Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology

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Garnet

ETHAN F. BAXTER, MARK J. CADDICK, and JAY J. AGUE, Guest Editors

Elements

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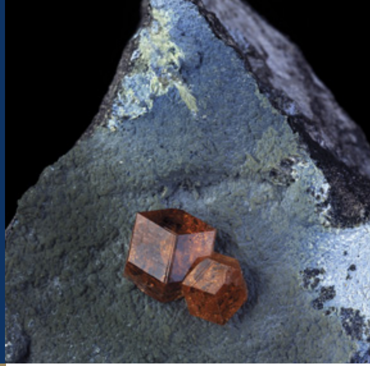

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ABOUT THE COVER: The Jeffrey mine, in Asbestos, Québec, Canada, is world famous for its beautiful crystals of orange, pink, and green grossular. These transparent, almost complete "cinnamon" garnet crystals, the largest of which measures 16 mm across, display perfect shapes with smooth dodecahedral {110} faces. Their coloration arises from substituted Fe^{3+}. FROM THE MINERAL COLLECTION OF UNIVERSITÉ PIERRE ET MARIE CURIE, PARIS; PHOTO COURTESY OF JEAN-PIERRE BOISSEAU

Garnet: Common Mineral, Uncommonly Useful

Guest Editors: **Ethan F. Baxter, Mark J. Caddick,** and **Jay J. Ague**

DEPARTMENTS

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

Elements is published six times a year. Individuals are encouraged to join any one of the participating societies to receive *Elements*. Institutional subscribers to any of the following journals—*American Mineralogist*, *Clay Minerals*, *Clays and Clay Minerals*, *Mineralogical Magazine*, and *The Canadian Mineralogist*—also receive one copy of *Elements* as part of their 2014 subscription. Institutional subscriptions are available for US$160 (US$175 non-US addresses) a year in 2014. Contact the managing editor (tremblpi@ete.inrs.ca) for information.

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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.

Society News Editor: Andrea Koziol (Andrea.Koziol@notes.udayton.edu)

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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.

Society News Editor: Pierrette Tremblay (ptremblay@mineralogicalassociation.ca)

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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* and the CMS Workshop Lectures series. Membership benefits include reduced registration fees to the annual meeting, discounts on the CMS Workshop Lectures, and *Elements*.

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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 cohosting 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 *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*, *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.

Society News Editor: Urs Schaltegger (urs.schaltegger@unige.ch)

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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.

Society News Editor: Cari Corrigan (corriganc@si.edu)

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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.

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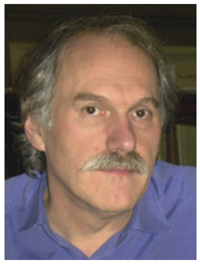

Georges Calas

On the way back from our *Elements* editorial meeting, held just prior to the Geological Society of America's 125th-anniversary meeting in Denver, I realized that we lived wonderful moments at this special meeting. At the MSA awards ceremony, the Distinguished Public Service Medal was awarded to Pierrette Tremblay for making a dream a reality. This ceremony was a unique occasion to gather friends of *Elements*. The magazine is made by you—the authors and guest editors—in close cooperation with our supporting societies. Yes, Rod, you had the foresight to recognize the potential usefulness of a magazine without borders—a magazine linking members of the many societies in our scientific fields! I remember our discussions while walking around Notre Dame de Paris over 10 years ago, when you were explaining to me your vision of this challenge. But all our communities were not ready at that time. Now, 17 societies support *Elements*, and the link keeps growing.

Diogenes in his barrel at Corinth (early-19th-century engraving)

This issue presents another kind of link, one that we all cherish as Earth scientists: understanding the past and present of planet Earth using the links offered by the observables that we can understand and quantify. Here is garnet, surely among the major witnesses that allow us to travel back in space and time with the help of the record of detailed events it preserves in its deep memory. But we need adequate tools to open these "cans" and decrypt the messages they contain. Garnet is one of the most frequently observed and visible minerals, and it is common to find specimens with unrivaled colors and well-preserved crystal shapes. But garnet deserves deeper attention, beyond the admiring surprise of children and teenagers who discover garnet crystals for the first time during vacation trips—I was one of these—and who start asking questions about these intriguing natural objects, often the first mineral they pay attention to.

Recent innovations and developments have allowed a progressive convergence of mineralogy, petrology, and geochemistry, to the point that it is sometimes not easy to tell in which field a research topic falls. We, the editors, experience such a feeling while discussing the many proposals we receive for future *Elements* issues. This convergence among our fields has been facilitated by the increasing use of tools that allow micro- and nanoscale approaches. At the scale of the crystal, and below, everyone speaks about the same object, though based on different approaches. And by observing and measuring this crystal, we learn what happened hundreds of millions of years ago. Diogenes (ca 400–325 BC) in his barrel was observing humankind and reflecting on how to link man to Nature, despite the limited space he had. We do not hesitate to spend much time on a tiny crystal to gain a deeper knowledge about complex geological processes. Indeed, this approach represents a positive and attractive evolution of our scientific domains.

