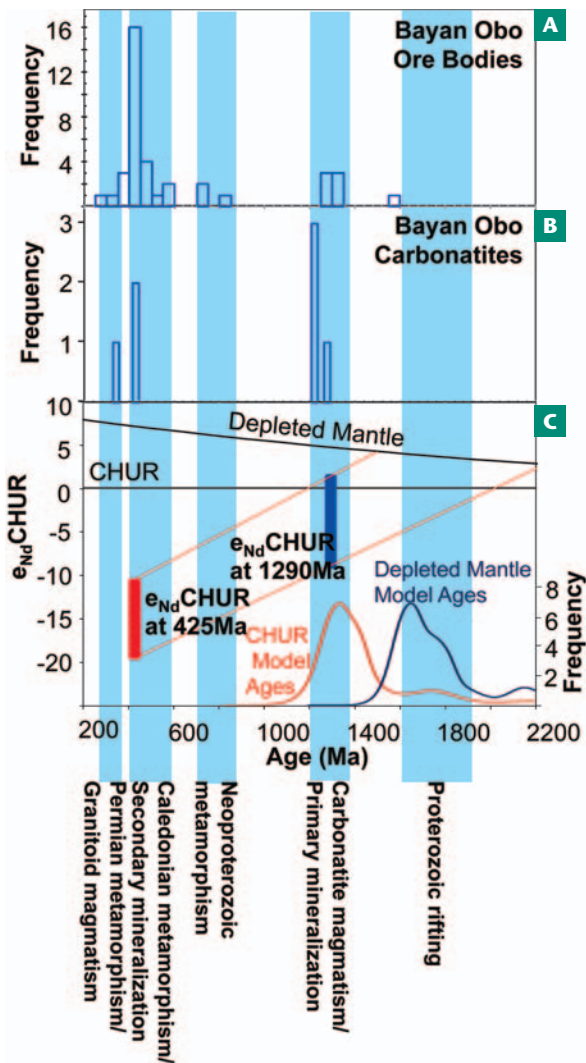
FIGURE 4 Summary of the geochronology of the Bayan Obo deposit, based on sources given in the text. (**A**) Age–frequency plot for Bayan Obo ore bodies. (**B**) Age–frequency plot for Bayan Obo carbonatite dykes. (**C**) Multistage evolution model for the Nd isotope composition of the Bayan Obo ores based on the data of Wang et al. (1994) and Philpotts et al. (1991). The model ages are the hypothetical time elapsed since Sm and Nd separated from a defined reservoir – either the chondritic uniform reservoir (CHUR) or depleted mantle. The red and blue curves show the cumulative probability of the model ages for the number of analyses, incorporating the 2σ error. The data are consistent with the derivation of primary carbonatite magmas and REE mineralization via Proterozoic melting of enriched mantle, and subsequent modification of the ore by metamorphism and repeated episodes of magmatism and fluid flow.

adsorbed on clay minerals can be desorbed by cation exchange with ammonium salts [e.g. $(NH_4)_2SO_4$], and then the REEs are recovered with oxalic acid.

Nature of Ion-Adsorption Clays

The residual REE-clay profiles can be subdivided stratigraphically into four units on the basis of their mineral assemblage. The uppermost unit consists of soil and colluvium, whilst the second, the most important unit, is a deeply weathered zone ~5–10 m in thickness (FIG. 1M). Within this layer, REE ions are adsorbed onto the surfaces of kaolinite, halloysite, and smectites, and are enriched up to five times in comparison with the igneous protolith. The third unit, up to 30 m in thickness, consists of less-weathered parental rock with a high proportion of kaolinite. The fourth unit is incipiently weathered protolith with

well-developed kaolinization of potassium feldspar. Other rock-forming and accessory minerals do not show evidence of intensive alteration and disintegration. The protoliths preserved below the weathering profile are almost invariably Mesozoic granitoids (Kanazawa and Kamitani 2006; Chi and Tian 2008).

Although lateritic clay deposits contain low REE grades (0.05–0.2 wt% REE_2O_3) in comparison with other deposit types, they represent an attractive exploration target due to their large areal distribution, their low operating costs, and the low U and Th contents in the ore (Kanazawa and Kamitani 2006). Residual REE-clays probably constitute more than 80% of the world's economic HREE resources (Chi and Tian 2008).

CARBONATITES IN OROGENIC BELTS

Mianning–Dechang REE Belt

The Himalayan Mianning–Dechang orogenic belt (Panxi region) is located between the cities of Panzhihua and Xichang, Sichuan Province, along the western margin of the South China block. This area underwent a complex tectonic evolution, beginning with Proterozoic lithospheric accretion, followed by a Paleozoic–Mesozoic continental-margin stage, and culminating in Cenozoic collisional orogeny. Eight high-grade REE deposits of strategic significance are found here in association with carbonatite–syenite intrusions (Pu 2001); these intrusions were emplaced into Proterozoic basement rocks and Paleozoic–Mesozoic sedimentary sequences along a 270 km long belt.

The Maoniuping deposit is located in the northern Panxi region and represents the largest REE deposit in the belt and the second largest in China. A variety of igneous rocks occur in the area, including the Yanshanian granite, Mesozoic rhyolite, and Himalayan alkalic syenites and carbonatites. Ore occurs as pegmatitic barite and calcite veins and stockworks (FIG. 1I, L), which are hosted mostly by the carbonatite–syenite intrusions. Associated metasomatic processes include the development of biotite, aegirine-augite, arfvedsonite and albite in the wallrock, followed by the deposition of calcite, barite, fluorite and bastnäsite. In addition, some proportion of REEs is adsorbed on the surface of Fe–Mn oxide minerals in soils formed during supergene alteration. The hypogene REE mineral assemblages consist mainly of bastnäsite (76–92%), associated with minor chevkinite, parisite, allanite, aeschynite, monazite and cerianite. Potassium–Ar dating of biotite and magnesio-arfvedsonite from barite veins gave an age range of 32–40 Ma.

The Daluxiang deposit in the middle Panxi region is the second largest in the belt. Here, REE orebodies intrude syenites, which are extensively altered at the contact with ore veins to mineral assemblages containing aegirine-augite, fluorite, carbonates and bastnäsite. The major ore types are Sr-rich barite, Ba-rich celestine and "thread" veins. Potassium–Ar dating of biotite from celestine veins gave ages ranging from 9.8 to 10.6 Ma, and Rb–Sr isochron dating of biotite, calcite and REE ores from "thread" veins gave an age of 15.3 Ma (Pu 2001).

The REE deposits at Maoniuping and Daluxiang are genetically linked to carbonatite–syenite magmatism and ore-forming fluids derived from enriched mantle sources (Xu et al. 2003; Hou et al. 2009). These fluids were dominantly aqueous and evolved over a large range of temperatures and salinities. Fluid–melt inclusions with homogenization temperatures of >600 °C were found in fluorite associated with the mineralization (Pu 2001). The trace element analysis of calcite from the carbonatites suggests that these rocks are cumulates (Xu et al. 2008). Because REE partition

coefficients between rock-forming carbonate minerals and melts are low, crystallization and fractionation of calcite caused REE enrichment in the F^-- and SO_4^{2-}-bearing ore-forming melt and, subsequently, in later, high-temperature, orthomagmatic fluids. The fluids interacted with the wall-rocks to produce the REE fluorocarbonate–fluorite-rich mineralization.

Qinling Orogenic Belt

The Qinling orogenic belt is divided into the North Qinling and South Qinling, which are separated by the Shangdan suture. The northern border of the North Qinling is marked by the Machaoying fault zone, which is a normal fault associated with a Cenozoic rift basin to the north. The southern border of the South Qinling, separating it from the South China block, is the Mianlue suture; details on the tectonic evolution of this area can be found in Ratschbacher et al. (2003).

The Miaoya deposit is the third largest REE deposit in China (TABLE 1). It is located in the southwestern margin of the Wudang Terrane at the southern margin of the Qinling orogenic belt. Many smaller deposits (e.g. Shaxiongdong) occur in an 80 km long REE belt within the Wudang Terrane. At Miaoya, carbonatites and associated syenites are emplaced into Mesoproterozoic low-grade metavolcanic rocks and Paleozoic carbonaceous shale. Carbonatites hosting primary magmatic REE mineralization intrude the syenites as stocks and dikes covering a total area of <10 km^2 at the current erosion level. Ore bodies are composed predominantly (>80 vol%) of medium- to fine-grained calcite. Minor phases include biotite, alkali feldspar, magnetite, ilmenite and rutile. The major REE hosts in the ore bodies are REE-rich fluorapatite (up to 9 wt% REE_2O_3), monazite, bastnäsite and synchysite. As commonly observed in carbonatites, fluorapatite and monazite are early liquidus phases that precipitated prior to calcite and fluorocarbonates, whereas bastnäsite and synchysite crystallized later to form syntaxial intergrowths (Xu et al. 2010). Less common REE-bearing accessory phases include allanite, perovskite, nioboaeschynite, fergusonite (dominated by Nd) and ferrocolumbite.

The Huanglongpu Pb–Mo–REE deposit and the Huayangchuan Pb–Th–REE deposit are situated in central China in the northern margin of the Qinling belt. The Huanglongpu deposit comprises four ore fields currently being mined (Yuantou, Dashigou, Shijiawan and Taoyuan). Here, molybdenite and associated rare-metal mineralization occur in dikes of calcite carbonatite enriched in sulfide, REE fluorocarbonate and REE phosphate minerals (Xu et al. 2007; Kynicky et al. 2011; FIG. 1A–D). The most important REE hosts are fluorocarbonates, monazite and xenotime. Minor and accessory phases include microcline, aegirine-augite, arfvedsonite, phlogopite, quartz, celestine, barite, magnetite, thorite, brannerite, liandratite, pyrochlore, yttrobetafite, allanite-(Y) and other HREE-rich phases; the presence of these minerals is reflected in high whole-rock HREE levels (up to 2550 ppm), unusual for carbonatites.

DISCUSSION

Origins of China's REE Endowment

China is the second-largest country in the world by land area; its sheer size and geological diversity account in a significant way for the REE resources available for extraction. Tectonic accretion of Precambrian cratons from the Paleozoic to the Cenozoic resulted in at least six stages of orogeny before cratonization. Cenozoic collision of the Eurasian and Indian plates produced the deformation and uplift of the Himalayas, strongly influencing the tectonics of western China. In contrast, the Mesozoic–Tertiary

evolution of eastern China exhibits a typical basin-and-range geology, and included development of deep sedimentary basins and calc-alkaline plutonic and volcanic activity associated with crustal thinning and high heat flow.

Overall, China has undergone an extremely mobile tectonic history (Zhang et al. 1984), with the potential for multiple stages of mantle metasomatism and enrichment. The world's largest REE deposit, at Bayan Obo, may be an outcome of continuous reactivation of such mantle sources, with repeated reworking by metamorphism and fluid flow. Other sites of alkaline magmatism with the potential for tectonic reworking may be highly prospective for superlarge REE deposits. The Qinling orogenic belt was incorporated into Rodinia during the Grenvillian orogeny, which was followed by rifting, then subduction in the Paleozoic and early Mesozoic, reactivation in the Cretaceous to Palaeogene, and finally extension in the Neogene (Ratschbacher et al. 2003). Again, the extended geological history may be responsible for the geochemically unusual carbonatite magmatism and REE mineralization of the area. Circum-Pacific subduction and basin-and-range tectonics in the Triassic to Cretaceous also resulted in crustal recycling and the generation of REE-enriched post-orogenic granitoids in southeastern China. The location of these granitoids in a (sub)tropical climate is responsible for the extreme weathering that elevated the bulk REE content to economically extractable levels. The development of such deposits by in situ weathering means that their preservation potential in the rock record is limited – they only occur as economic deposits because of processes that will ultimately result in their destruction. Any other such deposits preserved in pre-Mesozoic systems will be exceptional, but the potential for new discoveries in Mesozoic and Cenozoic orogenic belts that have been subjected to (sub)tropical weathering conditions is high.

Environmental Impact of REE Mining

In China, a number of environmental issues are associated with REE production as a result of both ore characteristics and the refinement process. Most REE deposits, with the exception of the lateritic deposits, are associated with significant concentrations of radioactive elements (U and Th), and processing typically involves the use of sulfuric and hydrofluoric acid. Separation of individual REEs produces ammonium-rich waste water (separation of one tonne of 92% REE concentrate requires 1–1.2 tonnes of NH_4HCO_3). Processing acids have the potential to contaminate both surface water and groundwater, and have been responsible for soil contamination in southern China. Individual deposits have been associated with specific issues. The Bayan Obo mines (FIG. 5) are situated in semi-arid steppe; strong winds from the Gobi Desert cause dust and sand storms, which pick up, and become contaminated with, material from the mines (detected as far away as Beijing). Lateritic deposits are typically less problematic, as they have minimal drilling or milling requirements and the

FIGURE 5   The main ore body at Bayan Obo, mined from a large open pit

mined material is free from radioactive elements. They are, however, mined by in situ acid leaching, which may result in groundwater pollution. Ponding and in situ leaching have now been banned, and future operations may make use of hydrological barriers to reduce the environmental impact.

CONCLUSIONS

Many types of REE deposits occur in China, but only a few of these are of significant economic importance. On a global scale, many of these deposits are unusually large. China has essentially monopolized the production of both LREEs (Bayan Obo) and HREEs (ion-adsorption clays). Global production of REEs in the last decade (2001–2011) has increased from approximately 90 to 130 kt, of which some 97% has been produced by China. The Bayan Obo superlarge deposit currently accounts for some 90% of the REE production and clays for merely 6–7%; however, the former mainly produces the economically less attractive LREEs, while ion-adsorption clays produce both HREEs and LREEs. The rapid development of the REE market has led China to be more careful with its phenomenal REE resources, especially given that some 10–15% of its reserves have already been mined. In addition,

China has recently reduced export quotas to combat environmental problems associated with REE mining and to cope with its own growing demand. World demand for rare earth elements has tripled in the past decade, and observers are now predicting a 10–30 kt supply shortfall by 2015 (Hatch 2012 this issue). Although several countries without current domestic production of REEs are actively exploring for new REE deposits, China, in both the present and the future, will dominate the market. The fact that this country already controls many REE exploration projects outside its borders will undoubtedly help it retain and further its dominant position.

ACKNOWLEDGMENTS

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Rare Earth Mining and Exploration in North America
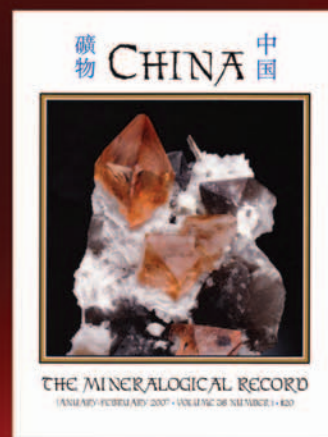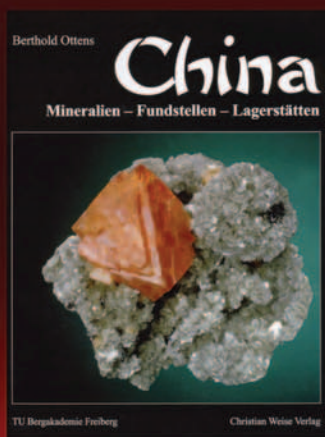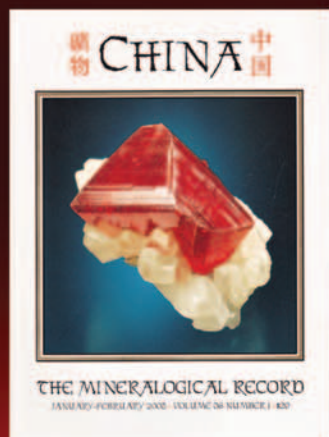
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The Mountain Pass deposit, California

The occurrences of rare earth elements (REEs) in North America are abundant and diverse in mineralogy and geology. The Mountain Pass carbonatite in California historically has been a major world source for the light REEs. Monazite sands have also been mined on a moderate level in the southeastern United States. Fluids released from the mining of uraninite at Elliot Lake, Ontario, were intermittently a source for yttrium. Peralkaline igneous rocks in several areas of North America are currently under exploration for the entire REE spectrum, with emphasis on the heavy REEs. Although many REE occurrences contain a substantial tonnage of REEs, amenability to mineral processing and extraction of the REEs must be definitively established in each case.

KEYWORDS: rare earth elements, deposits, economics, exploration, carbonatite, peralkaline igneous rocks

INTRODUCTION

Interest in rare earth element (REE) exploration in North America has surged in recent years, and a wide variety of deposits with diverse geological settings and mineralogy are currently being investigated. The continent's only hard rock past producer, Mountain Pass in California, is proceeding rapidly towards resumption of production. Concentrations of REEs with real or potential economic significance are found in a variety of geologic environments, as independent REE minerals and substituent in other mineral hosts (TABLE 1, FIG. 1). This article emphasizes the economic aspects of REE deposits and their exploitation. Many REE occurrences that are currently being explored have been considered to be attractive targets by companies and investors based on grade and tonnage. However, although tonnage is always of paramount importance, the grade of REEs that can be economically recovered is less easily evaluated because the economics are totally dependent on the nature of the mineralogy.

The choices made in defining light and heavy REEs (LREEs and HREEs) are somewhat arbitrary (Chakhmouradian and Wall 2012 this issue). In economic studies, the definition may be motivated by promotional interests because of the current demand for the HREEs. The 14 lanthanides (La through Lu) can simply be divided into two groups, with La through Gd classified as LREEs and Tb through Lu as HREEs. This distinction is supported by the structural difference in the two sets, where the orthophosphates $LaPO_4$ through $GdPO_4$ assume a monoclinic structure, while $TbPO_4$ through $LuPO_4$ have the tetragonal zircon structure (Ni et al. 1995).

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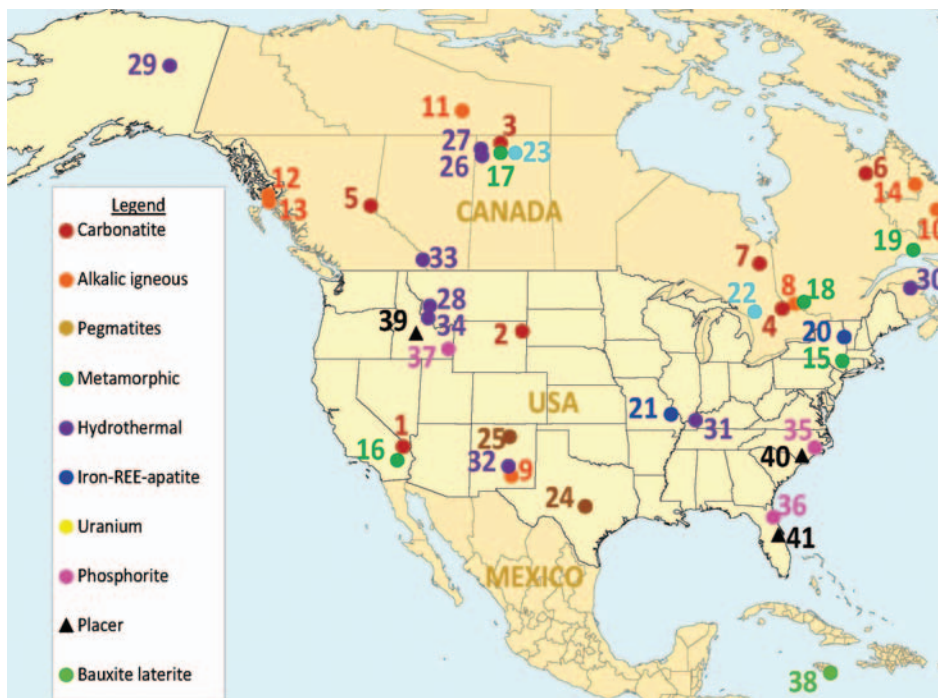2 1134 North Road, Carlisle, MA 01741, USA
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ECONOMIC CONSIDERATIONS OF REE MINERALOGY

Mineralogical, geochemical, and petrological characterizations are a vital requirement in mineral exploration and are particularly important in working with REE occurrences. However, the ability to put these data into the context of economic evaluation requires a long and sustained understanding and exposure to what constitutes a viable mineral deposit for the commodity in question. A keen understanding of the mineralogy and its relationship to the geologic environment is essential to the exploration and beneficiation process. The mineralogy of a deposit predicates the ease with which the REEs can be processed in order to compete in the world market. This is best illustrated by the ion-adsorbed REE-clays in South China, which control the world market for HREEs but have average total REE (ΣREE) grades running <0.1 wt% (Kynicky et al. 2012 this issue).

