Ophiolites and their Origins

Immobile Element Fingerprinting

Records of Ocean Growth and Destruction in the Oman–UAE Ophiolite

Izu-Bonin-Mariana Forearc as a Modern Ophiolite Analogue

Deep Biosphere Record of Oceanic Lithosphere and Ophiolites

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Ophiolites

Guest Editors: Yildirim Dilek and Harald Furnes

Ophiolites and Their Origins

Yildirim Dilek and Harald Furnes

Immobile Element Fingerprinting of Ophiolites

Julian A. Pearce

Records of Ocean Growth and Destruction in the Oman-UAE Ophiolite

Kathryn M. Goodenough, Robert J. Thomas, Michael T. Styles, David I. Schofield, and Christopher J. MacLeod

Izu-Bonin-Mariana Forearc Crust as a Modern Ophiolite Analogue

Osamu Ishizuka, Kenichiro Tani, and Mark K. Reagan

Deep Biosphere Record of In Situ Oceanic Lithosphere and Ophiolites

Hubert Staudigel, Harald Furnes, and Mark Smits

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About the Cover: Pillow lavas, hyaloclastic rocks, and dike swarms of basaltic andesite composition in the Akaki River Canyon along the northern edge of the Troodos ophiolite, Cyprus. Dikes with chilled margins on one side or both sides intrude into and feed these pillow lava flows, which make up the uppermost eruptive units in the Troodos extrusive sequence (width of view 60–65 meters). Photo courtesy of Leo Puech, Research School of Earth Sciences, Australian National University, Canberra, Australia.
The Mineralogical Society of America (MSA) is an international organization founded in 1919, the Society promotes, through education and research, the understanding and appreciation of minerals and mineralogy. Founded on March 21, 1908, to foster cooperation in the advancement of mineralogy, petrology, and geochemistry. The Society was founded on March 21, 1908, by professionals from the United States and Canada. The International Association of Geoanalysts (IAGC) was founded in 1955 for students and educators to advance the study of meteorites and extraterrestrial material and their parent asteroids, comets, and planets. Members receive our journal, Meteoritics & Planetary Science, reduced rates for Geochimica et Cosmochimica Acta and related disciplines. Membership benefits include receiving the European Journal of Mineralogy, and the EWS (European Journal of Mineralogy and Geochemistry). The Polish Society of Mineralogy (PISM) was founded in 1969, draws together researchers and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The Society promotes links between earth scientists and academia, and promotes research and education through annual conferences, field trips, invited lectures, and lab tours. Membership benefits include subscriptions to Minerals and Elements.

The Meteoro logical Society is an international organization founded in 1933 for scientists, educators, and students working in mineralogy, petrology, and geochemistry, and to promote the study of meteorites and extraterrestrial material and their parent asteroids, comets, and planets. Members receive our journal, Meteoritics & Planetary Science, reduced rates for Geochimica et Cosmochimica Acta and related disciplines. Membership benefits include receiving the European Journal of Mineralogy, and the EWS (European Journal of Mineralogy and Geochemistry). The Polish Society of Mineralogy (PISM) was founded in 1969, draws together researchers and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The Society promotes links between earth scientists and academia, and promotes research and education through annual conferences, field trips, invited lectures, and lab tours. Membership benefits include subscriptions to Minerals and Elements.

The Mineralogical Society of Britain and Ireland is an international organization for those working in the mineral sciences. The Society was founded in 1955 to advance the knowledge of the science of mineralogy and to publish relevant scientific papers on crystallography, geochemistry, petrology, environmental studies, and economic geology. The Society holds an annual meeting, an annual symposium, a biennial conference, and publishes Mineralogical Record, a peer-reviewed journal. The Society is incorporated with the primary purpose of disseminating research and disseminating information to all aspects of clay science and technology. CMS holds annual meetings, workshops, and field trips, and publishes Clays and Clay Minerals, a peer-reviewed journal. The Society is incorporated with the primary purpose of disseminating research and disseminating information to all aspects of clay science and technology. CMS holds annual meetings, workshops, and field trips, and publishes Clays and Clay Minerals, a peer-reviewed journal. The Society is incorporated with the primary purpose of disseminating research and disseminating information to all aspects of clay science and technology. CMS holds annual meetings, workshops, and field trips, and publishes Clays and Clay Minerals, a peer-reviewed journal. The Society is incorporated with the primary purpose of disseminating research and disseminating information to all aspects of clay science and technology. CMS holds annual meetings, workshops, and field trips, and publishes Clays and Clay Minerals, a peer-reviewed journal.

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The German Mineralogical Society (DGG) is an international organization founded in 1924 by professionals from Germany. The DGG promotes links between earth scientists and academia, and promotes research and education through annual conferences, field trips, invited lectures, and lab tours. Membership benefits include subscriptions to Minerals and Elements.

The Polskie Towarzystwo Mineralogiczne (Polish Society of Mineralogy) was founded in 1928. JAMS covers the wide field of mineral sciences, geochemistry, and petrology. Membership benefits include receiving the Journal of Mineralogical and Petrological Sciences (JMP) and Tschermak's Mineralogische Zeitschrift.