Making links between ideas from various scientific fields is an important responsibility that we all share. And this issue on garnet is a nice illustration of that. Garnet is a ubiquitous mineral occurring in a broad range of rock types. Witnesses to complex geological processes, garnet crystals may record details on Earth's evolving crust and lithosphere, allowing us to decipher metamorphic conditions and histories. And they contain important information on tectonometamorphic events, as shown by the compositional zoning preserved by slow diffusional resetting. Acting like "tree rings," this zonation provides a detailed chronology spanning millions of years. Garnet is a witness, but more than that, it is an actor: it gives peculiar seismic and other properties to the mantle, influences the budget of volatiles, affects the dynamics of subducting slabs, and provides distinctive geochemical signatures to deep magmas.

This issue of *Elements* also illustrates the link between garnet and societal questions—a strong component of most *Elements* issues—by highlighting high-tech applications of oxide materials with the garnet structure and by recalling the historical and artistic influence played by this multifaceted mineral. In the former case, the unique crystal structure of garnet imposes its law, and the original applications of nonsilicate materials based on the garnet structure arise from the peculiar crystal chemistry of this structure, including cation site geometries and the structural relationships among the three types of cation sites. In the latter case, the scenic trip through the garnet kaleidoscope perfectly illustrates the links to geochemistry, an evocative illustration of the importance of structure–property links. And these links relate to a frequently asked question by undergrads when they observe garnet crystals: why are these crystals usually red, rather than the shades of green and brown displayed by most ferromagnesian minerals?

Despite the fact that major progress has recently been made in our understanding of Earth's crust and mantle using the information contained in this multicolored mineral, we are far from being able to write a book "On Nature," as Diogenes did in his barrel home. But we learn that important knowledge can be gained by observing Earth from the perspective of a garnet crystal.

Georges Calas
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* Principal editor in charge of this issue

THIS ISSUE

Take a small crystal of garnet, a common mineral with built-in chronometers and uncommon properties due to its crystalline structure, study it, and suddenly you have insights on large-scale processes like plate subduction, timing and duration of metamorphism, seismicity, and more. The authors in this issue, assembled by guest editors Ethan Baxter, Mark Caddick, and Jay Ague, take us on a whirlwind tour of the mantle and crust, and inform us on the technological applications and the place in history of this beloved mineral.

EDITORIAL MEETING AT GSA

The editors met in Denver for their annual meeting on Saturday, October 26, just prior to the Geological Society of America conference. This was a departure from the last several years, when our meeting was held in conjunction with the Goldschmidt Conference. We welcomed Gordon Brown, whose term of office will officially start on January 1. A large portion of our meeting was devoted to evaluating the 18 thematic proposals we have received for our 2015 lineup. Overall, we strive to ensure that, in any given year, there is a mix of mineralogy, geochemistry, and petrology topics. We ask ourselves several questions when we evaluate a proposal: Is *Elements* the right venue for this proposal? Will this topic be relevant to a significant proportion of our readership? Is the proposed list of authors diversified? And Tim Drever's ultimate question: "Would I want to read about this topic if I was stuck in an airport for several hours?" Six proposals have been selected, and proposers have been asked to finalize their list of authors for final approval.

Pierrette Tremblay receiving the Distinguished Public Service Award from John Hughes (left) at the Mineralogical Society of America's awards luncheon in Denver. The citationist was Rod Ewing (right).

THANKS

We thank the guest editors and authors who contributed to the six issues of volume 9. Their efforts to bring their science to the nonspecialist audience of *Elements* and to respect the constraints of *Elements* regarding deadlines and article length are much appreciated. We also acknowledge the contributions of reviewers, copyeditors, and proofreaders, who toil in the background.

We also thank our advertisers for their support: AHF Analysentechnik, Applied Spectra, Australian Scientific Instruments, Beta Analytic, Bruker AXS, Bruker Nano GmbH, Cambridge University Press, CAMECA, CrystalMaker, Elsevier, Endecotts, ESI New Wave Research Corporation, Excalibur Minerals Corporation, FEI, Gemological Institute of America, Geochemical Journal, The Geochemist's Workbench, GNS Science, IAGOD Symposium, IUMAS meeting, IWA Publishing, McCrone Microscopes and Accessories, Rigaku, Savillex, SPECTRO, Thermo Scientific, TSI, and Wiley. A special mention goes to **The Geochemist's Workbench**, **Savillex**, **Rigaku**, **SPECTRO**, **Bruker**, **Bruker Nano**, and **Excalibur Minerals Corporation**, who advertised in each issue during the year.

2014 PREVIEW

Finally, we are pleased to introduce our lineup for 2014. We are confident that there will be something of interest for everyone.

Best wishes to everyone for the coming year!

Georges Calas, John Valley, Patricia Dove, and **Pierrette Tremblay**

THEMATIC TOPICS IN 2014

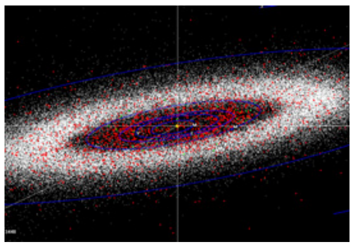
Volume 10, Number 1 (February)

ASTEROIDS: LINKING METEORITES AND PLANETS

GUEST EDITORS: **Catherine Corrigan** (Smithsonian Institution, Washington) and **Guy Libourel** (Observatoire de la Côte d'Azur, Nice, and CRPG, Université de Lorraine)

Asteroids number in the millions. Orbiting the Sun between Mars and Jupiter, they are thought to be the shattered remnants of small bodies formed within the young Sun's solar nebula and that never accreted large enough to become planets. By presenting several case studies, this issue will present what we know about the physical and chemical compositions of asteroids and how they are related to meteorites and planet formation. We will show why these "minor bodies" are key to understanding how the Solar System formed and how it works; why they are clues to the origin of life, having possibly delivered organics and water to Earth; and why the international space agencies have funded sample-return missions to asteroids.