- **Bastnäsite** ($REECO_3F$) occurs in both established and potential economic quantities in carbonatites, where its composition is strongly dominated by the LREEs. Currently and recently mined sources where bastnäsite is the main REE ore mineral include Bayan Obo, Maoniuping, and a few other carbonatite-related deposits in China, and the Mountain Pass mine in California. Mountain Pass was for many years the world's main REE provider, and it is scheduled to resume operations in the near future. Compositionally bastnäsite contains ~75 wt% rare earth oxides (REOs) and in the above-mentioned confirmed ore bodies, concentrates have been prepared, after physical processing, varying in grade from 45 wt% to approaching 65 wt% REO. In some noncarbonatite environments, including peralkaline granites and syenites, Y- and HREE-rich bastnäsite is known to occur associated with other largely HREE-dominant minerals, but bastnäsite-(Y) has thus far not been confirmed to occur in potential ore quantities.

- **Monazite** ($REEPO_4$) is a common accessory mineral in granites and some metamorphic rocks. Monazite concentrations occur in beach sands and river placers in many parts of the world and are often processed as by-products of ilmenite, zircon, and cassiterite mining. These monazites are generally relatively high in Th, a substituent in the monazite structure; its ThO_2 content ranges from ~1 wt% to as high as 27 wt%. Primary monazite may occur in substantial quantities in carbonatites (e.g. Kangankunde, Malawi; Wicheeda Lake, British Columbia, Canada). This

Legend
- Carbonatite
- Alkalic igneous
- Pegmatites
- Metamorphic
- Hydrothermal
- Iron-REE-apatite
- Uranium
- Phosphorite
- Placer
- Bauxite laterite

FIGURE 1 North American REE occurrences. See Table 1 for the characteristics of the numbered deposits on this map.

monazite is relatively low in Th content, usually <1 wt%, and in the aforementioned occurrences, it can be easily concentrated by physical means. Supergene monazite can be found in large tonnages and with high grades in laterites derived from the chemical weathering of carbonatites. Examples include Mt. Weld (Australia), Araxá and Catalão I (Brazil), Mrima Hill (Kenya), Mabouni (Gabon), and several other carbonatite laterites in the Amazon region of Brazil. There are no known laterite-derived REE occurrences in carbonatites in North America. Monazite-(Nd) from Lemhi Pass (Idaho–Montana) occurs in quartz–biotite–hematite–thorite-bearing veins within metamorphic rock units.

■ **Xenotime** (YPO_4) is most often encountered as a trace accessory in granites and metamorphic rocks, and in such settings, it is usually inferior in quantity to monazite. Beach sands and placer deposits have been inconsistent sources of by-product xenotime, especially from ilmenite and cassiterite mining. The stoichiometric value of Y in the formula YPO_4 is equivalent to 61.4 wt% Y_2O_3. However, in nature, the average Y_2O_3 content of xenotime is approximately 30 wt%, and the remainder of the Y site is occupied mostly by the HREEs Dy, Er, Yb, and Lu. As such, xenotime is one of the most ideal sources for these elements.

■ **Eudialyte** $[Na_{15}Ca_6(Fe,Mn)_3Zr_3(Si,Nb)(Si_{25}O_{73})(O,OH,H_2O)_3(Cl,OH)_2]$ is a rock-forming mineral in several localities worldwide, where its grade and tonnage can constitute a sustained mining source. Eudialyte can be a major source of ZrO_2 and in addition, although not always shown in the chemical formula, it almost invariably contains a substantial amount of REEs. In some occurrences, the ΣREE content in eudialyte concentrates ranges between 4 and 7 wt%. The lanthanide distribution in eudialyte from various world localities almost invariably shows enrichment in HREEs (Fryer and Edgar 1977). Despite the high solubility of eudialyte in weak acids, the isolation of ZrO_2, Y_2O_3, and REE_2O_3 is problematic owing to the formation of an intimately associated SiO_2 gel. Some progress is being made with innovative experiments to

solve the problems related to the economic chemical processing of eudialyte. In North America, eudialyte mineralization with significant tonnage and REE content occurs at Kipawa (Québec), Pajarito (New Mexico), and, to a lesser extent, Red Wine (Labrador).

■ **Allanite** $[(REE,Ca,Y)_2(Al,Fe^{2+},Fe^{3+})_3(SiO_4)_3(OH)]$ is a member of the epidote group. The structure of allanite can incorporate either LREEs or HREEs, but in virtually all cases where allanite occurs in near-economic grade, it is LREE-dominant (Mariano 1989). Occurrences in which allanite preferentially incorporates LREEs in environments where other cocrystallized REE minerals show HREE enrichment include the Nipissis granite-gneiss at Kwyjibo River (Québec), Thor Lake (Northwest Territories), Mineville (New York), and a granitic pegmatite near Timmins (Ontario). The element distribution has significant economic implications for allanite as a REE source. The REO content of allanite rarely exceeds 15 wt%, and it is a refractory mineral relatively resistant to chemical breakdown. Consequently, allanite cannot compete with bastnäsite or monazite, which have much higher REO contents and are readily susceptible to chemical cracking. As such, allanite is not competitive as an economic source for the LREEs, unless it contains exceptionally high values of Nd or if it occurs as allanite-(Y) in economic quantities.

■ **Zircon** ($ZrSiO_4$) is commonly the major heavy mineral in beach sands and river placers and is also a by-product of Sn, Ti, and Au mining. It is an important accessory mineral in carbonatites, granites, syenites, nepheline syenites, and metamorphic rocks, and is locally enriched in some hydrothermal occurrences. The crystal chemistry of zircon strongly favors the substitution of the HREEs. The ΣREE content of zircon rarely exceeds 1 wt%, but in some North American occurrences, including Pajarito, Kipawa, Thor Lake, Strange Lake (Quebec–Labrador), and Bokan Mountain (Alaska), secondary zircon occurring mostly as pseudomorphic replacements of earlier alkali zirconosilicates may contain in excess of 6 wt% HREEs. This type of zircon is very fine grained and inextricably associated with other high-field-strength-element-bearing minerals and quartz. A recent publication on this type of zircon from Thor Lake (Sheard et al. 2012) reported a $ΣREE_2O_3 + Y_2O_3$ value of 6.42 wt%. The strong refractory nature of zircon and its resistance to chemical dissolution present a problem in chemical processing.

■ **Apatite** $[Ca_5(PO_4)_3(F,Cl,OH)]$ can contain substantial quantities of REEs substituting for Ca. The best economic grades of apatite, with as much as 6 wt% REE, are rare. Examples are Mineville (USA), Nolan's Bore (Australia), and Mushgai Khudag (Mongolia). The Hoidas Lake (Saskatchewan) apatite contains as much as 5 wt% REE. In all cases, with the exception of Mineville (see below), the apatite is LREE-dominant. The extraction of REEs from apatite as a by-product of marine- and igneous-phosphate mining has also been considered in Florida, Russia, South Africa, Brazil, and Canada.

TABLE 1

NORTH AMERICAN REE OCCURRENCES. See Figure 1 for locations of map references.

Geologic Environment and Mode of Occurrence	Map Reference	Occurrence	Mineralogy
Carbonatites			
As independent minerals, including carbonates, phosphates,and silicates, or as substitutional elements in other mineral hosts	• 1	Mountain Pass, CA	Bastnäsite, etc.
	• 2	Bear Lodge, WY	Ancylite, monazite, bastnäsite, etc.
	• 3	Hoidas Lake, SK	Allanite and substitutional REE in apatite
	• 4	Springer Lavergne, ON	Synchysite
	• 5	Wicheeda Lake, BC	Bastnäsite, monazite
	• 6	Eldor, QC	Bastnäsite, monazite
	• 7	Cargill, ON	Substitutional REE in eluvial apatite
Peralkaline Granites, Syenites, Nepheline Syenites			
Diverse mineralogy	• 8	Kipawa, QC	Eudialyte, mosandrite, britholite, etc.
	• 9	Pajarito, NM	Eudialyte, kainosite, etc.
	• 10	Red Wine, NL	Eudialyte, cerite, bastnäsite, monazite
	• 11	Thor Lake, NT	Allanite, zircon, monazite, bastnäsite, etc.
	• 12	Dora Bay, AK	Eudialyte
	• 13	Bokan Mountain, AK	Kainosite and diverse mineralogy
	• 14	Strange Lake, QC-NL	Kainosite and diverse mineralogy
Metamorphic Rocks – Gneisses, Schists, Quartzites			
Independent minerals, including monazite and xenotime, in localized high-grade accumulations	• 15	Highland Falls, NY	Xenotime, monazite
	• 16	Music Valley, CA	Xenotime, monazite
	• 17	Archie Lake, SK	Monazite
	• 18	Surprise Area, Kipawa, QC	Xenotime, fergusonite, euxenite
	• 19	Kwyjibo River, QC	Apatite, allanite, kainosite
Magnetite Ore Deposits			
REE and Y as substitutional impurities and mineral inclusions in apatite, and as independent REE minerals	• 20	Mineville, NY	HREEs substituting in apatite
	• 21	Pea Ridge, MO	REEs in apatite, xenotime, etc.
Uraninite Deposits			
Predominantly as REEs and Y substituting in uraninite	• 22	Blind River/Elliot Lake, ON	Uraninite, unrecovered brannerite
	• 23	Athabaska, SK	Uraninite
Pegmatites			
Diverse mineralogy	• 24	Llano, Baringer Hill, TX	Xenotime, etc.
	• 25	Harding Mine, NM	Xenotime, etc.
Hydrothermal			
Mineralization in quartzites and sandstones	• 26	Maw Zone/Athabaska, SK	Xenotime
	• 27	Beatty River, SK	Xenotime
Fluorite and REE mineralization	• 28	Snowbird Mine, MT	Parisite
Hydrothermal mineralization in syenite	• 29	Mt. Prindle, AK	Britholite, parisite, synchysite
Hydrothermal veins in gabbro	• 30	Benjamin River, NB	REE substituting in apatite
Fluorite and REE mineralization in carbonatite environments	• 31	Hicks Dome, IL	Cheralite, brockite, florencite, xenotime
	• 32	Gallinas Mountains, NM	Bastnäsite
	• 33	Rock Canyon Creek, BC	Monazite, synchysite, bastnäsite, gorceixite
REE mineralization of carbonatite origin in gneisses	• 34	Lemhi Pass area, ID/MT	Monazite-(Nd)
Phosphorite			
Low-grade REE in apatite	• 35	North Carolina	Apatite
	• 36	Florida	Apatite
	• 37	Enoch Valley Mine, ID	Apatite
Bauxite Laterites	• 38	Jamaica	
Beach Sands, River Placers, and Paleoplacers			
Monazite and xenotime detrital accumulations derived from weathering of granites and metamorphic rocks	▲ 39	Bear Valley, ID	Euxenite
	▲ 40	Piedmont Placer area, VA, NC, SC, GA	Monazite
	▲ 41	Florida/Atlantic coast beaches	Monazite

■ The HREE-bearing oxide minerals **fergusonite** ($YNbO_4$), **euxenite** [$(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$], and **brannerite** [$(U,Ca,Y,Ce)(Ti,Fe)_2O_6$] have attractive HREE contents and are frequently encountered in peralkaline granites, pegmatites, metamorphic rocks, unconformities associated with uranium deposits, and colluvial accumulations derived from weathered granites. However, these minerals have never been found to occur in quantities that could constitute a sustained source either as the primary ore mineral or as a by-product.

PAST REE MINING AND CURRENT EXPLORATION IN NORTH AMERICA

Potential REE resources in North America have been defined by broad-brush resource evaluation conducted by the United States Geological Survey (USGS) and the Geological Survey of Canada and by private exploration companies. In the regional evaluation programs, rocks and soils are typically chemically assayed, and these data are then applied to tonnage calculations and less frequently to the establishment of grade. The current market value for the individual REEs is factored to the grade and tonnage values for assessing the merit of the areas being investigated. In most cases, a mineralogical assessment of the feasibility of physical and/or chemical processing has not been carried out. As a result, many areas that are treated in government bulletins and company reports as potential sources for REEs have not been evaluated in comparison with deposits that historically and currently provide these elements to the market place on a sound economic basis.

The major historic sources of REEs in North America were the Mountain Pass carbonatite and monazite sands in various states in the southeastern USA. Although predominantly a LREE deposit, Mountain Pass also served as the major source of Eu and contributed much of the required Sm and Gd. Monazite beach sands, when exploited, are also able to provide mid–atomic number lanthanides (MREEs) and low quantities of HREEs. For a limited time, HREEs were also extracted from raffinate fluids derived from uraninite mining at Elliot Lake, Ontario.

Carbonatite-Related Occurrences

Carbonatite occurrences are abundant in North America (Woolley and Kjarsgaard 2008). All are anomalous in REEs, with the LREEs dominating. The LREEs and trace quantities of the HREEs and Y occur as early crystallized, independent REE minerals; as minerals originating from hydrothermal events; and, less frequently, as supergene products of weathering. The distinction between what constitutes primary and hydrothermal REE mineralization in carbonatites is debatable. With the exception of extrusive carbonatite lavas, virtually all carbonatites undergo recrystallization. In this context, we define primary REE minerals as those that have cocrystallized texturally with the carbonates, exclusive of quartz, fluorite, and other obvious late-crystallizing phases. Bastnäsite at Mountain Pass is an example of primary REE mineralization in a North American carbonatite (FIGS. 2 AND 3).

A good example of hydrothermal mineralization in carbonatites is found in the Bear Lodge Complex of Wyoming, which contains abundant (OH)-bearing REE minerals that occur as transgressive veins in sövite (coarse-grained calcite carbonatite) and as pseudomorphic replacements of earlier phases (FIG. 4). A more comprehensive treatment of the sequence of REE mineralization in carbonatites can be found in Wall and Mariano (1996).

Mountain Pass, California

The Mountain Pass carbonatite is the largest-known LREE deposit of economic significance in North America. The ore body consists of a carbonatite sill with an average thickness of 75 m and dipping at an angle of 45° to the southwest. An early description of the outcropping carbonatite (Olson et al. 1954) documented an irregular, north-striking mass about 700 m long and with an average thickness of about 120 m. Detailed mapping of the carbonatite sill identified 14 separate rock units consisting of calcite and dolomite carbonatites with substantial quantities of LREE mineralization occurring predominantly as bastnäsite (FIGS. 2, 3). Other LREE accessory minerals include parisite, synchysite, monazite, and, less often, allanite. Sahamalite and cerite also appear in trace quantities as small, localized concentrations. The carbonatite units contain varying amounts of barite, celestine, strontianite, cerussite, phlogopite, and fluorite. Asbestiform magnesioriebeckite and quartz occur in varying amounts as late phases. The proven and probable reserves, announced by Molycorp in April 2012, are 16.7 million tonnes at an ore grade of 7.98 wt% REO, with a cutoff grade of 5% (9 April 2012 press release, www.molycorp.com).

The Mountain Pass sill and subordinate carbonatite bodies occur as isolated units that are always spatially associated with shonkinite, syenite, and granite, all of which show mineralogy and ages that support a possible cogenetic origin from an alkaline magma source. The age of the carbonatite obtained by U–Th–Pb and $^{40}Ar/^{39}Ar$ dating is 1375 ± 5 Ma (DeWitt et al. 1986). Shonkinite and syenite are older than the carbonatite (1410 ± 5 Ma and 1403 ± 5 Ma, respectively). In the field, xenoliths of shonkinite can be seen within the syenite body (FIG. 2A). None of the primary minerals in the shonkinite are peralkaline. Late

FIGURE 2 Mountain Pass rocks. (**A**) Xenolith of shonkinite in amphibole syenite, providing a sequence of emplacement. (**B**) Asbestiform magnesio-riebeckite in amphibole syenite. (**C**) "Birthday Claim" tabular bastnäsite in a ferruginous dolomite matrix (field of view = 8 cm). (**D**) Bastnäsite-rich barite sövite in plain light (field of view = 3.6 cm)

FIGURE 3 Mountain Pass minerals in thin section. (**A, B**) "Black ore" bastnäsite in ferruginous calcite carbonatite; X-ray element map and photomicrograph (plane-polarized light), respectively. In the element map, pink is bastnäsite, green is barite, blue is strontianite, red is dispersed Fe oxide in calcite, and mustard brown is calcite. (**C**) Cathodoluminescence micrograph of Sm^{3+}-activated apatite (light pink) in a dolomite carbonatite matrix (field of view = 2.5 mm). (**D**) Photomicrograph (plane-polarized light) of monazite (Mnz) and pyrochlore (Pch) in parisite-rich calcite carbonatite (field of view = 1.8 mm)
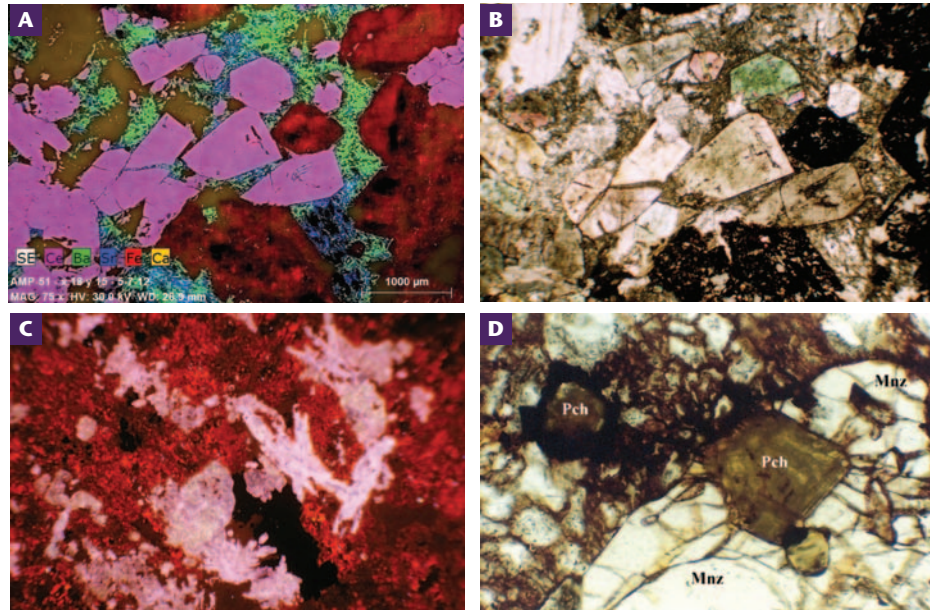
metasomatic fluids introduced alkalis to the shonkinite. In contrast, the syenite contains peralkaline magnesio-riebeckite and other indications of strong alkali buildup.

There are numerous references in the literature to the geology, mineralogy, and origin of the Mountain Pass carbonatite (summarized in Castor 2008). Carbonatite and REE occurrences from other world localities are often compared with Mountain Pass, with emphasis on the similarities; however, it should be stressed that no other carbonatite occurrence in the world closely resembles Mountain Pass.

Bear Lodge Carbonatite, Wyoming

Second to Mountain Pass with respect to grade, tonnage, and amenability to processing, the Bear Lodge carbonatite may be one of the best LREE-mineralized occurrences in North America. The Bear Lodge Mountains form a dome in the Black Hills area, Wyoming. The dome contains an 8.4 × 3.4 km core of Tertiary igneous rocks, together with more than 30 separate igneous bodies that are concentrated

in the north. Tertiary, alkaline igneous rocks that have intruded and domed the surrounding Paleozoic and Mesozoic sedimentary rocks include carbonatite dikes, stockworks, and oxidized equivalents, all of which are located in the north-central core of the Bear Lodge dome, plus multiple intrusions of phonolite, trachyte, other alkaline igneous rocks, and a variety of associated breccias and diatremes (Clark and Mariano 2011). These intrusions range in age from 35 to 50 Ma.