- **Asteroids: New challenges, new targets**
  Guy Libourel and Catherine Corrigan
- **Asteroid formation and physical properties**
  Patrick Michel (Observatoire de la Côte d'Azur, Nice)
- **Forging asteroid–meteorite links**
  Edward Cloutis (University of Winnipeg), Richard Binzel (Massachusetts Institute of Technology), and Michael J. Gaffey (University of North Dakota)



Tilted view of the main asteroid belt from outside the orbit of Jupiter and from about 30 degrees above the ecliptic (plane of the Earth's orbit)

- **Asteroid 2008 TC_3 and the fall of Almahata Sitta, a unique meteorite breccia**
  Cyrena Goodrich (Planetary Science Institute, Tucson), Addi Bischoff (University of Münster), and David O'Brien (Planetary Science Institute, Tucson)
- **Unique, antique Vesta**
  Harry Y. McSween (University of Tennessee), Cristina De Sanctis (Institute for Space Astrophysics and Planetology, Italy), Thomas H. Prettyman (Planetary Science Institute, Tucson), and the Dawn Science Team
- **Asteroid Itokawa: A source of ordinary chondrites and processes on its surface**
  Akira Tsuchiyama (Kyoto University)

Volume 10, Number 2 (April)

OPHIOLITES

GUEST EDITORS: **Yildirim Dilek** (Miami University of Ohio) and **Harald Furnes** (University of Bergen, Norway)

This thematic issue will cover some of the most exciting advances in ophiolite science. Focus is directed toward ophiolite classification during the formation and destruction of ocean basins; the mineralogy, petrology, and isotope geochemistry of ophiolites; and the trace element behavior of crustal and upper-mantle units in ophiolites. The issue will cover the history of origin, the geochemical and petrological development, and the final emplacement of one of the largest and most studied ophiolites, the classical Semail ophiolite in Oman. Further, for a better understanding of ophiolites in relation to subduction processes, one of the papers deals with the lithological and geochemical development of the Izu-Bonin-Mariana forearc crust as a modern analogue. Finally, the issue will present some of the new and exciting aspects of microbial interaction with the volcanic component of oceanic crust, as observed in ophiolites as old as the young Earth.

- **Origin of ophiolites**
  Yildirim Dilek and Harald Furnes
- **Immobile-element fingerprinting of ophiolites**
  Julian A. Pearce (Cardiff University)
- **Records of ocean growth and destruction in the Oman–UAE ophiolite**
  Kathryn Goodenough, Bob Thomas, Mike Styles, David Schofield (all of the British Geological Survey), and Chris MacLeod (Cardiff University)
- **The Izu-Bonin-Mariana forearc crust as a modern ophiolite analogue**
  Osamu Ishizuka (Geological Survey of Japan), Kenichiro Tani (JAMSTEC, Japan), and Mark K. Reagan (University of Iowa)

Leucogabbro cut by basalt dikes at the gabbro–dike transition, Karmøy ophiolite, western Norway

- **The deep biosphere record in modern oceanic lithosphere and ophiolites**
  Hubert Staudigel (Scripps Institution of Oceanography), Harald Furnes (University of Bergen), and Mark Smits (Hasselt University)

Volume 10, Number 3 (June)

KAOLIN: FROM ANCIENT PROCELAINS TO NANOCOMPOSITES

GUEST EDITORS: **Paul A. Schroeder** (University of Georgia) and **David L. Bish** (Indiana University)

Although bearing the simple name "kaolin," this natural material has a variety of geologic origins and many industrial applications significant to society. Known as china clay, kaolin has a long history dating back to Kauling, China, and its first exploitation in the field of ceramics. Kaolin is one of nature's most abundant nanomaterials. Its fine, clay-sized particles, unique shapes, and layered structures make it central to Earth's near-surface critical zone. Concerns for energy efficiency and environmental awareness in the industry have led to advances in mining and reclamation practices. The crystallographic and elemental varieties of kaolin require them to be carefully characterized as they lend themselves for use in plastics, papers, pigments, and ceramics. Kaolin minerals are being probed with computational chemistry and new spectroscopic tools to expand their applications and to understand their significance in biology. We are now exploring how kaolin can be nanocomposited to create materials with novel properties.

- **History of kaolin**
  Paul A. Schroeder and Gary Erickson (Macalester College)
- **Kaolin types and structures**
  Etienne Balan (IRD and UPMC, Paris), David L. Bish (Indiana University), and Georges Calas (UPMC, Paris)
- **Kaolin mining and processing**
  Jessica Elzea-Kogel (IMERYS)
- **Toward understanding the interactions of kaolin minerals in the environment**
  Randall T. Cygan (Sandia National Laboratories) and Kazue Tazaki (Kanazawa University)
- **Kaolin nanocomposites**
  Christian Detellier (University of Ottawa) and Robert Schoonheydt (KU Leuven)
- **Kaolin and health**
  Lynda Williams (Arizona State University) and Stephen Hillier (The James Hutton Institute, Aberdeen)

Kaolin is a rock dominated by kaolin-group minerals formed in hydrothermal or near-surface weathering environments. In the hands of humans (upper panel), it makes an important industrial mineral and geological indicator. Pseudohexagonal kaolinite plates with dimensions of less than one hundredth of the thickness of a human hair (lower panel). The shape and surface chemistry of kaolin-group minerals give value-added rheological, thermal, color, and chemical properties, which benefit ceramics, papers, plastics, pigments, and pharmaceuticals. PHOTOS: PHIL JONES (IMERYS)

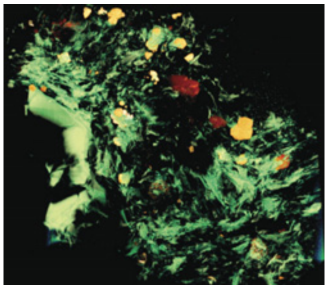
Volume 10, Number 4 (August)

UNCONVENTIONAL HYDROCARBONS

Guest Editors: **David R. Cole** (Ohio State University) and **Michael Arthur** (Pennsylvania State University)

The realization that unconventional hydrocarbons, such as gas and oil shale, oil sands, and heavy oil, can now be exploited more effectively and economically has stimulated exploration and exploitation on a global scale. This has led to a new economic and environmental landscape in energy matters that we are only now starting to understand. Exploiting unconventional hydrocarbons requires additional technology, energy, and capital compared to the industry standard. This thematic issue will address the geologic and geochemical nature of these resources and their impact on global socioeconomics and the environment.

- **A global view of unconventional hydrocarbons**
  Michael Arthur and David R. Cole
- **Dash for gas, 21st-century style**
  Seth Blumsack (Pennsylvania State University)
- **From source rock to reservoir: The evolution of self-sourced unconventional-resource plays**
  L. Taras Bryndzia and Neil R. Braunsdorf (Shell Oil Co.)
- **Oil sands and heavy oil: Origin, exploration, emissions, and alternative futures**
  Steve Larter (University of Calgary) and Ian Head (University of Newcastle)
- **Fingerprinting formation waters using stable isotopes and other natural tracers**
  Benjamin Rostron (University of Alberta) and Serguey Arkadakskiy (Isobrine Solutions Inc.)
- **Abiotic gas: Atypical but not rare**
  Giuseppe Etiope (Istituto Nazionale di Geofisica e Vulcanologia) and Martin Schoell (GasConsult International)



False-color image showing relationship between organics (green) and pyrite (yellow, amber) in a Utica Shale sample. Image is ~20 µm across.

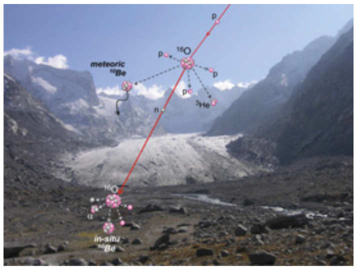
Volume 10, Number 5 (October)

COSMOGENIC NUCLIDES: EARTH'S SURFACE CLOCK

Guest editors: **Friedhelm von Blanckenburg** (GFZ Potsdam) and **Jane Willenbring** (University of Pennsylvania)

The Earth's surface is the thin, ever-changing layer on which we live. The geochemical study of cosmogenic nuclides is currently revolutionizing our understanding of the processes that shape this surface layer by providing their rates and dates. The underlying physical principles are simple and elegant: when rock or soil moves into the shallow zone of surface irradiation, cosmic rays interact with elements in minerals to produce very rare isotopes—the radioactive nuclides ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, and ^{53}Mn and the rare gases ^{3}He and ^{21}Ne. At this exact moment, the nuclide clock begins to tick. These nuclides can reveal the times when a river cuts down through a mountain range, when a glacial moraine was deposited, or when a river or marine terrace was abandoned. Cosmogenic nuclides also serve to measure erosion rates directly: the longer a soil resides at the surface before being eroded, the more nuclides accumulate. Hence, these nuclides provide rates of erosion, from the scale of a pebble to as large as an entire river basin.

- **Cosmogenic nuclides – Dates and rates of Earth-surface change**
  Friedhelm von Blanckenburg and Jane Willenbring
- **Measuring one in a million billion**
  Marcus Christl (ETH Zürich), Rainer Wieler (ETH Zürich), and Robert Finkel (Lawrence Livermore National Laboratory)
- **The nuts and bolts of nuclide production**
  Tibot J. Dunai (University of Cologne) and Nathaniel Lifton (Purdue University)
- **Shaken and stirred: Earthquakes, faults and toppled blocks**
  Lucilla Benedetti (Cerege, Aix-en-Provence, France) and Jérôme van der Woerd (Institut du Globe de Strasbourg)
- **Making soil**
  Jean L. Dixon (Montana State University) and Cliff Riebe (University of Wyoming)
- **Dating disappearing ice**
  Susan Ivy-Ochs (ETH Zürich) and Jason P. Briner (State University of New York at Buffalo)
- **Grinding down mountains**
  Darryl E. Granger (Purdue University) and Mirjam Schaller (Universität Tübingen)



The image illustrates how cosmic rays produce the meteoric cosmogenic nuclide ^{10}Be from oxygen in the atmosphere, which is then deposited on the Earth's surface. Cosmic rays also produce cosmogenic ^{10}Be in situ within rocks. Both varieties of this rare radioactive nuclide serve to date the time when glacial ice disappeared at the Forno glacier, Bergell Alps, Switzerland. Photo: Friedhelm von Blanckenburg