Dominant ancylite-(Ce) plus lesser carbocernaite occur in unoxidized carbonatite (FIG. 4). Other REE minerals occurring in both the oxidized and unoxidized carbonatites include calcioancylite, bastnäsite, parisite, synchysite, monazite, cheralite, burbankite, and cerianite. The lanthanide mineralization at Bear Lodge is predominantly of hydrothermal origin. It can be divided into at least two types: a hydrothermal type that formed at moderate depth under relatively reducing conditions and a low-temperature supergene type that formed under more oxidizing conditions.

FIGURE 4 Bear Lodge minerals. (**A**) Ancylite–parisite–fluorite vein transecting sövite (field of view = 40 mm). (**B**) Burbankite prisms in sövite (field of view = 4.4 mm). (**C**) Hexagonal pseudomorph with contained ancylite, carbocernaite, and strontianite in sövite (field of view = 1.8 mm). (**D**) Secondary electron image of carbocernaite (C), strontianite (S), and ancylite (A).
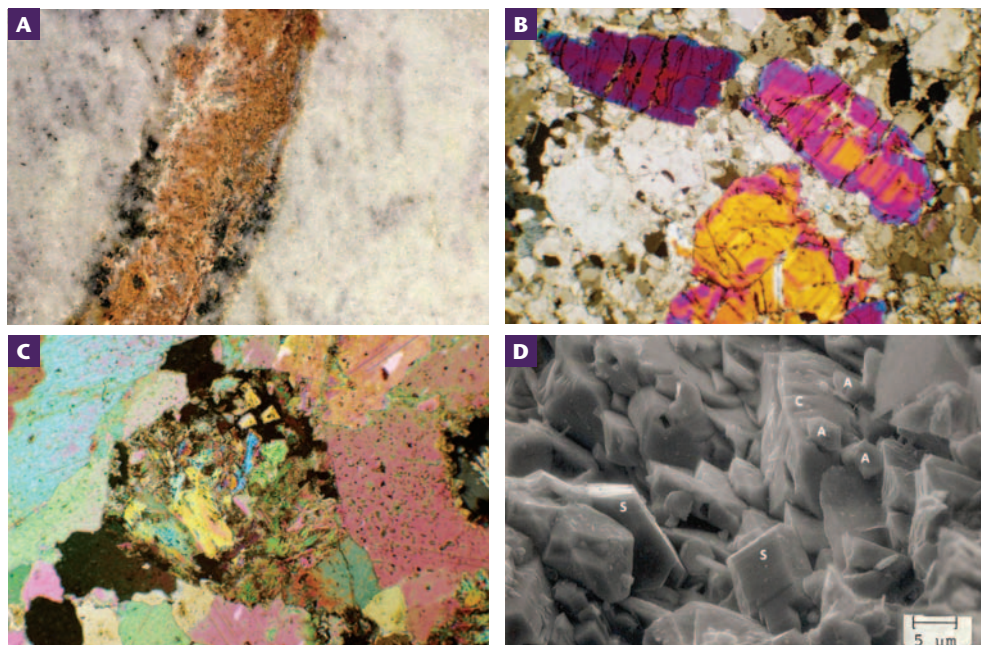
The ancylite and carbocernaite occur as microscopic stubby crystals of orthorhombic habit that are best observed in thin section or with a scanning electron microscope. The origin of the minerals is complex. They are most often found as intergrown aggregates together with strontianite. The mineral grains within these aggregates show some degree of crystallographic continuity and are surrounded by clearly defined hexagonal outlines. Some have residual cores of burbankite. This type of mineralization has been interpreted as pseudomorphic replacement, with preserved hexagonal prism outlines, of burbankite precursors in Khibina, Kola Peninsula, and other Russian occurrences (Vlasov 1966, p. 281). This mode of origin was also suggested for Bear Lodge (Wall et al. 1997). Invariably, sulfides, including abundant pyrite and pyrrhotite with minor bornite, chalcopyrite, galena, sphalerite, and molybdenite and rare covellite and arsenopyrite, are found together with the ancylite and carbocernaite.

A second generation of lanthanide mineralization is often found accompanying these minerals. These younger minerals partially or completely replace the earlier ones. They are considerably smaller in grain size and formed under oxidizing conditions, as indicated by the association of cerianite and the negative Ce anomalies in the parisite and bastnäsite.

Grade and tonnage estimations for REE mineralization are currently underway at Bear Lodge. Rare Element Resources Ltd. reported a measured and indicated resource of 6.8 million tonnes at 3.75 wt% REO, with a 1.5 wt% cutoff grade, and an additional inferred mineral resource of 24.2 million tonnes at 2.74 wt% REO with a 1.5 wt% cutoff (www.rareelemetresources.com).

Peralkaline Igneous Occurrences

A number of igneous occurrences in North America contain substantial quantities of REEs, and are currently the focus of exploration programs. They include: Nechalacho or Thor Lake, Northwest Territories: syenites and granitic phases of the Blachford Lake complex (Trueman et al. 1988); Pajarito Mountain, New Mexico: peralkaline granites and quartz syenites (Moore et al. 1988); Kipawa, Québec: syenite gneiss (van Breeman and Currie 2004); Strange Lake, Québec–Labrador: peralkaline granite (Zajac et al. 1984); Red Wine, Labrador: agpaitic alkaline rocks and peralkaline quartzofeldspathic gneisses (Curtis and Currie 1981); and Bokan Mountain, Alaska: peralkaline granite (Keyser 2010). Geophysically, the peralkaline rock units produce positive radiometric and negative magnetic anomalies.

In these occurrences, REE mineralization is complex and consists of many discrete REE-bearing minerals and rock-forming minerals containing substitutional REEs. The complexity of the mineralogy is manifest in the diversity of the mineral species, which occur as fine-grained, low-grade mineralization dispersed in a felsic matrix. Some of these occurrences have been explored for more than 25 years and are currently being subjected to physical and chemical processing tests to determine the potential for economic beneficiation. These deposits tend to contain a higher proportion of the more valuable HREEs than carbonatites. One example is the Kipawa metamorphosed syenite, which is one of the most extraordinary REE-mineralized occurrences in North America. The coarse-grained phases are readily amenable to physical processing (Fig. 5). The most abundant independent REE minerals are mosandrite and britholite. Other minerals that contain REEs as substitutional impurities include eudialyte, titanite, apatite, and hiortdahlite. Of these minerals, eudialyte occurs in potentially economic quantities.

Heavy REEs in Apatite

If there is an urgent need for HREEs in North America, the apatite tailings at Mineville, NY, may be the best source. The tailings encompass a volume of 5 million cubic meters and appear as small mountains on topographic maps. Mineville is situated on the eastern edge of the Adirondack Mountains, just 6 km west of Lake Champlain. It has become almost a ghost town since Republic Steel Corporation suspended magnetite-mining activities in the 1970s.

In 1980, Molycorp examined the apatite-bearing tailings piles, bulldozed a road through one pile and sampled the tailings extensively by drilling, establishing the presence of 8–9 million kilograms of contained Y_2O_3 with an average grade of 0.12 wt% Y_2O_3 and 0.6 wt% REO, mainly in the
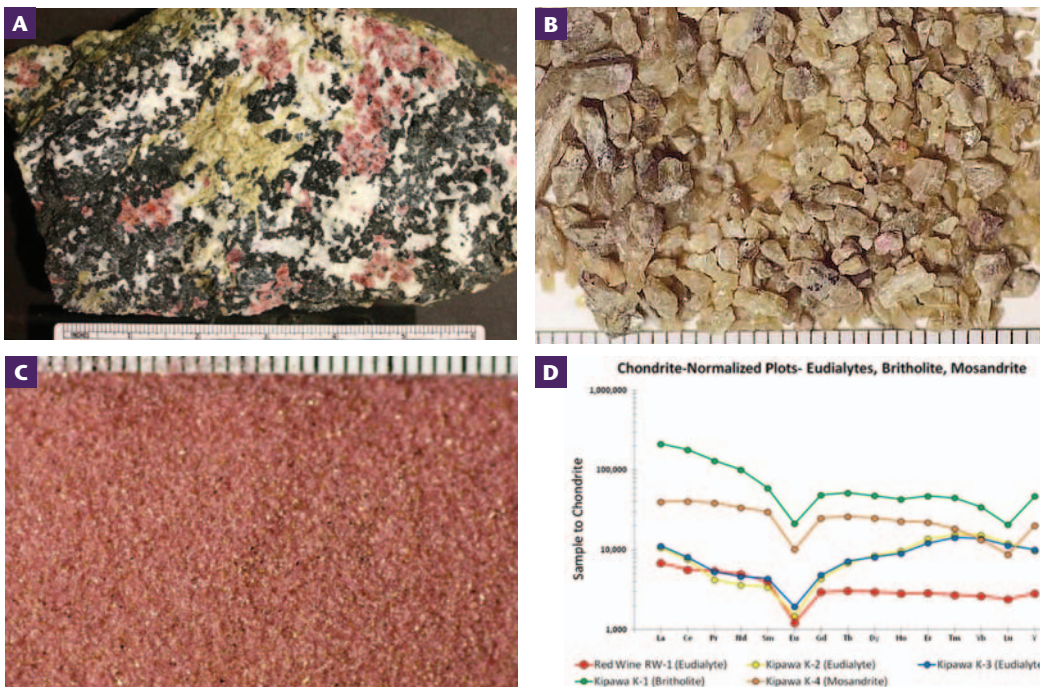
FIGURE 5 (**A**) Eudialyte with mosandrite from Kipawa, Québec (inch scale). (**B**) Mosandrite concentrate from Kipawa (mm scale). (**C**) Eudialyte concentrate from Kipawa (mm scale). (**D**) Chondrite-normalized REE plots of Red Wine eudialyte and Kipawa eudialyte, mosandrite, and britholite

apatite. Apatite concentrates run in excess of 6 wt% ΣREE with a HREE-dominant distribution (McKeown and Klemic 1956). Both Molycorp and Rhône Poulenc eventually abandoned the Mineville project because the results at that time suggested that they could not compete with the Chinese producers in terms of costs.

Quartz-Pebble Conglomerates

Heavy REEs were extracted from raffinates produced during the chemical processing of uraninite from the Precambrian quartz-pebble conglomerates of the Elliot Lake area of Ontario. A recent report by Cox et al. (2012) covers the geology and economic assessment of the Eco Ridge project, which is currently being investigated.

Predominantly Y was recovered from raffinates at the Denison plant during the periods 1963–1973 and 1985–1990. Creation of residual ion-exchange solutions resulting from the leaching of uraninite with sulfuric acid was followed by solvent extraction to produce an upgraded Y product. At that time, Y compounds were used as the host for REE phosphors in color televisions, but there was little demand for the HREEs. The REE concentrates shipped to the Louviers Molycorp plant, Colorado, contained ~50% Y. Details of the processing of the REEs in the Elliot Lake ore are well documented by Goode (2012). Mining of the REEs was terminated because of the reduced price of Y resulting from the development of the South China REE-clays.

It should be emphasized that the major mineral sources of Y and HREEs in the quartz-pebble conglomerates are almost exclusively uraninite and coffinite (Fryer and Taylor 1987). Other REE-bearing minerals occurring in near trace amounts include monazite, brannerite, bastnäsite, and unidentified species.

Sandstones and Quartzites

Remobilized yttrium occurs in sandstones and quartzites in Saskatchewan as xenotime mineralization. At Beatty River, the interstitial spaces in quartz sandstone are completely filled in with bands of fine-grained xenotime. Some of the outcropping rocks are composed of more than 30 vol% xenotime. This area is currently being explored by Great Western Minerals Group Ltd.

In the McArthur River–Wheeler River area in the southern Athabasca Basin, xenotime occurs in quartzites. The Maw Zone is related to unconformity-type uranium mineralization (Quirt et al. 1991). The presence of xenotime is considered to be a result of the remobilization of Y and HREEs from uraninite and reactions with mobile phosphates.

Xenotime and Monazite in Metamorphic Rocks

Spectacular occurrences of xenotime and monazite are often observed in metamorphic rocks; they are locally of high grade and relatively coarse grained. Examples include the Pinto Gneiss of Music Valley in California (Evans 1964) and paragneiss and migmatites in the Crystal Lake pluton of southern New York (Aleinikoff and Grauch 1990). The Archie Lake property in northern Saskatchewan is another example, where xenoblastic monazite grains occur in localized major quantities in a metamorphosed arkosic arenite unit. These occurrences may have originated as detrital accumulations in paleoplacers that were subsequently recrystallized during a metamorphic event. None has yet proved large enough to make an economic deposit.

REE, Y, and Sc in Jamaican Red Mud Tailings

Red mud tailings from bauxite mining may contain substantial amounts of REEs, Y, and Sc (Wagh and Pinnock 1987). In Jamaica, the ΣREE + Y content of the red mud is 0.23–0.38 wt% and thus exceeds that of South China clays. Their REE distribution shows a higher HREE content than representative Chinese clay samples (FIG. 6). However, mineralogical SEM analysis performed on the Jamaican samples suggests that the REEs are dispersed throughout the red mud, either as ion-adsorbed elements in the clays or as an unknown phase intimately associated with Fe oxides.
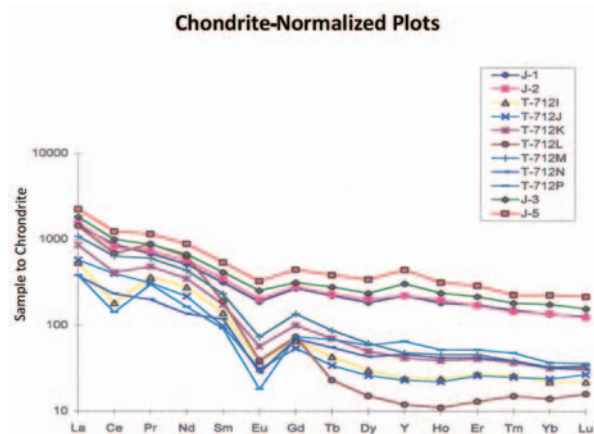
FIGURE 6 Chondrite-normalized REE plots of four Jamaican red mud samples (J set) and seven South China clay samples (T-712 set). The Jamaican samples all show a higher ΣREE + Y content and a higher proportion of MREEs and HREEs relative to the clays.

CONCLUDING COMMENTS

Mountain Pass clearly ranks as the premier LREE deposit in North America and is the only deposit to have a record of sustained production and successful processing. To compete, other occurrences need favorable permitting and environmental considerations, sufficient grade and tonnage, better REE distribution (i.e. more Nd and HREEs), and, most importantly, proven amenability to competitive economic processing. Mountain Pass is the only REE resource in North America that has processing facilities and proven technology for the mining and separation of REEs.

At this time, many carbonatite complexes in North America are being explored for REEs, and in most cases the total REE grades are ~2 wt% or less. It should be emphasized that when the Mountain Pass carbonatite mine was operated by Molycorp, the mine tailings were running ~2 wt% ΣREE! The economics are different if HREEs are involved, and much lower grades are potentially viable. However, again, an understanding of the mineralogy is key to successful exploitation of any deposit.

ACKNOWLEDGMENTS

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Japan Association of Mineralogical Sciences

http://jams.la.coocan.jp

2012 AWARDEES

The Japan Association of Mineralogical Sciences (JAMS) is proud to announce the recipients of its 2012 society awards. Each year, the **Japan Association of Mineralogical Sciences Award** is given to a maximum of two scientists for exceptional contributions to the mineralogical and related sciences. The **Manjiro Watanabe Award**—named in honor of Professor Manjiro Watanabe, a famous Japanese mineralogist, and funded by his own contribution—is awarded every year to one scientist who has contributed significantly to the mineralogical and related sciences over his/her long career. The **Sakurai Medal**—named in honor of Dr. Kin-ichi Sakurai, famous for finding new minerals—is awarded to one scientist who has made great contributions to studies on new minerals.

Japan Association of Mineralogical Sciences Award to Akira Yoshiasa

Akira Yoshiasa, of the Graduate School of Science and Technology, Kumamoto University, Japan, is a mineralogist who has studied the correlation between the structures and physical properties of minerals. In his research, he has derived dynamical structural information from both the long-range-order structure using the diffraction method and the local structure by the XAFS method. Using a combination of both techniques, he successfully determined the pressure-dependent potential parameters and characteristic values of various materials under high P–T conditions, and he contributed to the quantitative understanding of their structural stability. He elucidated the conduction mechanism of ionic superconductors such as AgI and CuI, by performing anharmonic thermal vibration analysis; he also clarified their phase relations and phase transition mechanism through in situ experiments under various P–T conditions using synchrotron radiation. He applied this technique to the study of mantle minerals and proposed that their ionic superconduction attributed to anharmonic thermal vibrations can result in high electric and low thermal conductivities in the Earth's lower mantle. His research interests also include the structures of melt and glass. He discovered that the local structures of atoms in a melt change rapidly with pressure following first-order phase transition processes. He attempted to understand the past histories of the Earth and planets from the local structures of the trace elements in minerals, tektite impactite glass, and K–T boundary clays. Recently, he extended his research to atomic-level structural analyses under extreme conditions, such as ultragravity. He has thus contributed significantly to the advancement of fundamental Earth science knowledge.

Akira Yoshiasa

Manjiro Watanabe Award to Masayasu Tokonami

Masayasu Tokonami was matriculated to the graduate course of the University of Tokyo in 1958. Along with Profs. R. Sadanaga and Y. Takeuchi, he elucidated the crystal structure of mullite, Al_2SiO_5, using the single-crystal X-ray diffraction method. He accepted a position in the Institute for Solid State Physics, University of Tokyo, in 1962 and, along with Prof. S. Hosoya, put forth a systematic method for unraveling a periodic vector set. He also

Masayasu Tokonami

presented a table of values of the atomic scattering factor for O^{2-}. In 1967, he moved to the Institute of Scientific and Industrial Research, Osaka University. Along with Prof. N. Morimoto, he discovered the domain structure of pigeonite and clinoenstatite, and with Prof. K. Otsuka and others, he studied the crystal structure of stress-induced β_1 martensite in a Cu–Al–Ni alloy using neutron diffraction. From 1971, he worked as a guest professor for two years with Prof. E. Helmer at Marburg University, Germany, and solved the complicated structure of the sulfosalt senandorite, $PbAgSb_3S_6$. In 1981, he moved to the University of Tokyo, where, with Dr. J. Ye and Prof. K. Otsuka, he analyzed the structure of $\gamma_1'Cu$–Al–Ni martensite using conventional X-rays and synchrotron radiation. In 1998, he moved to the Saitama Institute of Technology and, with Prof. R. Negishi and others, he showed that elliptically polarized light can propagate in a crystal of alkali amphibole.

Sakurai Medal to Tetsuo Minakawa

Tetsuo Minakawa, of the Department of Earth Science, Ehime University, has made great contributions to the field of descriptive mineralogy. In the nomenclature of epidote-group minerals, $A_2M_3(T_2O_7)(TO_4)(O,F)(O,OH)$, as recommended by Armbruster et al. (2006), piemontite-(Sr), clinozoisite-(Sr), and manganipiemontite-(Sr) have been described as clinozoisite subgroup minerals with Sr dominant in the A2 site. Although the Sr analogue of epidote, $CaSrAl_2Fe^{3+}(Si_2O_7)(SiO_4)O(OH)$, was undiscovered in nature, Armbruster et al. (2006) had listed it as a possible member of the clinozoisite subgroup minerals. Minakawa and his coworkers discovered Sr-rich epidote as a gangue mineral in the Nagakawara, Matsukabu, and Honomori deposits in the Ananai manganese mine in Kochi Prefecture, Japan. They identified this mineral as similar to epidote-(Sr). In 2006, data on the new mineral and the name *epidote-(Sr)* were approved by the IMA Commission on New Minerals, Nomenclature and Classification (#2006-055). The details of the mode of occurrence and the mineralogical data concerning epidote-(Sr) were provided by Minakawa et al. (2008). Epidote-(Sr) occurs as prismatic crystals up to 1 cm in length in the manganaxinite veins cutting braunite–caryopilite ores and is associated closely with Mn^{2+}-pumpellyite and bannisterite. The crystals are brown to brownish red in color, owing to the high Mn^{3+} content. Subsequently, Minakawa and coworkers also discovered a new manganese–vanadium garnet, momoiite, $(Mn,Ca)_3(V^{3+},Al)_2Si_3O_{12}$ (IMA CNMNC, #2009-026), from the Kurase (Ehime Pref.), Fujii (Fukui Pref.), and Hokkejino (Kyoto Pref.) metamorphosed manganese deposits in Japan.