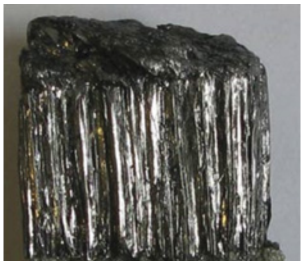
Volume 10, Number 6 (December)

GRAPHITIC CARBONS

Guest editors: **Olivier Beyssac** (CNRS and Université Pierre et Marie Curie, Paris) and **Douglas Rumble** (Carnegie Institution of Washington)

In natural systems, graphitic carbons are widespread and exhibit an infinite range of structure, from amorphous-like compounds (e.g. soots, charcoal) to crystalline graphite through a myriad of turbostratic structures (e.g. coals, kerogens). A variety of structures and chemistries down to the nanometer scale control the physicochemical properties of graphitic carbons and determine their behavior and fate during geological processes. This issue of *Elements* will present recent advances in our understanding of the formation of graphitic carbons (graphitization, fluid deposition) and will discuss their role as actors and/or tracers in cosmochemistry, geobiology, geochemistry, and petrology. In particular, graphitic carbons may carry an important biological legacy in rocks, they may be used for assessing the thermal history of rocks, and they buffer the chemical composition of fluids in equilibrium with rocks. The issue will also present an introduction to the new carbon nanomaterials (e.g. graphene, carbon nanotubes), which bear structural similarities to natural graphitic carbons, and to their technological applications.

- **Graphitic carbons**
  Olivier Beyssac and Douglas Rumble
- **From organic matter to graphite: Graphitization**
  Olivier Beyssac (UPMC Paris) and Peter Buseck (Arizona State University)
- **Graphitic carbons as traces of life**
  Sylvain Bernard (Museum National d'Histoire Naturelle, Paris) and Dominic Papineau (University College London)
- **Hydrothermal graphite**
  Douglas Rumble (Carnegie Institution of Washington)
- **Laboratory studies of carbonaceous stardust**
  Thomas J. Bernatowicz, T. Kevin Croat, and T. Dalton (Washington University in St Louis)
- **Graphene, the new nanotechnology leader**
  Michele Lazzeri (UPMC Paris) and A. Barreiro Megino (Columbia University)



Vein of hydrothermal graphite from Ceylon

GEOLOGICAL SOCIETY OF AMERICA AWARDS

At its Denver meeting last October, the Geological Society of America recognized some members of our community.

Day Medal to Richard Carlson

Richard W. Carlson of the Carnegie Institution of Washington was awarded the Arthur L. Day Medal. Nominator Stan R. Hart writes, "There is hardly any field of geochemistry and cosmochemistry that Rick has not strongly impacted and this impact has extended to the whole Earth and Planetary Sciences." The Arthur L. Day Medal was established in 1948 through a donation by Arthur L. Day, founding director of the Geophysical Laboratory of the Carnegie Institution of Washington. It is awarded to recognize outstanding distinction in the application of physics and chemistry to the solution of geologic problems, with no restriction as to the particular field of geologic research.

Donath Medal to Naomi Levin

Naomi E. Levin, an assistant professor at Johns Hopkins University, received the Young Scientist Award (Donath Medal) and a cash prize of US$10,000 for her outstanding contributions to the understanding of the environments of human origins in Africa. The Young Scientist Award was established in 1988 and is given to a young scientist for outstanding achievement in contributing to geologic knowledge through original research that marks a major advance in the Earth sciences. Nominator Jonathan G. Wynn notes that Levin's work ethic and "ability to establish constructive working relationships" have "allowed her to make major contributions, and move forward scientific progress in the field of human evolution, in ways that would have otherwise not been thought possible." Levin's research centers on understanding how landscapes and terrestrial organisms respond to past climate change. She uses a combination of sedimentary geology and isotope geochemistry to study interactions between mammals, vegetation, and climate in past ecosystems, with a focus on early hominids in East Africa.

2013 Distinguished Geologic Career Award to Gerhard Wörner

The 2013 Distinguished Geologic Career Award of the Mineralogy, Geochemistry, Petrology, and Volcanology (MGPV) Division of the Geological Society of America was awarded to **Gerhard Wörner** of Georg August Universität Göttingen, Germany. The award was presented to him following a session in his honor: T169 "Volcanology, Mineralogy, Geochemistry & Petrogenesis of Circum-Pacific Magmatism: A Tribute Session to Gerhard Wörner." Dr. Wörner is cited for his important contributions in each of the research fields of the Division. His research has been based on multidisciplinary, field-based foundations in which the problem under consideration is cast in the framework of the Earth as a natural laboratory. His research has focused on physical volcanology; the evolution of magmatic systems, from crystal to orogen scale; magmatism in continental rifts (Rhine Graben, West Antarctic Rift) and at convergent plate boundaries (Kamchatka, Central America, Andes); and the interaction between tectonic and magmatic processes in orogenic belts.