Tetsuo Minakawa

Association of Applied Geochemists

NEWS FROM AAG REGIONAL COUNCILLORS

Pakistan

The University of Peshawar's National Centre of Excellence in Geology (NCEG; see www.upesh.edu.pk/academics/researchcenter/nceg/nceg.html) has recently completed a synthesis of the entire available geochemical data set for gold and base metals in northern Pakistan covering a period of two decades (1992–2012). During this period, more than 5000 samples were analyzed by various agencies, such as the Pakistan Mineral Development Corporation, the Sarhad Development Authority, and international bodies like MINORCO. The entire data set was scanned, digitized, and stored in a GIS database. The database also includes satellite imagery, digital elevation model data, and other related information. From this, the NCEG has identified six target areas for further gold and base metal studies: (1) Bagrot Valley, (2) Golo Das, (3) Machulu Valley, (4) Shigri Bala, (5) Ranthak, and (6) Chapursan Valley (see map). According to the NCEG, these areas may hold potential for gold mineralization.

On the basis of the above studies, a joint program funded by the National Academies of Science has been started with Houston University (see www.geosc.uh.edu/features/geos-nsm/gold-prospecting.php). Three field trips were conducted in the northern areas of Pakistan in 2011 (see photo). The first field trip was conducted by the University of Peshawar group in April. During this trip, 30 water and 30 sediment samples were collected along the Gilgit River; in addition, 25 blood, 25 urine, and 25 nail samples were provided by the gold panners and their family members. During the second field campaign in June, the University of Houston group collected 40 water and 37 sediment samples along the Indus, Gilgit, and Hunza rivers. The third field campaign was conducted in July by the University of Peshawar group, which collected more than 120 rock samples in four of the six identified target areas: Bagrot Valley, Golo Das, Machulu Valley, and Shigri Bala. Currently, water and sediment samples are being analyzed at the University of Houston, while rock samples are being cut and pulverized at the University of Peshawar. About 90 thin sections were prepared for petrographic study. Representative samples were selected for geochemical work after splitting the pulverized samples. The University of Peshawar group has started laboratory work on these representative samples. About 90 rock chips have been shipped to the University of Houston for geochemical and spectral analyses. In parallel to this, remote
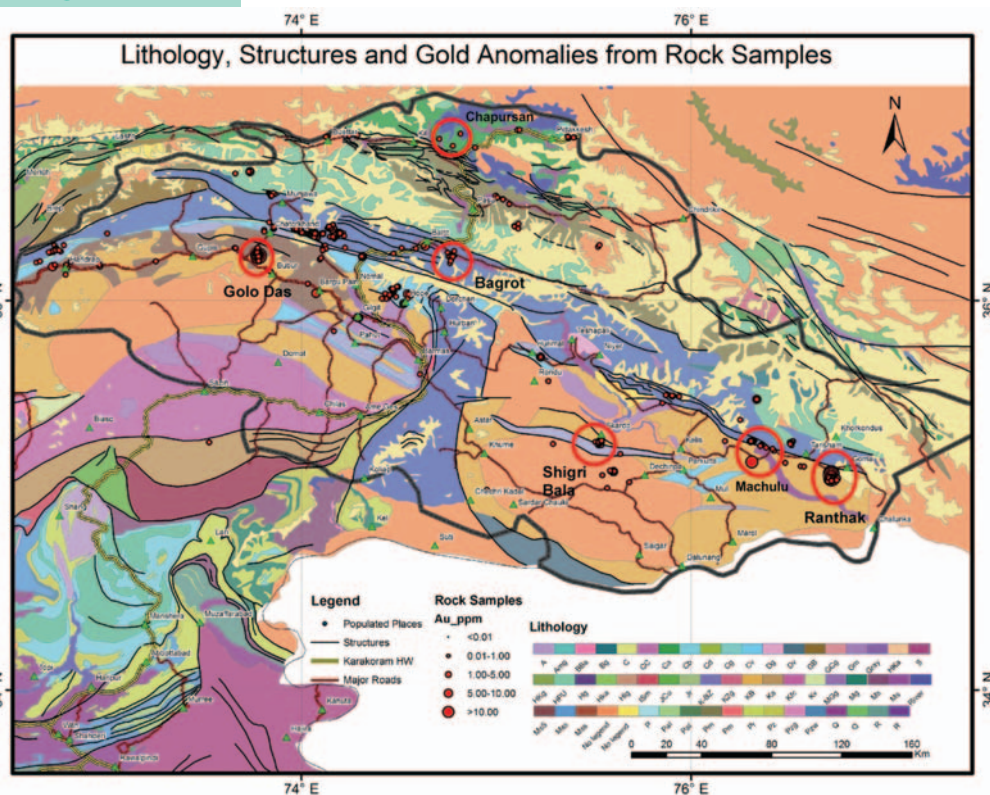
Geological map of northern Pakistan (after Searle and Khan, 1996, Oxford University), showing the concentration of gold in rock samples and the locations of identified target areas

Prof. Dr. Tahir Shah flanked by graduate students Laeiq Ahmad and Sadaf Miandad of the NCEG, University of Peshawar, during field work in the Bargot Valley

sensing analysis is helping identify alteration zones that could contain gold. The project includes training Pakistani scientists in the processing of remotely sensed images and in trace element geochemistry. The area's gold panners will also be trained in safer, more efficient methods of panning, which will reduce mercury pollution of river water and groundwater. Prof. Dr. Tahir Shah of the NCEG, University of Peshawar, is acknowledged for providing the above information.

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AAB (pvt) Ltd Islamabad,
AAG Regional Councillor

STUDENT–INDUSTRY WORKSHOP AND FIELD TRIP

In an effort to attract more students into the mineral exploration industry, the Prospectors and Developers Association of Canada (PDAC) ran its sixth annual Student–Industry Mineral Exploration Workshop (S-IMEW) on May 5–18, 2012, in Sudbury, Ontario. The top 26 Canadian postsecondary geoscience students were selected from across the country to attend the workshop. Students participated in lectures, presentations, and hands-on courses covering exploration techniques, mineral deposits, geophysics, and geochemistry, as well as environmental, health and safety, and corporate social responsibility issues. Field trips to Timmins and Rouyn-Noranda were included in the workshop, allowing students to see what these world-class mining regions have to offer.

Among the highlights of this program is "Geochemistry Day," organized and taught by Stew Hamilton and Richard Dyer from the Ontario Geological Survey, Beth McClenaghan from the Geological Survey of Canada, and Noelle Shriver from Vale, all of whom are members or fellows of the AAG. They introduced students to exploration geochemical techniques, but the main focus of the day was to provide the students with practical experience that they are unlikely to receive in the university setting. To that end, students carried out lake sediment sampling firsthand in boats on Ramsey Lake in Sudbury. Beth then introduced the students to the microscopic world of indicator minerals and to hands-on mineral picking using microscopes. Noelle took the students on a short field traverse to explore and review soil profiles and carry out soil sampling in typical glaciated terrain.

The field trip was a great opportunity for students to see new parts of Canada, learn about the wide variety of career opportunities in mineral exploration, gain experience with exploration techniques not typically taught to undergraduate students, and experience some of the adventures of being a geoscientist.

Beth McClenaghan (Beth.McClenaghan@NRCan-RNCan.gc.ca)
Geological Survey of Canada

26th International Applied Geochemistry Symposium, incorporating the New Zealand Geothermal Workshop

White Island, New Zealand

18-21 November, 2013
Rotorua, New Zealand
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First Circular & information on
• Technical programme
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• Field trips
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German Mineralogical Society

REPORT ON THE DMG SHORT COURSE "APPLICATIONS OF SOLID STATE NMR SPECTROSCOPY IN MINERALOGICAL AND GEOSCIENTIFIC RESEARCH"

May 29–June 1, 2012, Bochum
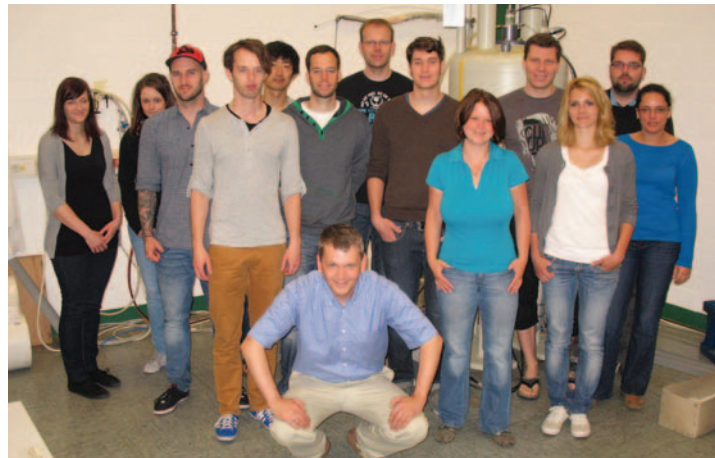
Participants in the NMR short course at the University of Bochum, Germany

Now almost a tradition, the DMG/DGK short course on NMR spectroscopy took place at the University of Bochum from May 29 to June 1. Under the supervision of Dr. Michael Fechtelkord, 14 participants from universities in Germany, Austria, and Switzerland dedicated four days to exploring the possibilities of NMR spectroscopy.

After a theoretical introduction in the morning, the newly learned knowledge was carried into the lab to test it in the real world. Thus Tuesday afternoon was devoted to measuring the spin-relaxation of ^1H and the dynamics of tetramethylammonium iodide. In doing so, the participants learned how to handle a spectrometer and to prepare samples for measurement. But no analytical procedure is complete without the actual evaluation of the measured data.

Thus after getting to know the huge magnet better (see photo), the second day started with the theory of dipole and chemical interactions in solids. The aim was to find a solution to the problem of how to measure a good spectrum despite the presence of anisotropy effects. The answer is simple and fascinating at the same time: by using the magic angle. After solving these problems, the evaluation of spectra still needs a lot of experience and patience.

On Thursday, the participants took a peek into the rabbit hole. NMR spectroscopy not only can show the local distortions in the crystal lattice induced by doping, it can also distinguish between different atomic neighbors.

It is fascinating to see the possibilities provided by NMR spectroscopy for finding answers to many scientific problems. Also it is amazing to see how scientists come up with new solutions to experimental problems and measure what could not be measured before.

Last, but not least, this short course gave young scientists the opportunity to exchange experiences in a relaxed atmosphere. The two social events were well organized and great successes.

Naemi Waeselmann
University of Hamburg

Meteoritical Society

http://meteoriticalsociety.org

2013 ANNUAL MEETING INVITATION

The 76th annual meeting of the Meteoritical Society will take place in Edmonton, the capital city of Alberta, Canada. The meeting will be held on July 29–August 2 at the Crowne Plaza Chateau Lacombe in Edmonton's downtown core, within walking distance of the Arts District, shopping, nightlife, restaurants, and coffee shops. Edmonton is the most northerly major city in Canada. Long daylight hours and warm weather are therefore expected during the summer months. Situated on the North Saskatchewan River, Edmonton is close to UNESCO World Heritage Sites such as Jasper and Banff national parks in the Canadian Rocky Mountains, Head-Smashed-In Buffalo Jump, and Dinosaur Provincial Park. Less than an hour from Edmonton is Elk Island National Park. In addition to being an opportunity to observe bison, moose, and deer in a natural setting, this dark-sky preserve is also a prime viewing area for the aurora borealis, a light show we may be treated to as the next northern lights activity maximum is approached. The conference banquet will be held on Wednesday, July 31, on the picturesque campus of the University of Alberta.

76th Annual Meeting of the Meteoritical Society

Edmonton, Canada
July 29 – August 2, 2013

We expect to have a wide variety of interesting scientific sessions at our meeting. Several field trips are planned, including an excursion to the Whitecourt Meteorite Impact Crater, one of a few Holocene craters worldwide; a K/T boundary locality; and the world-famous Royal Tyrell Museum of paleontology. Full details can be found in the first announcement, available on the LPI website, www.lpi.usra.edu. Additional details can be found on the local meeting website, www.metsoc2013edmonton.org. For more information, please contact Organizing Committee Chair Chris Herd at herd@ualberta.ca.

We look forward to welcoming you to Edmonton next summer!

SECOND CONFERENCE ON THE LUNAR HIGHLANDS CRUST – MEETING REPORT

The lunar highlands are the accessible exposures of the Moon's pre-mare crust, and so are a principal source of data on the Moon's origin and early history. Lunar meteorites are essential contributors to understanding the lunar highlands; they provide "ground truths" from outside the Apollo and Luna sampling sites for remote sensing data (optical, radar, and gravity). The last conference devoted solely to the lunar highlands was in 1979, the year of the first find of a lunar meteorite. So, it seemed timely to hold another such conference, augmented by

Anaïs Fourny, one of the two students sponsored by the Meteoritical Society to attend the workshop. PHOTO CREDIT: ALLAN TREIMAN

field study of a terrestrial analog for lunar crust formation. The Meteoritical Society was a cosponsor, and supported attendance by two students, Corey Wall and Anaïs Fourny of the University of British Columbia.

The workshop, held on July 12–16, 2012, was convened by Dr. Allan Treiman of the Lunar and Planetary Institute (and Fellow of the Society) in Bozeman, Montana. The workshop featured invited contributions by Dr. David Kring, who talked about the Moon's impact history (including the nature of the putative cataclysm) and the sources of the impactors; Dr. Maria Zuber, on the new gravity maps from the GRAIL mission; Dr. Carlé Pieters, on optical remote sensing and the mineral constitution of the lunar surface; and Dr. Randy Korotev, on the nature of the lunar highlands revealed by meteorites and the returned samples. Contributed talks and posters spanned a huge range of topics, such as terrestrial analogs, details of optical properties and models, and petrologic studies of samples new and old. Free discussion was an important part of the meeting, and the conversations were active and cordial.

To complement the technical sessions, Dr. Stewart McCallum (University of Washington) led two field trips to view rocks of the nearby Stillwater Complex, a layered basic intrusion that has provided much of the conceptual basis for understanding lunar highlands rocks. Before the workshop, participants examined rocks of the lower section of the Stillwater, including peridotites, pyroxenites, chromite-rich rocks, and some anorthosites. After the workshop, Dr. McCallum and a dozen young hardies climbed up Picket Pin Mountain to see part of the upper section, including massive anorthosites, norites with sedimentary structures, and a sulfide-rich zone. After summiting, the group retreated from a massive thunderstorm, soaked, but alive and happy.

To view the complete program and abstracts for this workshop, see www.lpi.usra.edu/meetings/highlands2012/.

FUTURE ANNUAL MEETINGS

2013 July 29–August 2 Edmonton, Alberta, Canada
Contact Chris Herd (herd@ualberta.ca)

2014 September 7–14 Casablanca, Morocco
Contact Hassna Chennaoui (chennaoui_h@yahoo.fr)

2015 July 27–31 Berkeley, California

2016 Dates to be announced Berlin, Germany

STUDENT TRAVEL AWARDS

Over 45 students attending the annual meeting of the Society in Cairns, Australia, in August 2012, received travel grants. Student travel grants and travel grants for scientists from countries with limited financial resources are generously sponsored by the Barringer Crater Company, the Planetary Studies Foundation, NASA (Cosmochemistry Program), the Meteoritical Society Endowment Fund, the International Meteorite Collectors Association (Brian Mason Award), and the Australian National University (Research School of Earth Sciences and ICOG-7 awards).

The Barringer Crater Company

- Feargus Abernethy, *Open University*
- Marlene Giscard, *Imperial College*
- Michael Goodyear, *Open University*
- Maartje Hamers, *Utrecht University*
- Leon Hicks, *University of Leicester*
- Yoshihiro Hidaka, *Tokyo Metropolitan University*
- Jesper Holst, *University of Copenhagen*
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- Yi-Jen Lai, *University of Bristol*
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- Mia Olsen, *University of Copenhagen*
- Claudiu Tănăselia, *Babes-Bolyai University*
- Nicole Spring, *University of Manchester*
- Hiroko Suzuki, *University of Tokyo*
- Mona Weyrauch, *Westfälische Wilhelms Universität, Münster*
- Felicity Williams, *Open University*
- Niel Williams, *University of Manchester*
- Yuchen Xu, *Chinese Academy of Science, Guiyang*
- Shogo Yakame, *University of Tokyo*

NASA–Cosmochemistry

- Robert Beauford, *University of Arkansas*
- Timothy Bowling, *Purdue University*
- Patrick Gasda, *University of Hawaii*
- Evan Groopman, *Washington University in St. Louis*
- Pierre Haenecour, *Washington University in St. Louis*
- Junko Isa, *University of California, Los Angeles*
- Christine Jilly, *University of Hawaii*
- Jordan Kendall, *Purdue University*
- Takafumi Niihara, *Lunar and Planetary Institute*
- Caitlin Schnitzer, *University of Arizona*
- Lev Spivak-Birndorf, *Arizona State University*
- Reto Tappitsch, *University of Chicago*
- Myriam Telus, *University of Hawaii*
- Curtis Williams, *Arizona State University*
- Kelsey Young, *Arizona State University*

Planetary Studies Foundation

- Marc Biren, *University of New Brunswick*
- Matthew Huber, *University of Vienna*

Australian National University Research School of Earth Sciences

- Vicki Darlington, *James Cook University*
- Francesco Pignatale, *Swinburne University*

Australian National University ICOG-7 Conference Fund

- Joelene Buntain, *Monash University*
- Barbara Frasl, *Australian National University*

Meteoritical Society Endowment Fund

- Rogelio Acevedo, *Centro Austral de Investigaciones Científicas, Argentina*
- Hasnaa Chennaoui Aoudjehane, *Hassan II University, Morocco*
- Assia Laroussi, *Hassan II University, Morocco*
- Kuljeet Marhas, *Physical Research Lab, India*
- S. V. S. Murty, *Physical Research Lab, India*

International Meteorite Collectors Association (Brian Mason Award)

- Natasha Stephen, *Imperial College*

Natasha Stephen, winner of the Brian Mason Award. PHOTO CREDIT: DIAMOND LIGHT SOURCE

Brian Mason Award

In 1997, Joel Schiff, the first editor of the popular *Meteorite* magazine, created a travel award in honor of Brian Mason, who was born in New Zealand. The award is given to a student attending the annual meeting of the Society who submits an abstract that presents clearly explained, exciting results of particular interest to readers of *Meteorite* magazine. The recipient is required to write a popular account of his/her work for the magazine. Since 2008, the award has been generously funded by the International Meteorite Collectors Association.

This year the Program Committee for the Cairns, Australia, meeting selected Natasha R. Stephen as the winner of the Brian Mason Award. Natasha is a student at Imperial College in London, UK, and she submitted an abstract entitled "The Tissint Meteorite: A pristine and unique sample of the Martian sub-surface," authored by N. R. Stephen, M. Genge, and S. Russell. This paper discusses the newest Martian meteorite, Tissint, which was recovered quickly after it fell and represents a rare opportunity to study unweathered Martian material (see the August 2012 "CosmoElements" feature in this magazine for a discussion of Tissint).

CALL FOR AWARD NOMINATIONS

Please consider nominating a colleague for one of the Society's awards. Nominations should be sent to Secretary Greg Herzog (herzog@rutchem.rutgers.edu) by January 15 (January 31 for the Service Award and the Pellas–Ryder Award). For more information and details on how to submit a nomination for any of these awards, please see the latest Newsletter at the Society website (http://meteoriticalsociety.org/Newsletter/nlett11.pdf - see page 9) or e-mail the secretary (metsocsec@gmail.com).

The Society gives a number of awards each year. The **Leonard Medal** honors outstanding contributions to the science of meteoritics and closely allied fields. The **Barringer Medal and Award** recognize outstanding work in the field of impact cratering and/or work that has led to a better understanding of impact phenomena. The **Nier Prize** recognizes outstanding research in meteoritics and closely allied fields by young scientists (under 35). The **Service Award** honors members who have advanced the goals of the Meteoritical Society to promote research and education in meteoritics and planetary science in ways other than by conducting scientific research. The **Paul Pellas–Graham Ryder Award** is given for the best student paper in planetary science and is awarded jointly by the Meteoritical Society and the Planetary Geology Division of the Geological Society of America.

Mineralogical Society of Great Britain and Ireland

www.minersoc.org

LONDON CALLING

Setting Priorities

By the time you read this, the London Olympics will have come and gone. It is a huge honour to be asked to host the Olympic Games. The budget at the time of the bid was in the region of £2 billion, which has since ballooned to ~£9 billion. Television rights, ticket sales, etc. will be used to claw back some of the money, but, but, as is often the case with major events such as the Olympics, the host is left out of pocket.

In mid-July, the UK Government announced that, from 2014, all publicly funded research is to be made freely available to any reader. In detail, we will move to an 'author-pays open access' model, with £2000 per paper to be paid by the author to the publisher. It is expected that £50 million will be required during the period of transition from the traditional subscription model to the author-pays model, and government has stated that this sum must be found from within the existing education budget. I wonder whether the people who were tasked with setting up and running the Olympics could be brought in to manage the move to 'author-pays' – seems like we might get a better deal. We could call it "Olympic Access".

There are many unanswered questions:

- What about authors who cannot pay, either because they don't have research funding or because their original research grant did not include money for the particular work being published?

- What about the work of authors from other countries? When and if other administrations follow the UK lead, how will the 'author-pays' versus 'library-pays' gap be managed?

- What about content that is included in international aggregates, e.g. GeoScienceWorld?

- Rightly or wrongly, the profits of publishing behemoths such as Elsevier and Springer have been oft-quoted in the decision to move to this author-pays open access model. If authors continue to publish in the same journals as they do now, will they not still make a profit? And what is wrong with business making a profit?

And

- The argument about profits completely ignores a very important point: not all publishers are in it for the money. Some, such as the publishers involved in *Elements*, plough their income back into the science.

- Finally, given a sustainable financial model, many publishers will support author-pays open access. It might help to level the playing field between the "big-deal" commercial publishers and small publishers who have increasingly been squeezed out in recent years. If all content is equally available to all readers, citations might become more dependent on the quality of the article and not just on what's available in the library.

Kevin Murphy
Executive Director

CHARTERED STATUS

Applications for Chartered Status continue to trickle in. Go now to www.minersoc.org/chartered.html to download the application form and other information. Note that fast-track application is available for those who have been members of the Society for a significant period: *"A 'Mature Entry' procedure is important to the Mineralogical Society because…few members are of Chartered or equivalent status but many are senior researchers and practitioners and 'overqualified' compared with the minimum standard required for CSci. The Society is keen to encourage this body of membership to become Chartered Scientists and therefore has sought to devise a rigorous but not too arduous fast track process for Fellows who meet the qualification standard of M level or PhD and have more than 10 years post graduate experience."*

The cost is £50 for the initial application and £45 per year thereafter.

MEETINGS IN 2013

The Society has a number of significant meetings coming up in 2013, meetings which it is running itself or supporting extensively. Visit the links below for more information.

2–4 January 2013
Applied Mineralogy Group–Mineral Deposits Studies Group Annual Meeting
www.mdsg.org.uk/maintext.php?ID=4
Venue: University of Leicester, UK
Convenors: Dave Holwell, Gawen Jenkin, Dan Smith

7–9 January 2013
Volcanic and Magmatic Studies Group Annual Meeting
www.vmsg.org.uk/vmsg-bristol/VMSG_2013/VMSG%20Bristol%20 2013%3A%20Home.html
Venue: Bristol University, UK
Contacts: Alison Rust, Kate Saunders, Elena Melekhova, Emma Johnston, Jonathan Hanson, Rose Burden

26–29 March 2013
Volcanic and Magmatic Studies Group
Volcanism, Impacts, and Mass Extinctions: Causes and Effects
Register online at www.minersoc.org/mass-extinctions.html
Venue: Natural History Museum, London, UK
Contacts: A. Kerr, M. Widdowson, N. MacLeod, G. Keller

17–19 June 2013
Mineralogical Society Annual Meeting
Minerals for Life: Living with Resource Constraints
www.minersoc.org/minerals-for-life.html
Venue: University of Edinburgh, UK
Contacts: M. Tyrer, K. Murphy

ROBERT ANDREW HOWIE OBITUARY, PUBLISHED IN *MINERALOGICAL MAGAZINE*

Robert A. Howie

Written by a former colleague at Royal Holloway University of London, Dr Nick Walsh, a wonderful obituary for Mineralogical Society stalwart Prof. R. A. Howie has been published in *Mineralogical Magazine*. "Many senior academics (and others) will also have abiding memories of his offers of 'a lift up to Senate House'. A lift in Bob's car was a never-to-be-forgotten 'Alton Towers'-type experience; Bob had learned to fly before he drove a car, and it showed." The obituary is available for all to read at www.minersoc.org/files/Howie-obituary.pdf.

MINERALOGICAL MAGAZINE

The list of contents for the bumper June 2012 issue of the journal is given below. Included is the paper by Brookshaw et al., which is available on an open access basis at http://tinyurl.com/cgbsbd6.

European Association of Geochemistry

2012 DISTINGUISHED LECTURE TOUR

The European Association of Geochemistry started its Distinguished Lecture Program in 2011. This program aims to introduce and motivate scientists and students located in under-represented regions of the world to emerging research areas in geochemistry; the program currently focuses on Central and Eastern Europe. The Distinguished Lecturer is selected each year based on a combination of outstanding research contributions to geochemistry and the lecturer's ability to clearly communicate these contributions to a broad audience.

The Distinguished Lecturer for 2012 will be Prof. Tim Elliott, of the University of Bristol, UK. Tim's research focuses on the chemical evolution of the Earth. He is interested in planetary formation and differentiation, sampling of the hidden Earth via melts, and the interaction of the deep and surface reservoirs and how this has influenced the terrestrial environment. His tools of choice are dominantly isotopic, in tandem with elemental abundance measurements and the judicious application of petrology and field-

Tim Elliott

work. He has developed measurements of novel isotopic systems and is enthused by the new vistas of isotopic determination offered by plasma mass spectrometry.

As part of his tour, to take place in November 2012, Tim will visit:
- the University of Warsaw, Poland
- the Institute of Geological Sciences, Wroclaw, Poland
- the Universitatea Babeș-Bolyai, Cluj-Napoca, Romania
- the University of Sofia, Bulgaria

Tim will propose the following talks: "The Origin of Precious Metals on Earth," "Supernova Contributions to the Solar System," and "Tracing Mantle Evolution with Novel Isotopic Systems." Additional details can be found at www.eag.eu.com/education/dlp/.
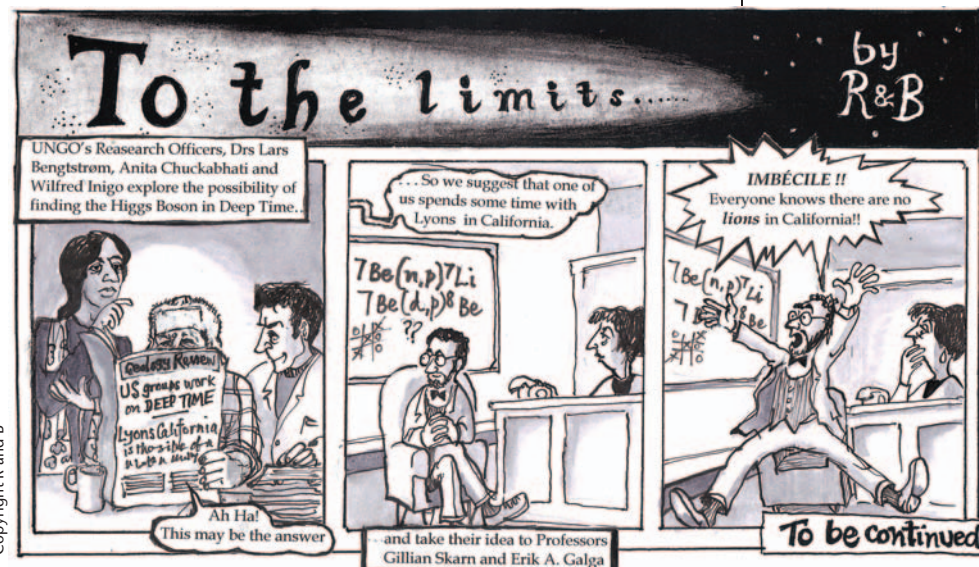
goldschmidt 2013
geochemistry's conference

Florence Italy

August 25–30

Abstract submission and online registration will open in February 2013.

goldschmidt.info/2013

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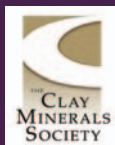
The Clay Minerals Society

THE PRESIDENT'S CORNER

David Laird

"Shales and Imposters" was the theme of the 49th annual meeting of The Clay Minerals Society, held at the Colorado School of Mines in Golden, Colorado, on July 7–11, 2012. The conference, organized by Manika Prasad and her colleagues, featured a coordinated preconference workshop focusing on organic-rich rocks, a Sunday field trip to visit outcrops of such rocks, and sessions on the themes "Pore-Systems in Organic Shales" and "Clay Diagenesis and Organic Maturity." The restaurants of lovely downtown Golden and the excellent conference facilities on the nearby Colorado School of Mines campus provided fertile ground for interdisciplinary discussions relating clay mineralogy, diagenesis, rock structure, and surface chemistry to the formation and potential availability of hydrocarbons in organic shales. Clearly, clay science is foundational to the rapidly growing industry of extracting energy resources from organic shales. Other highlights of the meeting included a symposium organized by Lynda Williams on the topic "Clays and Human Health," during which there was much discussion on the mode of action of antibacterial clays and the impact of clays mixed with animal feed on the fate and toxicity of aflatoxins. An intriguing symposium entitled "Multi-Scale Modeling of Clays and Layered Minerals," organized by Jeff Greathouse and Chris Greenwell, provided a state-of-the-art *ab initio* view of clay surface chemistry, hydration, and swelling and interactions of clays with PAHs, supercritical CO_2, and CO_2 nanodroplets in deep saline aquifers. The latter work helps establish a theoretical foundation for the geological sequestration of CO_2. David Bish described the miniature transmission X-ray diffractometer that is aboard Curiosity, NASA's exciting new Mars rover. If all works well, the first diffraction patterns of clay minerals in Martian soils will be arriving on Earth later this year.

CMS President David Laird (left) and 2012 Jackson awardee Jeffrey Post

Dr. Jeffrey Post, a research geologist in the Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, USA, was the 2012 recipient of the Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist Award. Dr. Post gave us a fascinating tour of the dark world of manganese oxides in a lecture titled "Unraveling Manganese Oxides–Tales from the Dark Side of Mineralogy." Often fine-grained and black in color, Mn oxides have drawn little attention, yet the more than 30 redox-active Mn oxide phases play a crucial and biologically mediated role in soils and sediments. Dr. Post and his many collaborators have brought together X-ray and neutron diffraction, computer modeling, spectroscopy, and time-resolved synchrotron X-ray diffraction techniques to unravel the structure and reactivity of this family of fascinating minerals.

Dr. Akihiko Yamagishi, a professor in the Department of Chemistry, Toho University, Chiba, Japan, was the recipient of the Marilyn and Sturges W. Bailey Distinguished Member Award. The Bailey Award is the highest honor of The Clay Minerals Society. It is awarded for scientific eminence in clay mineralogy as evidenced by the publication of outstanding original scientific research and by the impact of this research on the clay sciences. In his lecture titled "Stereochemistry and Molecular Recognition on a Clay Surface," Dr. Yamagishi began with an appeal to his colleagues for help in finding a way to deal with Cs137 and other radionuclides released into the soils of Japan in the wake of

CMS President David Laird (left) and 2012 Bailey awardee Akihiko Yamagishi

2013 President Peter Komadel (left) and 2012 President David Laird

the Fukushima nuclear disaster. Dr. Yamagishi then reviewed his well-known work on the synthesis and use of chiral clays and on Langmuir-Blodgett films of clays. Chiral clays can simply be prepared by exchanging chiral transition metal ion complexes of the right size and charge. These chiral clays specifically interact with chiral molecules, thus leading to applications such as chiral separation and chiral catalysis.

It has been an honor for me to serve as CMS president this past year. My job was made easy by the dedicated staff at the CMS office in Chantilly, Virginia. I offer my sincere thanks to Mary Gray, Alex Speer, and Gordon Nord for all their help. I also want to thank members of the CMS Executive Committee for their dedication to clay science and to our Society. Finally, it is my honor to introduce as the new CMS president Dr. Peter Komadel of the Slovak Academy of Sciences, Institute of Inorganic Chemistry, in Bratislava, Slovakia. Dr. Komadel will be writing this column and guiding our Society forward through our 50th anniversary celebration at the University of Illinois in Urbana-Champaign, October 6–10, 2013 (see ad on page 376).

David Laird
President, The Clay Minerals Society
dalaird@iastate.edu

STUDENT AWARDS AT 49th CMS ANNUAL MEETING

Student travel awardees (left to right): Sandra Londono, Asma Sadia, Keith Morrison, Luke Morgan, Michael Bishop, Baptiste Dazas, Kai Su, Laura Zaunbrecher, and Jing Zhang

The following students were recognized for their outstanding presentations at the CMS annual meeting.

First place: Keith Morrison, Arizona State University, USA – "Interaction between antibacterial clays and bacteria: Determining the reactivity and geochemistry of transition elements"

Second place: Tae-Hee Koo, Yonsei University, Korea – "Understanding the illitization step by observing structural and chemical changes in bioreduced nontronite in various redox conditions"

Third place: Hongi Yuan, Indiana University, USA – "Improved automated fitting of X-ray diffraction patterns from interstratified phyllosilicates"

CORRECTION

Graduate student Conni De Masi was highlighted in the June 2012 issue. Her master of science degree will be in geology, not biology.

Geochemical Society

www.geochemsoc.org

FROM THE PRESIDENT

Geochemical Curiosity

Rick Carlson

This article is being written the week after NASA successfully landed the Mars Science Laboratory (MSL) in Gale Crater, with the first pictures now being "phoned home" by the Curiosity rover. Not too many years ago, "curiosity-based science" carried a negative connotation amongst some overseers of science funding. Seeking such basic knowledge was viewed as a frivolous pursuit, akin to a Da Vinci painting or a Beethoven symphony, and clearly not worthy of government support. The only type of science deemed appropriate in this philosophy is that aimed directly at solving issues confronting humanity's continued health and welfare. The problem with such societally relevant science, however, is that it occasionally provides answers that certain groups do not want to hear. The raging debate over global warming and the controversy over the potential for groundwater contamination from various enhanced petroleum recovery methods are just two examples where scientific data have run head on into conflicting economic or political sentiment.

Perhaps more than most sciences, geochemistry can, and should, address both societally relevant concerns and those that advance basic human understanding. The MSL is dominated by a variety of analytical chemistry instruments (well described in *Geochemical News*: www.geochemsoc.org/publications/geochemicalnews/gn145jun11/). Why? Because geochemical methods have become the de facto "gold standard" when seeking to provide answers to critical questions of planetary evolution, in this case whether the Gale Crater sediments were deposited under conditions conducive to life. In my own field, isotopic methods now allow temporal resolution of less than a million years on events occurring during Earth formation beginning 4.568 billion years ago. Related approaches have discovered mineral grains that we can hold in our hand (well, actually, on NanoSIMS sample mounts) and that may be direct condensates of the supernova that caused our Solar System to form. The origin of the Solar System, Earth, and life must be included on any list of fundamental science questions. Geochemical methods are at the forefront of the investigation of all three. On the more applied front, this issue of *Elements* makes it clear that as materials science finds applications that take advantage of the unique properties of the less abundant elements in the periodic table, geochemical methods are going to be the lead approach in finding these rare resources, in evaluating their terrestrial inventories and hence price, and in providing the measurements that will monitor and hopefully help minimize the environmental damage associated with their extraction.

Although it sounds trivial to say so, the Geochemical Society (GS) supports geochemistry, both applied and basic. Support in this case means serving as a proponent for geochemistry, helping to bring together the diverse geochemical community, providing a forum for information exchange, and working to convey the strength and importance of geochemistry in the investigation of a wide range of problems. Our efforts are closely aligned with those of other societies whose interests overlap ours. The GS was a founding member of the large consortium that now supports *Elements*. We alternate with the European Association of Geochemistry (EAG) in the organization of the annual Goldschmidt Conference. We cosponsor *Geochimica et Cosmochimica Acta* with the Meteoritical Society, *G-cubed* with the American Geophysical Union, and the Reviews in Mineralogy and Geochemistry book series with the Mineralogical Society of America. We publish the weekly *Geochemical News*, which we hope the geochemistry community will use as a forum for exchanging breaking news, from meeting announcements to job and funding availability. We are working to build closer ties with other international geochemical organizations, such as the International Association of GeoChemistry, and with our long-time colleagues, the Geochemical Society of Japan, who will host the 2016 Goldschmidt Conference.

The membership of the GS spans from Argentina to Venezuela and about 60 countries alphabetically between these two. As reported in my message in the last issue of *Elements*, the GS leadership has taken steps to ensure that the governance of the Society better reflects its international membership. We have started, with EAG, outreach campaigns to bring geochemistry to people in countries that stand to benefit greatly from knowledge of, and access to, modern geochemical methods. Our new International Participation Program will sponsor membership in the GS for those to whom the minimal membership fee of the GS represents an economic hurdle. The success of this program will be aided greatly if members who can afford to do so offer a voluntary contribution when they renew their membership this year. Geochemistry has much to offer the world, both in practical matters that will improve the standard of living for all and by satisfying the curiosity of humans seeking to understand the universe around them. The Geochemical Society is working in support of both goals.

Rick Carlson (rcarlson@ciw.edu)
GS President

WELCOME GOLDSCHMIDT2012 MEMBERS

Delegates who paid the nonmember registration rate to attend the Goldschmidt 2012 conference in Montreal this past June are provided a two-year (2013 and 2014) membership in the Geochemical Society. As a special thank-you for their membership, they will also receive the October and December 2012 issues of *Elements* and access to the online *Elements* archive. For more information on GS member benefits, visit www.geochemsoc.org/society/benefitsofmembership.htm.

Additionally, the GS Board was very impressed with the initiative of the Student Program Committee in Montreal, and in appreciation of their effort will also be providing two-year memberships to the student committee members: Grant Cox, Stéphanie Desrochers, Nouha Dhahri, Nicole Hurtig, Mina Ibrahim, Julia King, Audrey Limoges, Marc-Antoine Longpré, Anja Moritz, Laurence Nuttin, André Pellerin, Dirk Schumann, and Geneviève Vautour.

ANNUAL MEMBERSHIP DRIVE

If you have not done so already, please take a moment to renew your membership in the Geochemical Society. Member dues for 2013 will increase by US$5, but members joining or renewing by November 30 may do so at the 2012 rate ($30 professional, $10 student, and $15 senior). You may renew online or download a membership form from our website at http://www.geochemsoc.org/join.

Please consider making a donation with your membership renewal. Donations are tax deductible where applicable. Remember to indicate how you would like your donation to be used.

And finally, word of mouth is a valuable part of our membership drive. If you know of a peer or student who isn't a member, please encourage them to join.

GEOCHEMICAL SOCIETY CONTRIBUTIONS

Many members contribute to the Geochemical Society each year by including a donation with their dues. Between January 1, 2011, and April 15, 2012, 299 members made contributions totaling US$9817.13. Of this amount, US$230 were donated to the Organic Geochemistry Division, US$3450 were for the Student Travel Grant Program, and US$6137.13 went to the General Support Fund. **Thank you for your contributions!**

Everything we do at the Geochemical Society is made possible through the generosity of our members, volunteers, and contributors. If you would like to contribute to the Geochemical Society, please visit our website at www.geochemsoc.org or contact the business office.

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GS AT GSA-CHARLOTTE

Isabel Montanez, 2012 F. Earl Ingerson Lecturer

Dr. Isabel Montanez (University of California–Davis) will present the **2012 F. Earl Ingerson Lecture**. Her lecture, "Modern soil system constraints on reconstructing deep-time atmospheric CO_2: A new view of Phanerozoic PCO_2," will be presented on Tuesday, 6 November 2012 at 9:50 am in Room 202AB of the Charlotte Convention Center. The Geochemical Society will again be sponsoring a ticketed reception with MSA and the GSA–MGPV Division, as well as welcoming attendees to our exhibit (Booth 806).