MINERALS IN THE AIR

Reto Gieré[1] and David J. Vaughan[2]

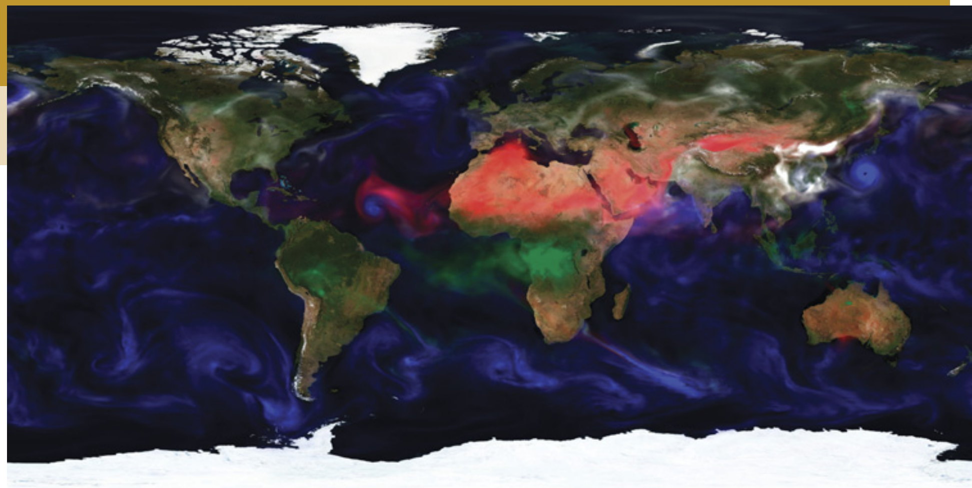


FIGURE 1 World map showing the distribution of various types of airborne particles: desert dust (red), sea salt (blue), particles emitted from wildfires and biomass burning (green), and anthropogenically emitted sulfates (white, excluding the white areas in the polar regions). IMAGE COURTESY OF MEEO, FERRARA (WWW.MEEO.IT); BASED ON DATA ACQUIRED ON SEPTEMBER 1, 2011, THROUGH THE MACC-II PROJECT (WWW.COPERNICUS-ATMOSPHERE.EU)

Mineralogists, petrologists, and geochemists do not typically reach for the skies when studying minerals except, perhaps, when threatened by a gigantic cloud of volcanic ash. It is during such events, for example, the April 2010 eruption of the Icelandic volcano Eyjafjallajökull and the 79 CE eruption of Mount Vesuvius described by Pliny the Younger, that humans become aware of the potential impact of airborne minerals. Similarly, major desert dust storms, such as those regularly engulfing cities in the Arabian Peninsula and the seasonal Kosa or Hwangsa storms in East Asia, draw our attention to the presence of minerals in the atmosphere. As previously discussed in *Elements* (Gieré and Querol 2010), atmospheric particulates may have a major impact on local to global climate, the cryosphere, marine and terrestrial ecosystems, agricultural productivity, and visibility, the latter affecting transportation systems. Furthermore, atmospheric particulates can adversely affect human health when inhaled.

Many of these effects are difficult to quantify, mainly due to the challenges involved in determining the physical and chemical characteristics and spatial variability of very small (nano- to micrometer-sized) atmospheric particles. Difficulties also arise because particulate matter may undergo significant changes while airborne. These processes, collectively known as ageing, include particle growth or dissolution due to absorption of moisture, reactions with gases or liquids (including acids), condensation of vapors on the particle surface, redox reactions, and coagulation (Usher et al. 2003; Choël et al. 2006). In understanding these processes, the techniques used in mineralogy can play a decisive role. Applying techniques such as optical and electron microscopy, synchrotron-based X-ray imaging and microspectroscopy, infrared and Raman spectroscopy, BET surface analysis, laser diffractometry, and mass spectrometry to airborne particles can lead to substantial improvements in our knowledge of their properties, behavior, and effects.

Depending on source, formation, and ageing, airborne solid particles encompass a wide variety of natural and anthropogenic materials, including sea-salt particles, silicates (such as clays and quartz), oxides (including those of iron and uranium), sulfates (gypsum, anglesite), carbonates (calcite, dolomite), alloys (such as those of iron and manganese), glass (particularly volcanic ash), biogenic material (pollen, spores, plant fragments, algae, bacteria, brochosomes), and combustion-derived carbonaceous particles (such as soot). The characterization of such particles helps us to understand key interactions between the atmosphere and the solid Earth, its hydrosphere, and its biosphere.

An example is research to determine the ultraviolet and visible light absorption properties of clays (Hoang-Minh et al. 2010), as this mineral group is prominent in desert dust clouds and, therefore, plays a critical role in modifying solar and terrestrial radiation. Such interactions, which strongly depend on the optical properties of the airborne particles, result in a direct change of the radiation balance of the atmosphere and the Earth's surface (Mahowald et al. 2011). This modification to the radiation budget, known as a *direct radiative effect*, leads, in turn, to changes in the surface temperature of both land and ocean with concomitant indirect effects on ecosystems, as recently discussed on the basis of coral growth rates (Kwiatkowski et al. 2013). Airborne minerals and other aerosol particles also have *indirect effects* on the radiation balance, because they are capable of acting as cloud condensation nuclei or ice-forming nuclei, thus modifying cloud properties and precipitation (Stevens and Feingold 2009). Both the direct and the indirect radiative effects influence climate, but the magnitude of this climate impact is associated with considerable uncertainties, largely because we do not know enough about the properties of the particles in the atmosphere and their so-called "mixing state," i.e. whether they occur as single-phase or multiple-phase particles (Pósfai and Buseck 2010). These phenomena can be further complicated by mixing with carbonaceous materials produced by biomass burning, which is carried out on a very large scale in areas such as Central Africa and Southeast Asia (FIG. 1) as part of the agricultural cycle (Hand et al. 2010).