Geochemical Society Business Office

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Mineralogical Society of America

PRESIDENT'S LETTER

Final Thoughts

This is my sixth, and last, President's Letter in *Elements*. If you look back at the titles of my previous five offerings, "MSA at a Crossroads," "Mineralogy, an Inch Deep and a Mile Wide?", "MSA and AGU: A Very Important New Partnership Begins," "Mineralogy to the Fore," and "MSA Marches On, Quickly," one can see that I have been writing about the challenges that MSA faces and the very important new opportunities that MSA has at its fingertips right now, particularly with new developments related to AGU and *American Mineralogist*. A third theme that I have also written about is the foundational status that mineralogy will always have in the Earth, planetary, and space sciences, and the opportunities this gives to us; I strongly believe that this simple fact underlies the health of our science in the long term and is arguably the most important subject for our discussions not only within the MSA membership but also with all the mineralogical societies around the world that represent our science so well.

As my final comment in the President's Letter, allow me to attempt to put together these three themes in a way that will result in a grand challenge. To do so, I need to start with a natural tendency among all of us: humans are deeply prone, and often for good reason, to put up dividing lines. We often categorize, organize, separate, classify, sort, and group. We all know this and experience it every day, whether in politics, religion, business, or any other human endeavor—including academics. Considering the latter, here at Virginia Tech, every science major will happily (or maybe not so happily) go through the usual "intro courses" where science is neatly separated—a.k.a. Introduction to Chemistry, Introduction to Physics, Introduction to Biology, and so on—usually within the first two years of their undergraduate tenure. However, these days, here at Virginia Tech and at some other schools, one can bypass the intro courses and take, for two years, what is often called an "integrated science curriculum." The historic barriers that we find so convenient have been removed in this case, and students are immersed in problem-driven science. In the process, they learn the fundamentals of all the sciences at once, as needed, to understand observed phenomena of all sorts. After all, in the real world, there are no dividing lines within the behavior and processes of nature. Thinking of this from the opposite direction, all aspects of nature operate not based on the principles of physics and then the principles of chemistry, but on both, and always combined. Closer to home, in the critical zone of Earth, no process is truly purely geo or bio, but geo-bio-phys-chem, all mixed into one. From this vantage point, the dividing lines need to go away, or we are fooling ourselves.

Now, take this same mindset and go to an AGU or GSA meeting or a Goldschmidt Conference and randomly walk into a session without even looking at the session schedule on the easel just outside the door. Listen to a few talks, then continue your random walk through the meeting venue and keep doing the same thing. The point is, it would be difficult to not find some aspect of the science of mineralogy, either directly or indirectly, in every talk you listen to. How many of the subdisciplines of the Earth and space sciences can say that? A few can; most cannot. The significance for us? In the natural world the science of mineralogy is everywhere, and it is relevant in some way or another to just about all things. The processes in which the science of mineralogy has critical relevance are not ubiquitous but are truly common. Also, mineralogists, especially these days, are also geochemists, or geophysicists, or petrologists, or atmospheric scientists, or contaminant hydrologists, or biologists, and so on, because they don't see the boundaries—a very good thing. The importance of and need for our science in the future is thus assured. Sure, the methods and emphasis and bounds of mineralogy will change. They always have and they always will. But that in no way should be mistaken for a reduction in mineralogy's relevance.

We should expect that the only constant thing is change. Change in the way in which mineralogy is taught; change in the courses where mineralogy is taught; change in the way mineralogy is done; and change in the way mineralogy is applied to understanding this planet, other planets, all the other types of bodies in space, and space itself.

How many sessions at AGU, GSA, Goldschmidt, and other international meetings can MSA cosponsor? We already cosponsor a remarkable number, and we will do more. And how much of this exciting science, whatever "field" it is in, might appear on the pages of *American Mineralogist*? Mineralogy is relevant not just to itself, but to everything outside of it. *AmMin* is now on a path to help promote that approach. And as this happens, journals like *Science*, instead of just going to other fine geoscience journals, such as *EPSL* and *JGR*, for their "Editor's Choice" column, will also be able to come to *American Mineralogist*.

Our grand challenge is to deconstruct artificial barriers, and at the same time actively show, always, how mineralogy is a science that is critically relevant to, and inseparable from, all aspects of the Earth and planetary sciences.

I have been deeply humbled to be president of this historic society, whose outlook is extraordinary, especially when seen from this angle. What a great pleasure it has been. My warmest and very best regards to all.

Michael F. Hochella Jr. (hochella@vt.edu)
Virginia Tech
President, Mineralogical Society of America

NOTES FROM CHANTILLY

• **Results of the 2012 MSA election:** The 2013 president is John M. Hughes; the vice president is David J. Vaughan. Andrea Koziol remains in office as secretary, and Howard W. Day was elected treasurer. The new councilors are Isabelle Daniel and Kirsten P. Nicolaysen. They will join continuing councilors Pamela C. Burnley, Guy L. Hovis, Christine M. Clark, and Kimberly T. Tait.

• MSA members were contacted electronically in September to renew their membership for 2013. Members who renew and pay online before 31 October 2012 will receive a $5 dues discount; the discount reflects cost savings to MSA from members who renew early online. There will be several electronic reminders before a paper copy is sent during November to those who do not renew online by the end of October.

• Honorary and life members and fellows are sent renewal notices. They need not pay dues, but are sent notices as the best way to prompt an update of membership information, particularly mail and e-mail addresses.

• Senior members and senior fellows also need not pay dues, but they do need to pay if they wish to subscribe to *American Mineralogist* or other journals.

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

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

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

IN MEMORIAM

Harold R. Steacy – Senior Fellow – 1967

2012–2013 MSA DISTINGUISHED LECTURERS

The Mineralogical Society of America is pleased to announce its Distinguished Lecturers and their lecture titles for 2012–2013:

Julia A. Baldwin, Department of Geosciences, University of Montana, Missoula, MT, USA: (1) "Metamorphic phase diagrams and geochronology: You can't have one without the other"; (2) "When the continental crust gets really hot: The petrology of ultrahigh-temperature metamorphism"

Matthew J. Kohn, Department of Geosciences, Boise State University, Boise, ID, USA: (1) "How to become a fossil: A geochemist's guide"; (2) "Making the Himalaya: Oozing, squashing or sliding?"

Hans-Peter Schertl, Institut für Geologie, Mineralogie und Geophysik, Ruhr Universität Bochum, Bochum, Germany: (1) "A time machine for rocks: Cathodoluminescence microscopy of metamorphic and magmatic minerals"; (2) "How do mountains form? The critical evidence from small-scale petrological observation"

The schedule of the Lecturers' tours will be posted on the MSA website (www.minsocam.org). Check to see if the lectures will be at a location near you. MSA expresses its appreciation to these individuals for undertaking such a service to our science.

MSA AWARDS

Harry W. Green II

At this year's annual meeting in Charlotte, North Carolina, USA, Harry W. Green II will receive the 2012 Roebling Medal, given for a lifetime of outstanding original research in mineralogy. Professor Green is Distinguished Professor of the Graduate Division in the Department of Earth Sciences, University of California–Riverside, California, USA. In his research, he uses microstructures to understand the effect of stress on mineral reactions and phase transformations, and the consequences of those interactions for flow and failure in Earth's mantle and their relationship to plate tectonics. He has devoted particular attention since 1989 to the mechanics of earthquakes and other processes operating within subducting lithosphere and at the interface of that lithosphere with the mantle wedge above; in this environment he and his colleagues have documented ultrahigh-pressure metamorphism occurring at depths approaching 400 km, followed by exhumation to the surface.

Karim Benzerara

The Mineralogical Society of America Award is given for outstanding contributions by a scientist beginning his or her career. Dr. Karim Benzerara is the 2011 MSA Award recipient. Dr. Benzerara is a CNRS director of research, Institute of Mineralogy and Physics of Condensed Matter (IMPMC), Paris, France. Dr. Benzerara's main research interest has been the study of interactions between microorganisms and minerals, i.e. how microbes form and/or alter minerals. The implications are as diverse as the search for traces of life in ancient rocks, the design of bioremediation strategies, and the study of processes leading to pathological calcifications in the human body. In particular, he has used microscopy and spectroscopy techniques extensively, including electron- and synchrotron-based X-ray microscopy (STXM), which provides information both on organic carbon and minerals down to the nanometer scale. Recently, his research has centered on the formation of amorphous carbonate phases within cyanobacteria cells.

MinPubs.org

Out-of-print Reviews volumes are back! You can now purchase the entire volume of your favorite, previously out-of-print Reviews volume in electronic or print form. These are: v1, *Sulfide Mineralogy*; v2, *Feldspar Mineralogy*; v3, *Oxide Minerals*; v4, *Mineralogy and Geology of Natural Zeolites*; v5, *Orthosilicates*; v6, *Marine Minerals*; v7, *Pyroxenes*; v9A, *Amphiboles and Other Hydrous Pyriboles: Mineralogy*; v12, *Fluid inclusions*; and v17, *Thermodynamic Modeling of Geologic Materials: Minerals, Fluids, and Melts*. An added advantage: you can word search the electronic versions.

You can also purchase single chapters from these and all Reviews volumes [v1 (1974) to present], and you can use chapters from any and all Reviews volumes for course packs and add to them articles from the *American Mineralogist* [v85 (2000) to present] and *Elements* [v1 (2005) to present].

For more description and ordering instructions, visit www.minpubs.org or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110, USA; phone: +1 (703) 652-9950; fax: +1 (703) 652-9951; e-mail: business@minsocam.org.

International Association of GeoChemistry

BIOGEOMON 2012

The lovely Point Lookout Resort in Northport, Maine, USA, was the ideal setting for the 7th International Symposium on Ecosystem Behavior (BIOGEOMON 2012), held July 15–20, 2012. This symposium was the proud continuation of the tradition of the BIOGEOMON series of meetings, which was started by the Czech Geological Survey (Prague) in 1987 as GEOMON. The meeting was renamed BIOGEOMON in 1992 to emphasize the biogeochemical scope and research that was represented. There have been well attended BIOGEOMON symposia in both North America and Europe since that time, and most recently the IAGC has formed a new Working Group on Biogeochemistry, with the BIOGEOMON symposium as its focus. Supporting the Working Group on Biogeochemistry is an exciting new direction for IAGC.

BIOGEOMON 2012 hosted over 200 scientists from 18 countries. The week included 20 invited speakers, more than 120 contributed talks, and 90 poster presentations. The six conference plenaries emphasized the use of time-series data, either empirical, experimental, or modeled, to define the trajectory of our past environments and project ecosystem behavior into the future. Conference research themes included: long-term integrated monitoring and modeling; biosphere–atmosphere interactions and exchanges: gases and aerosols; the role of extreme events in ecosystem biogeochemistry; linkages among biogeochemical cycles; critical unknowns in nitrogen dynamics and reactive N; biogeochemistry of peat lands; carbon cycling in well-drained forested soils; carbon cycling in poorly drained soils; experimental manipulations of ecosystems; trace element biogeochemistry and ecosystem impact; applications of isotopes and tracers; bioenergy-production impacts in forested systems; the role of biogeochemistry in ecosystem restoration and rehabilitation; and ecosystem management and ecosystem services.

Other highlights of the week included a copious lobster banquet, where participants were serenaded by Noel Paul Stookey (of Peter,

Participants on a field trip to Acadia National Park, with conference organizer Steve Norton (front, center, in blue shirt)

Senator George J. Mitchell delivering a moving closing keynote address

Paul and Mary fame), and a midweek day of field trips in the stunning Penobscot Bay region. In addition, attendees were honored to hear an inspiring closing keynote address by Senator George J. Mitchell, the former United States Senate majority leader from Maine who was instrumental in the reauthorization of the U.S. Clean Air Act in 1990 and played a leading role in peace negotiations in both Northern Ireland and the Middle East. Overall the week provided an excellent opportunity to be challenged by presentations on cutting-edge ecosystem science, to connect and reconnect with friends and colleagues in this highly international community, and to enjoy the beauty and hospitality of coastal Maine. This highly successful event was skillfully organized by an energetic team led by Steven Norton, Ivan Fernandez, and Tiffany Wilson from the University of Maine. Plans are already underway to hold the next BIOGEOMON in Bayreuth, Germany.

GSA ANNUAL MEETING

The Geological Society of America annual meeting will be held on 4–7 November in Charlotte, North Carolina. Please stop by the IAGC booth (#804) in the exhibit hall, or better yet, stay for a couple of hours to help recruit new members. The IAGC is also cosponsoring 6 sessions this year:

- **T1. Sources, Transport, Fate, and Toxicology of Trace Elements and Organics in the Environment** (Cochairs: David T. Long, W. B. Lyons, LeeAnn Munk)
- **T7. Progress in Forensic Geochemistry** (Cochairs: Russell Harmon, Jose R. Almirall)
- **T8. Hydrochemistry and Biogeochemistry of Tropical Mountainous Rivers and Estuaries** (Cochairs: Steven Goldsmith, Russell Harmon, Ryan Moyer)
- **T9. Geochemistry of Urban Environments** (Cochairs: W. B. Lyons, David T. Long, Russell Harmon)
- **T67. Innovative Classroom Approaches to Teaching Biogeochemistry** (Cochairs: Steven Goldsmith, Sarah K. Fortner, Stephen Levas)
- **T129. Advances in Spectroscopy for Geological and Mineralogical Analysis** (Cochairs: Thomas Tague, Sheila Seaman)

PhD STUDENT RESEARCH GRANTS

The IAGC PhD Student Research Grants help cover the cost of the analytical needs of PhD students in geochemistry. Up to three PhD Student Research Grants of up to US$3000 may be awarded annually.

Applications for Student Research Grants for 2013 will be accepted through 1 December 2012. Funds will be distributed to winning applicants before 1 May 2013. For application instructions and to download the necessary forms, please visit www.iagc-society.org/phd_grants.html.

CALL FOR 2013 AWARDS

Now is the time for the 2013 IAGC award nominations! Awards to be bestowed in 2013 are the Ebelman Award, the Distinguished Service Award, the IAGC Fellow award, and the IAGC Certificate of Recognition. For a summary of the awards and instructions on how to submit your nomination, visit www.iagc-society.org/awards.html. Deadline for submission is December 1.

BIOGEOMON 2012 attendees

Sociedad Española de Mineralogía

SEM-SEA 2012:
JOINT MEETING OF THE SPANISH MINERALOGICAL SOCIETY AND THE SPANISH CLAY SOCIETY

The joint meeting of the Spanish Mineralogical Society and the Spanish Clay Society (SEM-SEA 2012) was held in Bilbao on 27–30 June 2012. The event was organized by the Department of Mineralogy and Petrology of the University of the Basque Country UPV/EHU. The program can be downloaded from the conference website: congresomineralogia.es.

The opening ceremony was attended by the presidents of the two societies, Mercedes Suárez (SEA) and Carlos Ayora (SEM), and by representatives of the organizing committee (Javier Arostegi and Jose Miguel Herrero), the University of the Basque Country (Miguel Angel Gutierrez-Ortiz, vice chancellor, and Esther Dominguez, dean of the Faculty of Science and Technology), and the Basque Government (Begoña Ochoa).

These joint meetings have become the most important Spanish forum for discussion and debate among researchers and professionals working in mineralogy, petrology, geochemistry, mineral deposits and clays. More than 150 participants attended the meeting. A program of grants and awards encouraged the participation of young researchers.

A workshop entitled "Archaeometry and Cultural Heritage: The Contribution of Mineralogy," organized by the Spanish Mineralogical Society, was included in the meeting program. The workshop program featured 7 lectures (Dr. Dominguez Bella, Cadiz; Dr. Prudêncio, Lisbon; Dr. Maggetti, Fribourg; Dr. Artioli, Padova; Mr. Hradil, Prague; Dr. Vendrell, Barcelona; and Dr. Rodriguez-Navarro, Granada) and a discussion session. The papers have been published in volume 9 of the Seminars of the Spanish Society of Mineralogy collection and can be downloaded from the SEM server.

The SEM-SEA 2012 program included four plenary lectures: "Mineralogy in the study of historical buildings" (Dr. Vendrell), "Marine minerals as tracers of detrital provenance and transport agents" (Dr. Fagel), "Using clay to bioremediate oil spills" (Dr. Warr), and "Structure and lithology of the oceanic crust: What do we know today?" (Dr. Juteau). A total of 111 scientific contributions were presented at the conference (50 oral presentations and 61 posters), involving 385 authors. These contributions were on the following themes: "Archaeometry and Heritage Conservation" (24), "Teaching and Museums" (2), "Applied Mineralogy" (3), "Clay Minerals" (23), "Environmental Geochemistry" (13), "Mineral Synthesis and Crystal Growth" (8),

"Instrumental Techniques" (4), "Petrology and Geochemistry" (3), and "Mineral deposits" (31). The plenary lectures and communications have been published in volume 16 of *Macla* magazine, which also includes geological information about two scheduled field trips: "Cretaceous Submarine Volcanism of the Basque-Cantabrian Basin" and "Mineralogical Heritage of El Valle de Carranza."

Rubén Martos-Villa (left) receiving his award from Carlos Ayora (SEM president)

Chiara Cappelli receiving her award from Mercedes Suárez (SEA president)

Four awards for young researchers were given out for the best communications. The winners were:

- Rubén MARTOS-VILLA: "Molecular simulations of methane hydrate crystal structure and spectroscopic properties"

- Anna ARIZZI: "La influencia de la Interfase Árido-Matriz (ITZ) en las propiedades de Morteros de Cal"

- Ana C. S. ALCÂNTARA: "Bionanocomposites based on the megamolecular polysaccharide sacran and clay minerals"

- Chiara CAPPELLI: "Monitorización de la alteración de biotita mediante microscopio confocal de contraste de fase de interferencia diferencial"

Ana Alcântara receiving her award from Mercedes Suárez (SEA president)
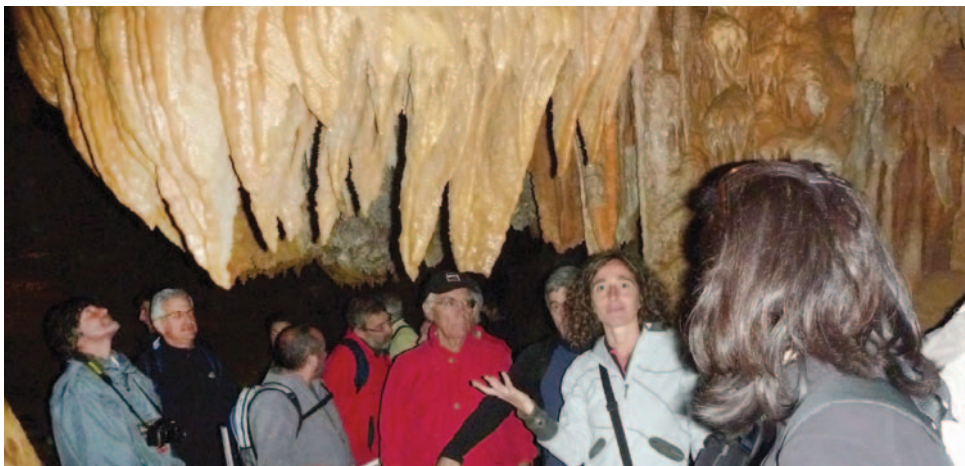
Participants in the SEM-SEA 2012 field trip to El Valle de Carranza

Mineralogical Association of Canada

PUBLICATION NEWS

2012 Thematic Issues of The Canadian Mineralogist

Two exceptional individuals, Emil Makovicky and Petr Černý, will be given a tribute in volume 50 of *The Canadian Mineralogist*. They have in common their decision to leave their country of origin, Czechoslovakia, in the late sixties, and to come to Canada to pursue their ambitions in the Earth sciences. Both Emil and Petr have gone on to be leaders in their respective fields. In these days of virtual thematic issues, I planned real *festschrifts* that could be bound and presented to the honorees and their families at an appropriate momentous occasion.
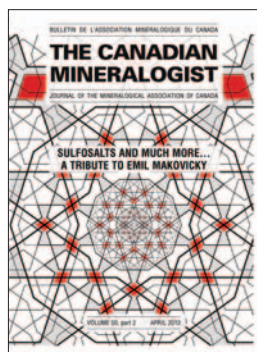
Emil Makovicky chose McGill University in Montreal to gain proficiency in the area of structural crystallography. He had begun his academic career at Comenius University in Bratislava fifty years ago. For his PhD thesis (1970), he worked on the very challenging structure of the sulfosalt *cylindrite,* under the guidance of Prof. Alfred Frueh Jr. Dr. Frueh was then at the forefront of crystallographic studies of complex sulfides and silicates showing non-Bragg reflections. By today's standards, gathering data with the film techniques then available was very laborious. Progress was slow, but this allowed Emil to acquire a solid grounding with which to tackle future systematic investigations of the sulfosalts. He went on to define homologous series important in the common sulfosalts, to propose a modular classification of sulfosalts, and to focus on incommensurate misfit-type structures. He teamed up with Milota, his wife, to establish the solubility of platinum-group elements in common sulfides. He spent his academic career at the University of Copenhagen as Professor of Crystallography and Mineralogy, and chose to publish many of his authoritative articles in *The Canadian Mineralogist*. In this way, Emil contributed significantly to the strength of this journal in he mineralogy of ores. Thus it was natural that his colleagues Tonci Balić-Žunić and Yves Moëlo came to me with a proposal for a thematic issue as a tribute to Emil on the occasion of his "retirement." The illustration chosen by Emil for the alluring cover of the April 2012 issue is a reflection of another aspect of Emil's fascination with symmetry operations, the ones displayed in ancient Islamic art. The example chosen was traced from a mosque in Maragha, Iran, and dates back to the late tenth century.
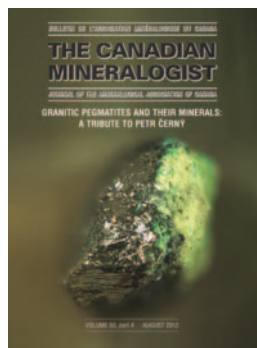
Petr Černý had a PhD from the Geological Institute of the Czech Academy of Science in Prague when he came to the University of Manitoba as a postdoctoral fellow. For his thesis (1966), he studied two granitic pegmatites from Věžná, in what is now the Czech Republic. Arriving in Winnipeg in 1968, Petr wasted no time in getting familiar with the enormous Tanco granitic pegmatite, then, as now, exploited for tantalum, cesium, and lithium. To date, Černý has published 46 articles, chapters, and reports dealing specifically with the Tanco mine, and many others in which the Tanco pegmatite is assessed in relation to other rare-element deposits around the world. Petr's impact lies in the broad area of the mineralogy, petrology, and geochemistry of granitic pegmatites. Many of his contributions have appeared in *The Canadian Mineralogist* and have contributed to the strength of the journal in this field. His work on Tanco culminated with a definitive statement of the bulk composition of the Tanco pegmatite, by now clearly acknowledged as the best-studied zoned pegmatite in the world. He organized a memorable short course on granitic pegmatites for the MAC in 1978. In 1990, he wrote about the anatomy of a pegmatite and about the influence of tectonic forces on the processes at work. In view of his strong focus and prolific output on matters pegmatitic, it was fitting that the organizers of the PEG2011 conference, Miguel Á. Galliski and María Florencia Márquez-Zavalía, dedicated the meeting to Petr. The response to a call for contributions to a thematic issue of *The Canadian Mineralogist* designed as a tribute to Petr was immediate and overwhelming, to the extent that I proposed to split the tribute into two separate issues, with Miguel Galliski, David London, and Milan Novák as guest editors. The August issue (volume 50, part 4) will be a 375-page *festschrift* covering mineralogical, petrological, and geochemical themes. The second installment will be our December 2012 issue. We anticipate presenting both issues to Petr in May 2013, at the MAC luncheon during the GAC-MAC meeting in Winnipeg. A special session in honor of Petr Černý and an excursion to the famous Tanco pegmatite will be feature attractions.

Robert F. Martin, Editor
The Canadian Mineralogist

Quantitative Mineralogy and Microanalysis of Sediments and Sedimentary Rocks
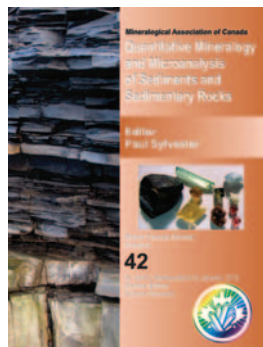
A two-day short course entitled Quantitative Mineralogy and Microanalysis of Sediments and Sedimentary Rocks was held on May 25–26, 2012, immediately prior to the Geological Association of Canada–Mineralogical Association of Canada joint annual meeting in St. John's, Newfoundland. The course was presented to some two dozen attendees by an accomplished group of international experts in the fields of mineralogy, analytical geochemistry, and exploration geology. It included lectures, discussion, and a tour of the analytical geochemistry labs for microanalysis in the Bruneau Centre for Research and Innovation at Memorial University of Newfoundland. Funding for the course was received from the MAC, Memorial University of Newfoundland, Apatite to Zircon Inc., and Isomass Scientific Inc., and Bruker Ltd.

The course introduced participants to a variety of analytical instrumentation and methods for understanding the mineralogy of sediments and sedimentary rocks. Instructors demonstrated how these techniques are being used to address a variety of topics in sedimentary geology, such as quantitative mapping of clastic and diagenetic minerals at various scales; determining the chemistry of organic matter, nanoporosity, nanopermeability, 3D grain size, and shape distribution in coarse- and fine-grained sedimentary rocks; documenting changes in paleofluid composition during growth of clays and carbonate cements; and characterizing reactive and bioavailable metals in minerals of contaminated environmental media. A particular application of many of the techniques presented was mineral provenance for paleodrainage models, stratigraphic correlation, and petroleum and mineral exploration. These studies rely on quantitative measurements of the abundances, morphology, and chemical and isotopic compositions of detrital grains in sedimentary systems, particularly refractory "heavy" minerals. Uranium–lead geochronology of zircon and apatite, the hafnium isotope composition of zircon, the lead isotope composition of feldspar, and fission track dating of apatite were explained in some detail.

An attractive, 299-page short course volume summarizing all the technical information covered in the course is available from the MAC at www.mineralogicalassociation.ca/index.php?p=25#SC42.

Paul Sylvester
Memorial University of Newfoundland, Canada

CALL FOR NOMINATIONS 2013 MAC AWARDS

Peacock Medal

The Peacock 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.

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' (now Peacock) Medal.

Pinch Medal

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

Please submit your nominations by December 31, 2012 (November 30 for the Pinch Medal). Check our website, **www.mineralogicalas-sociation.ca**, for additional details.

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 on their travel or research for possible publication by MAC.

For more information, see www.mineralogicalassociation.ca.

Deadline to apply: **January 15, 2013**

Uranium: Cradle to Grave

Mineralogical Association of Canada Short Course

Winnipeg, Manitoba, Canada

May 20–21, 2013

ORGANIZERS
Peter C. Burns and **Ginger E. Sigmon**
University of Notre Dame

The focus of this short course, which will immediately precede the GAC-MAC meeting, will be the many aspects of uranium, an element that changed the course of the world like no other. Content will span the mineralogy, geochemistry, and ore deposits of uranium, and will include nuclear waste challenges and solutions, weapons proliferation, and nuclear forensics for attribution and nuclear security.
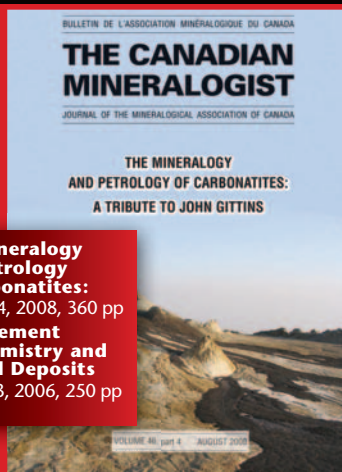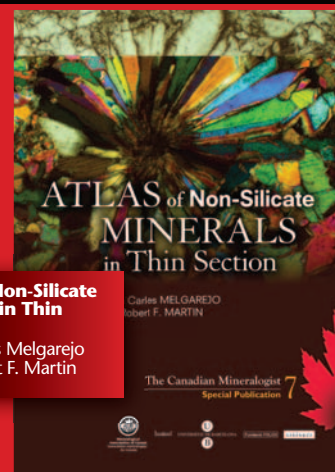
LAYERED MINERAL STRUCTURES AND THEIR APPLICATION IN ADVANCED TECHNOLOGIES*

The current information about the existence of clay minerals on extra-terrestrial bodies leads many to conclude that layered mineral structures facilitated the advent of self-replicating organic compounds on Earth (i.e. life as we know it, here or elsewhere). Coupling this notion with Akihiko Yamagishi's pioneering work on stereoselective molecular recognition of organics on clay surfaces further supports the long-standing hypothesis of mineral natural selection in biochemistry (see Cairns-Smith, *Elements*, volume 1, 2005) and the fact that we have much to learn from nature's world of clay nanocomposites. Also, a quick literature search using "clay nanocomposite" reveals hundreds of citations in seemingly disparate engineering, medicine, geoscience, and materials science journals. All of this collectively suggests that layered mineral structures harbor enormous potential for applications in advanced technologies. The recent publication on this very subject by the European Mineralogical Union, Notes in Mineralogy, volume 11 (EMU 11), edited by M. F. Brigatti and A. Mottana, arrives in a timely fashion to give us the latest insights. The importance of this book is derived from the coverage of the fundamental, yet complex, layered structures that are possible from combining one or more layer types. Such combinations help make new-aged technological materials or enable ways to interpret old-aged geologic materials.

I first digress by noting a slight misunderstanding hampering the explosion of experimental work driven by hopes of discovering poly-functional layered mineral structures. The incentive for finding new materials is to expand thermal, rheological, time-release, and redox inhibitory/promoting material boundaries for biomedical, engineering, and environmental enterprises. The problem I see is that researchers outside the field of mineralogy view natural layered mineral structures as some sort of reagent-grade compound, like those purchased from a chemical supply store. Natural clays have novel properties, but they are not all alike and are quite variable. A prime example is seen in the kaolin-group minerals, which are used in ceramics, paper coatings, pharmaceuticals, inks, and plastics. Kaolin occurs with a wide range of crystallite order/disorder, crystal sizes and aspect ratios, and degrees of isomorphous iron substitution. Committing a career of research to creating new materials without prior knowledge of the mineral structures will not only frustrate those who endeavor but also delay the potential benefits to society.

EMU 11 provides an ideal starting resource for those wanting to learn more about natural layered materials. Chapters 1, 2, 3, and 7, with first authors Brigatti, Guggenheim, Li, and Bergaya, respectively, give over-views of layered silicates, order/disorder schemes, titanosilicates, and intercalation, which collectively serve as a condensed resource for those needing a refresher in systematic clay mineralogy. Lanson's chapter eloquently nurtures the notion of using X-ray diffraction (XRD) to characterize anisotropic lamellar compounds (including layered double hydroxides) and the need to experimentally do this before, during, and after testing. Following up XRD studies with calculated XRD models assures the confidence needed to extract thermodynamic data, formulate reaction mechanisms, and anticipate kinetic effects needed to give new clay composites functionality. Speaking of models, Sainz-Díaz's delightfully readable chapter on computational mineralogy helps to see how using both classical and quantum mechanical methods specific to layered structures can be applied to interpreting spectroscopic properties, reactivity, and surface interactions with organic and water molecules. This *in silico* work is supported by discussions of published experimental vibrational and nuclear spectroscopic studies, which keep this book from being an isolated theoretical exercise.

The remaining chapters tackle more uncertain questions, such as "exactly how does water interact with layer charges of common smectite group minerals?" This question has long been of interest to industry. Christidis emphasizes a new, more insightful approach that promotes treating smectitic samples using a variety of saturations, like alkylammonium and potassium, to assess key properties of thixotrophy (i.e. the ability to form a gel upon standing and become fluid under stress—an essential process employed every time you brush your teeth). Clay minerals and double hydroxides are not the only layered structures in nature worthy of exploitation. Mottana and Aldega's chapter broadens the theatrical stage of layered materials to include graphene and addresses the pesky problem of how to define quasi-ordered nanosized intercalated structures. Traditional bulk methods, such as bulk powder XRD, often make hamburger out of the materials we are trying to define by averaging both bulk and surface properties. The closer we want to look at an intercalated structure, the less bulk XRD techniques can tell us (perhaps a new variant of Heisenberg to haunt us). The good news is that methods such as grazing incidence XRD and X-ray absorption spectroscopies are reviewed with practical examples to guide us in studying configurations.

The interaction of organic molecules with layered structures and surface properties of clay minerals represents the current frontier for advancement of new materials in technology. The ability to control crystal surfaces for the binding of molecules such as DNA is fundamental for biosensing, environmental science, and catalysis. Valdré and coauthors explore recent advances in surface imaging techniques with atomic force microscopy (AFM) and review some practical advances in understanding decontamination of biological warfare agents, biofilm formation, and prebiotic chemistry. They clearly demonstrate the nucleotide selectivity, using powerful AFM images of DNA ordering with linear confirmations on brucite-like edges of a chlorite sheet, while by comparison the siloxane region topography indicates a very different agglomeration of the same DNA. Being able to control adsorption of nucleic acid bases at different pHs and solution compositions on clay minerals raises the possibility of a genetic code based on purines and a mechanism for protecting biomolecules from degradation.

Next to zeolites, clay minerals and their cousin layered structures (e.g. graphene) provide maximal amount and diversity of surface reactivity sites, coming from outer surfaces, edge surfaces, and interlayer surfaces. Schnoonheydt and Johnston bring closure to EMU 11 by linking water–ion interactions with clay surfaces (most examples being smectites) and the amazing chiral discrimination that occurs when the organic complexes interact on these surfaces. Once these complex interactions are fully understood, the advances in electrochemistry, photochemistry, and catalysis should open the path for novel ways to selectively react enantiomeric (right- and left-handed) compounds. Some day we may realize a device, based on a clay-dye with extreme thermal, mechanical, and chemical stability, small in size, low in energy demand, and high in light-scattering efficiency, that will enable us to biosense medical problems well in advance of what we can do today.

The bottom line is that EMU 11 is a very nice review volume for state-of-the-art layered mineral characterization methods. The references cited within it and peer-reviewed journals give the ultimate resource. The lesson learned from this book is "get to know your layered mineral structure well," particularly if it is a natural material, and you will be well suited to discover the next nanocomposite to advance technology.

Paul Schroeder, University of Georgia

FULL STOP FOR MOTHER EARTH

As discussed elsewhere in this issue, many of the largest accumulations of rare earth elements (REEs) are associated with rift-related nepheline syenite and alkali granite plutons. The most extreme evolved magmas produced by our planet form the agpaitic suite, named after the headland of Agpat on Tunugdliarfik, a fjord that cuts through the extraordinary Ilímaussaq intrusion in the Mesoproterozoic Gardar rift province in South Greenland (FIG. 1). Agpaite, by definition, has a molar (Na + K) Al greater than 1.2; in other words, it contains much more Na and K than can be accommodated in feldspars and feldspathoids, and it also contains Na–Ti–Zr silicates.

FIGURE 1 Agpat headland, home to the agpaites

The modern view is that the Gardar alkaline rocks are the products of extreme fractionation of an alkali basaltic parent magma originating from asthenospheric mantle modified by alkaline, rare-element-enriched metasomatic fluids. The magmas ponded and fractionated, perhaps at multiple levels, on their ascent, and also during their final emplacement, since many rocks are clearly cumulates. In the final evolved juices, we have a blurring of silicate magma and silicate-rich aqueous fluids that precipitate a bewildering array of exotic minerals and concentrate rare elements beyond the wildest fantasies of geochemists. Many components, many phases, and a composition somewhere near the multiphase invariant point that represents the end of Earth evolution through igneous fractionation – full stop for Mother Earth!

Three localities in the Gardar rift (the Narsarsuk pegmatite, the Ivigtut cryolite body [*Elements* 5: 71, 2009] and the Ilímaussaq intrusion) have provided type samples for a total of 60 mineral species (that's about 1% of all known species), of which 17 have not been found elsewhere. Ilímaussaq is one of the most complicated and, it is turning out, valuable intrusions in the world. About 220 mineral species have been found there, so far. Below I give the formulae of a few them, just to show how exotic and complex they are.

FIGURE 2 shows a beautiful rock called naujaite, from the fjord Kangerdluarssuk, in the southern part of the 18 x 8 km Ilímaussaq complex. It is extremely coarse grained, and seen out of context you would expect it to have come from a pegmatite. In Ilímaussaq such rocks form whole mountainsides, and the naujaites make up more than half of the Ilímaussaq outcrop. The naujaite from Kangerdluarssuk is the type locality for three mineral species, all visible in the photograph:

FIGURE 2 Naujaite, Kangerdluarssuk fjord, Ilímaussaq intrusion. The rock is simultaneously the type locality of eudialyte (pink), arfvedsonite (black) and sodalite (grey prisms). The white areas are microcline and nepheline.

- eudialyte, $Na_{15}Ca_6Fe_3Zr_3Si(Si_{25}O_{73})(O,OH,H_2O)_3(Cl,OH)_2$ (strong pink)
- arfvedsonite, an alkali amphibole, $Na_3(Fe^{2+},Mg)_4Fe^{3+}Si_8O_{22}(OH)_2$ (black)
- sodalite, $Na_4(Si_3Al_3)O_{12}Cl$ (light grey prisms)

The sodalite is a variety known as hackmanite. It is purple on a fresh surface but its 1.13-billion-year-old colour fades to greenish grey in a few minutes on exposure to light. I used to demonstrate this to students, probably the only bit of the course they remembered!

Kangerdluarssuk is the type locality for a further 8 mineral species, all of which have subsequently been found elsewhere on Earth. These minerals, occurring mainly in late pegmatites and veins, are:

- aenigmatite, $Na_2(Fe^{2+})_5TiSi_6O_{20}$
- polylithionite, $KLi_2AlSi_4O_{10}(F,OH)_2$
- potassicarfvedsonite, $KNa_2Fe^{2+}_4Fe^{3+}Si_8O_{22}(OH)_2$
- rinkite, $Na(Na,Ca)_2(Ca,Ce)_4(Ti,Nb)(Si_2O_7)(O,F)_4$
- skinnerite, Cu_3SbS_3
- steenstrupine-(Ce), $Na_{14}Ce_6Mn^{2+}Mn^{3+}Fe^{3+}_2Zr(PO_4)_7$ $(Si_6O_{18})_2(OH)_2\cdot3H_2O$
- tundrite-(Nd), $Na_2Nd_2TiO_2SiO_4(CO_3)_2$
- ussingite, $Na_2AlSi_3O_8(OH)$

Not only do these formulae attest to the extraordinarily high concentrations of elements that normally occur in parts per million, they also illustrate the extremely alkaline character of the assemblage. Ussingite is essentially albite plus NaOH.

The type minerals in FIGURE 2 were collected on a remarkable journey started in 1806 by Karl Ludwig Giesecke, a German actor (his original name was Johann Georg Metzler). He had fallen on hard times in Vienna, left in a hurry without paying his bills and settled in Copenhagen, where he moved into mineral dealing. He arrived in Greenland intending to stay for two years, exploring and collecting minerals, but had to stay for seven because of the Napoleonic wars. His samples were sent in a Danish ship to Copenhagen in 1806, but the vessel was taken as a 'prize' by the British Royal Navy and the minerals were auctioned in Edinburgh in 1808. Giesecke arrived back in Europe in 1813, causing a stir by turning up in the English port of Hull clad in Inuit furs and feathers, his European clothes having long-since worn out. Every cloud, however, has a silver lining. His samples had been bought as a job-lot by a wealthy Scot, Thomas Allan, who recognised

their importance and invited Giesecke to his home in Edinburgh. Allan was impressed with his mineralogical skills and encouraged him to apply for the Professorship of Mineralogy in the Royal Dublin Society, a post Giesecke occupied until his death in 1833. One of Giesecke's samples was given the name allanite, so everyone was happy!