Airborne particles can also have a direct impact on ecosystems, both terrestrial and marine, by modifying their chemical compositions. This process has been investigated extensively with regard to deposition of nutrients contained in airborne particles. In this case it represents what is described as an *ecosystem fertilization* mechanism. Aeolian dust, for example, provides one of the dominant external sources of iron and other nutrients, such as phosphorus and silicon, to the surface waters of the open ocean (Jickells et al. 2005). Here, the dust-derived nutrients stimulate phytoplankton growth, which, in turn, increases the uptake of CO_2 from the atmosphere through conversion into biomass (Baker and Croot 2010). However, because the speciation of these nutrients is one of the main controlling factors in determining particle solubility and bioavailability (Schroth et al. 2009), the global models of ocean fertilization can be refined only if both the chemical and the mineralogical compositions of dust from various sources are better known. Globally, the most important dust-source areas, those which have received most attention, are located in the arid regions of the lower and middle latitudes (e.g. the Bodélé Depression in Chad). However, important dust sources also occur at high latitudes, such as in proglacial regions and in areas exposed through glacial retreat (Prospero et al. 2012). With increasing global temperatures and the associated shrinkage of glaciers, ice caps, and ice sheets, high-latitude dust sources could become more important globally in providing nutrients to various ecosystems. Dust deposition, however, may also have negative effects on ecosystems due to increases in the turbidity of the seawater and due to the possible delivery of pathogens (examples include fungal spores and bacteria) and toxins contained in the dust clouds.

The influence of airborne mineral particles on climate and ecosystems is a major topic of current research. Another key area of research is that concerning the impact of mineral dusts on human health, especially with respect to particles in the nanometer size range where properties

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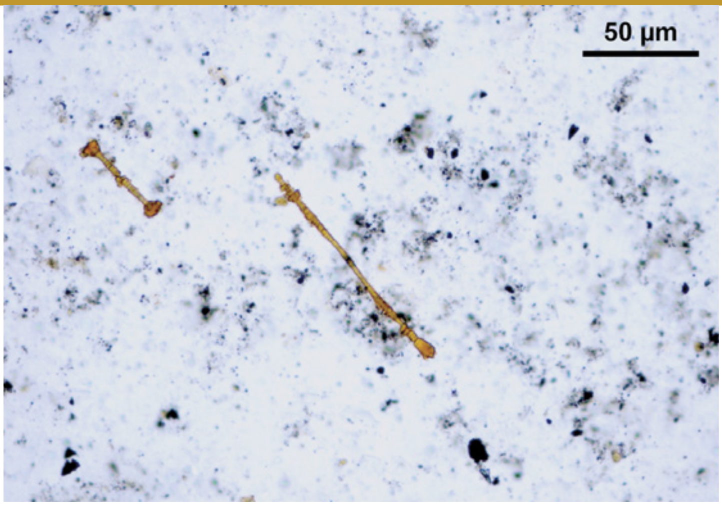

FIGURE 2 A photomicrograph of dust particles recovered from human lung tissue. The tissue contains numerous fine particles as well as two orange-colored objects, which are mineral fibers coated with iron compounds. SAMPLE COURTESY OF SILAG (WWW.SILAG.ETHZ.CH)

may differ significantly from those of larger particles. Millions of airborne particles enter the human respiratory system with each breath we take. Once inhaled, coarse particles may be deposited on the surfaces of the conducting airways of the upper respiratory system, whereas fine particles (generally defined as those with a diameter of <2.5 µm and known as $PM_{2.5}$) can migrate to the deepest parts of the lung where the gas exchange takes place (Plumlee et al. 2006). Ultrafine particles (<0.1 µm) may even penetrate through the cell tissue that lines the lung and then translocate to other parts of the body. The inhaled particles can interact with the lung fluid or with various types of cells present in the lungs. These interactions may have adverse health effects, both acute and chronic, and may also lead to the formation of endogenous particles, such as calcite and apatite, and of Fe^{3+}-rich coatings on inhaled fibrous minerals (FIG. 2). In addition to being dependent on size, the interactions are influenced by other particle characteristics, including structure, chemical composition, shape, surface area and reactivity, sorptive properties, and solubility.

Epidemiological and toxicological studies have shown that exposure to $PM_{2.5}$ is linked to increases in mortality and hospital admissions due to respiratory and cardiovascular diseases (Englert 2006). There is increasing evidence, however, that coarser particles may also produce adverse health effects (Brunekreef and Forsberg 2005). The adverse health effects include chronic bronchitis, exacerbation of asthma, fibrosis, and lung cancer (Fubini and Fenoglio 2007). The mechanisms behind these diseases and their dependence on particle properties are still poorly known; they are thought to involve excessive production of free radicals (which can lead to oxidative damage to cell membranes, proteins, and DNA) and the release of chemical substances that trigger and perpetuate inflammation (Donaldson and Tran 2002; Schoonen et al. 2006). To improve our knowledge of these biochemical processes, it is essential to perform careful toxicological experiments with human lung cells and tissue cultures. However, detailed characterization of the particles used in such experiments is only rarely reported in the medical literature (Könczöl et al. 2012). Additional information about the nature and abundance of particles in human lungs and their possible role in disease development comes from microscopic investigations of fluids that are extracted from the lung or from lung tissue samples excised during biopsy or autopsy.