It is the northern part of the Ilímaussaq intrusion that is currently attracting a lot of attention, mainly around a region of complex pegmatites called Kvanefjeld. So far Kvanefjeld is the type locality of a mere 7 mineral species, but remarkably *none* has so far been found outside Ilímaussaq. They are:

- kuannersuite-Ce, $Ba_6Na_2Ce_2(PO_4)_6FCl$
- kvanefjeldite, $Na_4(Ca,Mn)(Si_3O_7OH)_2$
- nabesite, $Na_2BeSi_4O_{10} \cdot 4H_2O$
- nacareniobsite-(Ce), $Na_3Ca_3CeNb(Si_2O_7)_2OF_3$
- orthojoaquinite-(La), $NaBa_2(La,Ce)_2Fe^{2+}Ti_2Si_8O_{26}(OH,O,F) \cdot H_2O$
- rohaite, $Tl_2Cu_{8.7}Sb_2S_4$
- sørensenite, $Na_4Be_2Sn^{4+}(Si_3O_9)_2 \cdot 2H_2O$

Naujakasite, $Na_6(Fe,Mn)Al_4Si_8O_{26}$, is a fascinating mineral (Fig. 3). It is a major rock-forming mineral at Kvanefjeld and over large areas of Ilímaussaq, its silvery, diamond-shaped plates sometimes making up 75% of the rock, but it is known from nowhere else. Nowhere. It mainly occurs in a rock type called arfvedsonite lujavrite, a bizarre peralkaline amphibolite. It is often accompanied by beetroot-coloured villiaumite, NaF, but it is so soluble in water that it does not survive on natural rock surfaces. There is evidence that natrosilite, $Na_2Si_2O_5$, was also present, although it dissolves very rapidly in moist air, forming – as older readers will know – water glass, once used for preserving eggs. Naujakasite has relatively simple chemistry, not far from a combination of the common minerals aegirine ($NaFeSi_2O_6$) and nepheline ($NaAlSiO_4$). Anderson and Sørensen (2005) have provided an intriguing assessment of the physical and chemical conditions that provided the tiny window of opportunity that gave naujakasite its moment as a rock star.

In 1955 Denmark began a programme to evaluate the uranium resources of Greenland, and Kvanefjeld was discovered in 1956. Intensive mapping and drilling by the Geological Survey of Greenland continued until the 1960s, and this work was followed up by detailed studies at the University of Copenhagen under the leadership of Henning Sørensen, whom you can see in Figure 4. Two adits were dug, the largest in 1979–1980. Most of the uranium and REEs are in steenstrupine. The uranium programme was dropped in 1983, but in 2010 the Greenland government lifted its ban on uranium mining and the area has been the subject of an intensive drilling programme by Greenland Minerals

Figure 4 The entrance to the Kvanefjeld adit in 1986. The man in the centre is Henning Sørensen.

and Energy Ltd, whose office address is in Subiaco, Western Australia. Kvanefjeld is now believed to be the second-largest deposit of REEs in the world, and the sixth largest uranium deposit. It has particularly high concentrations of heavy REEs, which are in much demand. It is nice to see that the operators have called one of their exploration zones the Sørensen deposit.

If mining goes ahead, I do not think it will be long before the list of weird minerals found in Ilímaussaq becomes considerably longer. It is a matter of great sadness to me that Mother Earth's ultimate igneous products will be dug up, but I fear it is inevitable. It is to be hoped that the developers dedicate time and money to systematically recording and interpreting features that they uncover, and take the trouble to preserve crucial sections. Once it's gone, it's gone, full stop.

Ian Parsons
University of Edinburgh, UK

Andersen T, Sørensen H (2005) Stability of naujakasite in hyperagpaitic melts, and the petrology of naujakasite lujavrite in the Ilímaussaq alkaline complex, South Greenland. Mineralogical Magazine 69: 125-136

The mineral data were largely taken from Petersen OV and Johnsen O (2005) Mineral Species First Described from Greenland. Canadian Mineralogist Special Publication 8, 184 pp

Figure 3 World's rarest rock-forming mineral? A silvery rhomb of naujakasite in naujakasite lujavrite, Kvanefjeld, Ilímaussaq. The crystal is 15 mm in largest dimension.

PARTING QUOTE

An ounce of example is worth a pound of generalities.

HENRY JAMES

ADVERTISERS IN THIS ISSUE

JOB POSTINGS

TENURE TRACK POSITION
MINERALOGY/MATERIAL SCIENCE

The Department of Earth and Environmental Science at TEMPLE UNIVERSITY seeks applicants for a tenure-track position at the level of Assistant or Associate Professor in mineralogy and material science whose research emphasizes the emerging fields of Environmental Mineralogy, Medical Mineralogy, or Nanoscience to begin in August 2013.

The successful candidate will have a Ph.D. degree, an established record of accomplishment in their discipline, a strong commitment to teaching and student mentoring, and a keen interest in collaboration with other faculty at Temple University to build a new Geoscience Ph.D. program. The candidate is expected to complement existing specialties in our department, including low-temperature aqueous geochemistry, hydrology, environmental geophysics, structural geology, mineralogy, coastal geomorphology, soils, sedimentology/stratigraphy, and paleoclimatology.

Available analytical instrumentation includes: X-ray fluorescence, magnetic susceptibility, electron microprobe, liquid chromatography/mass spectrometry, Raman spectroscopy, automated powder, single crystal, and thin film XRD, SEM and TEM with EDS, as well as access to high-performance computing.

The deadline for applications is January 7, 2013. Applications should include a CV, statement of research goals, description of potential classes and teaching philosophy, names and addresses of at least three references (five if applying at the Associate level), and copies of selected reprints. Applications should be submitted electronically via the link on the Department website: www.temple.edu/geology and letter of intent emailed to Jonathan Nyquist, Department chair (nyq@temple.edu).

Temple University is an affirmative action and equal opportunity employer committed to equal access and to achieving a diverse community. The department specifically invites and encourages applications from women and minorities. We will be available to meet with candidates at the 2012 Annual GSA and AGU meetings in Charlotte and San Francisco.

2012

December 3–7 AGU Fall Meeting, San Francisco, CA, USA. Details forthcoming

December 5–8 13th European Meeting on Environmental Chemistry, Moscow, Russia. Web page: www.euro-peanace.com/about/meetings

2013

January 2–4 Applied Mineralogy Group - Mineral Deposits Studies Group Annual Meeting, Leicester, UK. Web page: www.mdsg.org.uk/maintext.php?ID=4

January 6–10 93rd American Meteorological Society Meeting, Austin, TX, USA. Web page: http://annual.ametsoc.org/2013/?CFID=482669&CFTOKEN=89193527

January 7–9 Volcanic and Magmatic Studies Group Annual Meeting, Bristol, UK. Web page: www.vmsg.org.uk/vmsgbristol/VMSG_2013/VMSG%20Bristol%202013%3A%20Home.html

January 16–19 Granulites and Granulites 2013, Hyderabad, India. Web page: http://ggindia2013.com

January 27–February 1 Gordon Research Conference: Microbe–Mineral Interactions, Biomineralization, and the Rock Record, Ventura, CA, USA. Web page: www.grc.org/programs.aspx?year=2013&program=geobiology

January 27–February 1 37th International Conference and Expo on Advanced Ceramics and Composites, Daytona Beach, FL, USA. Web page: http://ceramics.org/meetings/acers-meetings

February 25–March 3 International DTTG-Workshop on Qualitative and Quantitative Analysis of Clays and Clay Minerals, Karlsruhe Institute of Technology (KIT), Germany. Web page: www.dttg.ethz.ch/workshop2013.html

March 3–7 TMS Annual Meeting, San Antonio, TX, USA. Web page: www.tms.org/Meetings/Meetings.aspx

March 3–8 Iron Biogeochemistry – From Molecular Processes to Global Cycles, Ascona, Switzerland. E-mail: fimin@bayceer.uni-bayreuth.de; website: www.bayceer.uni-bayreuth.de/fimin/conference

March 18–22 44th Lunar and Planetary Science Conference (LPSC 2013), Houston, TX, USA. Web page: www.lpi.usra.edu/meetings/lpsc2013

March 27–29 Volcanism, Impacts and Mass Extinctions: Causes and Effects, London, England. Website: http://massextinction.princeton.edu

April 1–5 MRS Spring Meeting & Exhibit, San Francisco, CA, USA. Web page: www.mrs.org/spring2013

April 7–11 245th American Chemical Society (ACS) National Meeting & Exposition, New Orleans, LA, USA. Web page: www.acs.org

April 24–28 Basalt 2013 – Cenozoic Magmatism in Central Europe, Görlitz, Germany. E-mail: basalt2013@senckenberg.de; website: www.senckenberg.de/root/index.php?page_id=15387&preview=true

May 5–8 Canadian Institute of Mining, Metallurgy, and Petroleum 2013 Conference & Exhibition, Toronto, Ontario, Canada. Web page: www.cim.org/calendar/calender.cfm?Year=All

May 19–22 AAPG 2013 Annual Convention & Exhibition, Pittsburgh, PA, USA. Web page: www.aapg.org

May 22–24 Geological Association of Canada /Mineralogical Association of Canada Annual Meeting, Winnipeg, Manitoba, Canada. Web page: http://gacmacwinnipeg2013.ca

June 2–7 Gordon Research Conference: Interior of the Earth, South Hadley, MA USA. Webpage: www.grc.org/programs.aspx?year=2013&program=interior

June 9–14 Water–Rock Interaction 14 (WRI 14), Avignon, France. E-mail: contact@wri14-2013.fr; web page: www.wri14-2013.fr/en/home.html

June 16–21 Gordon Research Conference: Catchment Science: Interactions of Hydrology, Biology & Geochemistry, Andover, NH,USA. Web page: www.grc.org/programs.aspx?year=2013&program=catchment

June 17–19 Mineralogical Society Annual Meeting: Minerals for Life: Living with Resource Constraints, University of Edinburgh, Scotland. Web page: www.minersoc.org/minerals-for-life.html

June 23–28 Gordon Research Conference: Origins of Solar Systems, South Hadley, MA, USA. Webpage: www.grc.org/programs.aspx?year=2013&program=origins

July 1th International Congress of Applied Mineralogy, Website: www.icam2013.org

July 1–5 1st International Conference on Tomography of Materials and Structures, Ghent, Belgium. E-mail: ictms2013@ugent.be; website: www.ictms.ugent.be

July 3–6 Conference on Raman and Luminescence Spectroscopy (Corals-2013), Vienna, Austria. Web page: www.univie.ac.at/Mineralogie/Corals2013

July 7–12 17th International Zeolite Conference, Moscow, Russia. Website: www.izc17.com

July 8–12 11th European Congress for Stereology and Image Analysis, Kaiserslautern, Germany. Web page: www.mathematik.uni-kl.de/events/ecs/

July 15–19 Eighth International Mars Conference, Pasadena, CA, USA. Web page: www.lpi.usra.edu/meetings

July 20–24 IAVCEI General Assembly 2013: Forecasting Volcanic Activity, Kagoshima, Japan. Details: Masato Iguchi, e-mail: iguchi@svo.dpri.kyoto-u.ac.jp; web page: www.iavcei.org/IAVCEI.htm

July 29–August 2 Annual Meeting of the Meteoritical Society, Edmonton, Alberta, Canada. Web page: www.meteoriticalsociety.org

August 4–8 Microscopy & Microanalysis 2013, Indianapolis, IN, USA. Web page: www.microprobe.org/events

August 11–16 17th International Conference on Crystal Growth and Epitaxy (ICCGE-17), Warsaw, Poland. Web page: http://science24.com/event/iccge17

August 12–15 SGA 12th Biennial Meeting, Uppsala, Sweden. Web page: www.akademikonferens.uu.se/sga2013

August 18–23 EnvironMetal Isotopes 2013, Ascona, Switzerland. E-mail: emi2013@env.ethz.ch; website: www.emi2013.ethz.ch

August 25–29 ECM-28: European Crystallographic Meeting, Warwick, UK. Website: http://ecm28.org

August 25–30 Goldschmidt 2013, Florence, Italy. Website: www.goldschmidt2013.org

August 26–30 Meteoroids 2013, Poznan, Poland. Web page: www.astro.amu.edu.pl/Meteoroids2013/index.php

September 2–10 10th International Eclogite Conference, Courmayeur, Aosta Valley, Italy. Web page: www.iec2013.unito.it

September 8–12 246th American Chemical Society National Meeting & Exposition, Indianapolis, IN, USA. Web page: www.acs.org

September 24–27 Whistler 2013: Geoscience for Discovery, Whistler, BC, Canada. Website: www.seg2013.org

October 2013 CMM Autumn School: Moisture Measurement in Porous Mineral Materials, Karlsruhe Institute of Technology (KIT), Germany. Web page: www.cmm.kit.edu/english/index.php

October 6–10 50th Clay Minerals Society Meeting, Urbana-Champaign, IL, USA. Website: www.clays.org/annual%20meeting/50th_annual_meeting_website

October 21–30 Short Course: Introduction to Secondary Ion Mass Spectrometry in the Earth and Environmental Sciences, Helmholtz Institutes in Dresden, Leipzig, Potsdam. Webpage: www.gfz-potsdam.de/SIMS/

October 27–30 Geological Society of America Annual Meeting, Denver, CO, USA. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings

October 27–31 MS&T'13: Materials Science & Technology Conference and Exhibition, Montréal, QC, Canada. Web page: www.matscitech.org/about/future-meetings

November 18–21 26th International Applied Geochemistry Symposium 2013, Incorporating the New Zealand Geothermal Workshop, Rotorua, New Zealand. Web page: www.gns.cri.nz/iags

December 1–6 MRS Fall Meeting & Exhibit, Boston, MA, USA. Web page: www.mrs.org/fall2013

2014

January 26–31 38th International Conference and Expo on Advanced Ceramics and Composites, Daytona Beach, FL, USA. Details forthcoming

March 16–20 247th ACS National Meeting & Exposition, Dallas, TX, USA. Web page: www.acs.org

April 21–25 MRS Spring Meeting, San Francisco, CA, USA. Web page: www.mrs.org/spring2014

May 21–23 Geological Association of Canada /Mineralogical Association of Canada Annual Meeting, Fredericton, Canada. Details forthcoming

June 9–13 Goldschmidt Conference, Sacramento, CA, USA. Details forthcoming

June 30–July 4 Asteroids, Comets, Meteors, Helsinki, Finland. E-mail: acm-2014@helsinki.fi; web page: www.helsinki.fi/acm2014

August 3–7 Microscopy & Microanalysis 2014, Hartford, CT, USA. Web page: www.microprobe.org/events/microscopy-microanalysis-2014

August 5–12 23rd Congress and General Assembly of the International Union of Crystallography, Montreal, Canada. Website: www.iucr2014.org

August 10–14 248th ACS National Meeting & Exposition, San Francisco, CA, USA. Web page: www.acs.org

September 1–5 21st General Meeting of the International Mineralogical Association (IMA2014), Johannesburg, South Africa. E-mail: info@ima2014.co.za; web page: www.ima2014.co.za

September 7–14 Annual Meeting of the Meteoritical Society, Casablanca, Morocco. Web page: www.meteoritical-society.org

October 12–16 MS&T'14: Materials Science & Technology Conference and Exhibition, Pittsburgh, PA, USA. Web page: www.matscitech.org/about/future-meetings

October 19–22 Geological Society of America Annual Meeting, Vancouver, BC, Canada. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings

November 30–December 5 MRS Fall Meeting & Exhibit, Boston, MA, USA. Web page: www.mrs.org/fall2014

2015

August 2–6 Microscopy & Microanalysis 2015, Portland, OR, USA. Web page: www.microprobe.org/events/microscopy-microanalysis-2015

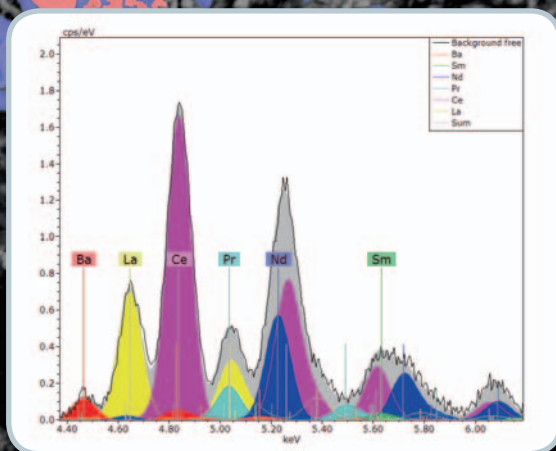**August 24–27** SGA 13th Biennial Meeting, Nancy, France. E-mail: sga-2015@univ-lorraine.fr.

September 9–11 8th European Conference on Mineralogy and Spectroscopy (ECMS 2015), Rome, Italy. Details forthcoming.

The meetings convened by the societies participating in *Elements* are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol (more meetings are listed on the calendar she maintains at http://homepages.udayton.edu/~akoziol1/meetings.html). To get meeting information listed, please contact her at Andrea.Koziol@notes.udayton.edu.

Concentration (µg/g)

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IMS 7f-GEO monocollection SIMS: analysis and mapping of Rare Earth Elements (REE) and trace elements down to sub-micron scale resolution.

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REE concentrations on various spots of a garnet grain.
Data obtained on the CAMECA IMS 7f-GEO

S I M S

Mnz core

Chondrite norm.

Nd Lα

1104±12
507±26
321±22   418±20   348±22
50µm
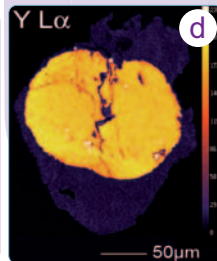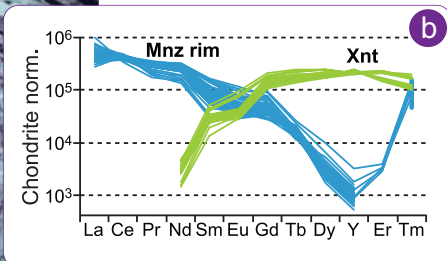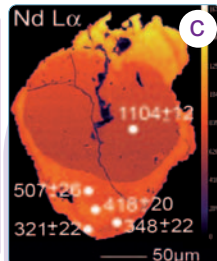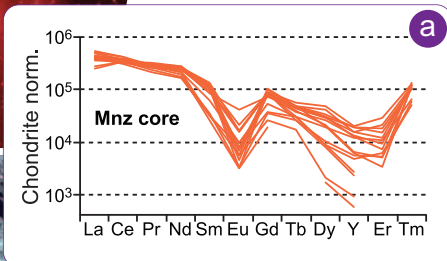
SXFive / SXFiveFE
### CAMECA's fifth generation Electron Microprobe

Quantitative microanalysis & X-ray mapping at sub-micron spatial resolution. Benchmark detection limits for trace and minor elements.

a&b: Chondrite-normalized REE profiles as determined by EPMA. Monazite cores contrast with monazite rims and associated xenotime.
c&d: WDS maps of Nd and Y distributions.
Points marked on the Nd map show EPMA age determinations in Ma, 2σ
Data acquired on the SX Ultrachron model, courtesy of Dr. Julien Allaz, Univ. of Colorado and Dr. Michael Jercinovic, Univ. of Massachusetts.

Mnz rim   Xnt

Y Lα
50µm

E P M A

Y

100nm
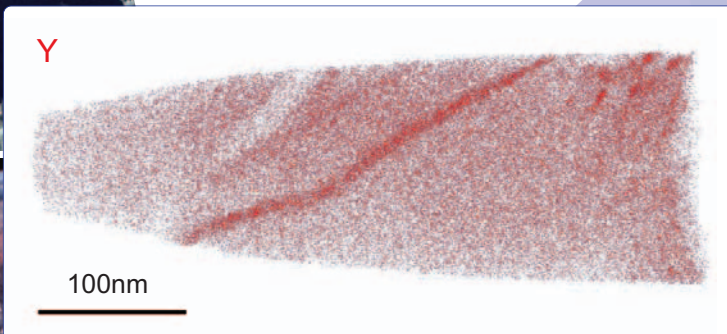
LEAP 4000 Atom Probe
Opening new frontiers of research in geosciences!

Atom Probe Tomograpgy (APT) is a powerful and promising elemental and isotope analysis technique for the nanoscale characterization of geological and extraterrestrial materials.

2D projection of 70 million atom 3D dataset from a metamorphic zircon. Y atoms (red) are concentrated along microfractures.

A P T