Although great efforts have been made to reduce particulate emissions, airborne particles still pose a significant threat to human health in many areas. Moreover, the success in cutting traffic emissions, especially diesel soot, through the installation of particle filters in vehicles has been partially negated by increased emissions resulting from biomass combustion. The recent increase in the use of wood as a cleaner alternative to fossil fuels has led to air pollution problems in both urban and remote areas, especially during winter months. Emissions from biomass combustion contain numerous chemical compounds, including mineral particulates with phases such as quartz, cristobalite, and various carbonates, halides, and sulfates. Little is known about the health effects of particles emitted by biomass combustion (Naeher et al. 2007); they may be as serious as those associated with diesel-exhaust particulates (Corsini et al. 2013). A large-scale, European Union–funded research project (www.biocombust.eu) is currently tackling these important issues. In these and other aspects of the study of atmospheric particles, clearly we can say that "mineralogy matters."

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Meet the Authors

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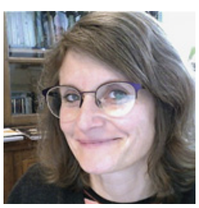
Mark J. Caddick is an assistant professor in the Department of Geosciences at Virginia Tech. His primary research involves unraveling the metamorphic history of subduction zones and orogenic belts by employing a variety of geochemical tools. He uses thermodynamic analysis and diffusion modeling to understand the mechanisms and rates of metamorphic evolution and decipher their primary driving forces. He received his PhD from the University of Cambridge before moving to ETH Zürich as a postdoc.

William D. Carlson is a professor and the P. T. Flawn Chair of Geology at the University of Texas at Austin, where he is also director of the High-Resolution X-ray Computed Tomography Facility. His current research combines petrological and geochemical observations with numerical simulation; the aim is to identify mechanisms of metamorphic reactions and processes and to quantify their rates, and thus to establish length scales and timescales of equilibration for rocks in the deep crust.



Laurence Galoisy is an associate professor of mineralogy at the Université Pierre et Marie Curie in Paris, where she conducts research at the Institut de minéralogie et de physique des milieux condensés. She completed her PhD at the Université Paris–Diderot in 1991 and was a postdoctoral fellow at SUNY Stony Brook in 1992. Her research focuses on structure–property relationships in minerals and glasses, using (micro)spectroscopic techniques (i.e. optical absorption spectroscopy at high pressure and temperature, X-ray absorption spectroscopy), with an interest in geochemical, industrial, and archeological applications. She has been an associate editor of *American Mineralogist* and a member of the Beam Time Allocation Panel at ESRF.

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Ekaterina S. (Kate) Kiseeva received her PhD in experimental petrology from the Australian National University in 2012. Her research interests include high-pressure mantle geochemistry, metasomatism in the cratonic mantle, upper- and lower-mantle inclusions in diamonds, and phase relations in the mantle transition zone. Currently, as a postdoctoral researcher at the University of Oxford, she studies the behavior of chalcophile elements in mantle processes and during Earth's accretion and differentiation.

Matthew J. Kohn is a University Distinguished Professor of Geosciences, Boise State University, Idaho, USA. Unlike Robert Frost (*The Road Not Taken*), his research simultaneously travels two divergent paths: one in metamorphic petrology/tectonics (PhD 1991, Rensselaer Polytechnic Institute), the other in paleoecology/paleoclimatology. His work on continent–continent collisions uses the major and trace element geochemistry of minerals like garnet to recover quantitative P–T evolution, and trace element thermometry and geochronology of accessory minerals to recover T–t histories. His work on Cenozoic climatological and ecological anomalies and transitions emphasizes the stable isotope geochemistry of fossil teeth. He is never, ever bored!

Andrew K. Matzen is a postdoctoral researcher in the experimental petrology group at the University of Oxford. His interests include the formation and evolution of magmas on the Earth and Mars. His research focuses on linking the compositions of primary magmas, and their early-crystallizing phases, to the compositions and conditions of the mantle sources that melted to produce these magmas. He received his PhD from the California Institute of Technology in 2012.

Erik E. Scherer is a professor of isotope geochemistry at the Institut für Mineralogie, Westfälische Wilhelms-Universität Münster. He received his BA degree in geology from Colgate University and his PhD in geochemistry from the University of California–Santa Cruz. His current research interests include the early differentiation of Earth, Moon, and Mars, the growth of continental crust, the evolution of the lower crust, and the fractionation of trace elements during eclogite and blueschist formation in subduction zones. He also strives to improve geochronology through the recalibration of decay constants and the development of specialized microsampling and analytical methods.

Bernard J. Wood is a research professor in the Department of Earth Sciences, University of Oxford. He previously held positions at Northwestern University, the University of Manchester, and the University of Bristol. His research interests are in the application of high-pressure, high-temperature experiments towards understanding the structure and evolution of the Earth. During his career he has applied experiments to problems such as the thermodynamic properties of minerals, geobarometry and geothermometry, the nature of the seismic discontinuities in the mantle, and the factors controlling crystal–melt partitioning of trace elements. Currently his principal interest is the accretion and differentiation of the Earth.


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