The Japan Association of Mineralogical Sciences (JAMS) was established in 2007 by merging the Mineralogical Society of Japan, founded in 1915, and the Japanese Association of Mineralogists, Petropologists, 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 (JMP) and Tschermak’s Mineralogische Zeitschrift (TMZ).
PLAYTHINGS VERSUS THE KILLER ROCK?

What could be stranger than a rock you can weave into cloth and liquid metal you can hold in your hand? Both of these useful materials were common playthings for children (and adults) not long ago, but we know more about their health effects now. Mercury chemistry is complex and methyl-mercury can do more than make you “mad as a hatter.” It can kill you. Likewise, “asbestos” refers to a range of minerals, some forms of which are more harmful than others and can be lethal if inhaled in sufficient quantities.

The regulatory response is mixed. Mercury use has declined, but the metal continues to pour into the environment, principally from burning coal. Other significant sources include small-scale gold production and, bizarrely, the cremation of bodies with mercury-amalgam tooth fillings. In contrast, six asbestos minerals are tightly regulated in the U.S. and billions are spent in asbestos removal of questionable value. Arguably, mercury is under-regulated and one form of asbestos (chrysotile) is probably overregulated. Basic mineralogical facts about asbestos are commonly confused. Few in the general public can distinguish one fibrous mineral from another. This was demonstrated in 2010 by the misinformed attempt to brand serpentinite “the killer rock” and dethrone it as the state rock of California. Geoscientists have an important role in this debate. These materials have been discussed before in Elements, most recently in the Serpentinites issue (Guillot and Hattori 2013), as having other natural materials occurring in the environment. Also, American Mineralogist has published a virtual special issue on asbestos, and the Mineralogical Society of America has crafted an asbestos “policy statement” (www.minsocam.org/msa/policy.html?policy=Asbestos).

Chrysotile is widely recognized by its silky, asbestiform fibers, which lend themselves to weaving fire-resistant cloth, but as most readers of Elements are aware, it is only one of the minerals in the serpentine group, and many other minerals can also occur with an asbestiform habit, including amphiboles. The regulatory definition of asbestos is confused and based only on shape, often ignoring chemistry (see Gunter 2009, 2010). One accepted regulatory definition is based on the so-called aspect ratio and considers a mineral to be a fiber if it is more than 3 times longer than it is wide. Thus a small, brick-shaped mineral grain might be considered a fiber if it is more than 3 times longer than it is wide. Such a small, brick-shaped mineral grain would be considered a fiber. This lapse is serious. Numerous epidemiological studies have strongly linked amosite and crocidolite (fibrous grunerite and riebeckite, respectively) to asbestosis, lung cancer, and mesothelioma (see Ross and Nolan 2003; Plumlee et al. 2006), while erionite (fibrous zeolite, currently unregulated) has been related to mesothelioma in Turkey. However, studies where chrysotile occurs in the absence of amphiboles have shown a less well-established link. Ross and Nolan conclude that chrysotile health risks are low and “indistinguishable from risks associated with substitute materials such as fiberglass, rock wool and various composites.”

Mineralogists can also help guide safe mineral extraction. Harmful amphibole asbestos is only sometimes found in serpentinities, where it occurs especially at intrusive contacts with other rock types and can be avoided during mining, if identified. Likewise, fibrous serpentine and amphibole typically form due to shearing or dilation, and areas of concern are predicted by geological setting.

This issue of Elements is dedicated to ophiolites, the most common source of chrysotile asbestos. How do these rocks form and where do we find them? What tectonic secrets do they reveal? Much has been learned since the first Penrose definition of an ophiolite. Multiple tectonic settings are now recognized and are summarized in this issue, and a geochemical basis is presented for their identification. The classic localities of Oman and the Izu-Bonin-Mariana arc are described in detail. This issue also reports on the discovery of diamonds and an amazing array of reduced and exotic minerals in chromitites from several ophiolites. The alteration of basaltic glass in ophiolites is discussed before in Elements, most recently in the Serpentinites issue (Guillot and Hattori 2013), as having other natural materials occurring in the environment. Also, American Mineralogist has published a virtual special issue on asbestos, and the Mineralogical Society of America has crafted an asbestos “policy statement” (www.minsocam.org/msa/policy.html?policy=Asbestos).

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Plumlee GS, Morman SA, Ziegler TL (2006) The toxicological geochemistry of earth materials: An overview of processes of the interdisciplinary methods used to understand them. Reviews in Mineralogy & Geochemistry 64: 5-57


John Valley (valley@geology.wisc.edu), principal editor in charge of this issue

Tailings from the Vermont Asbestos Group chrysotile mines at Belvidere Mountain, Vermont. Photo by André Lalande, provided by M. E. Gunter.
THIS ISSUE

When starting work on this issue, I checked the definition of ophiolites in the Glossary of Geology, third edition (1990): a group of mafic and ultramafic igneous rocks ranging from spilitite and basalt to gabbro and peridotite, including rocks rich in serpentine, chlorite, epidote, and albite derived from them by later metamorphism, whose origin is associated with an early phase of development of a geosyncline. The term was originated by Steinmann in 1905. Although this definition in the Glossary of Geology was in serious need of revision, still it reminds us that the plate tectonic revolution is just a little over 40 years old, and as an undergraduate student I learned about eugeosynclines and miogeosynclines. The study of ophiolitic sequences has been key to improving our understanding of plate tectonics. The fascinating story of ophiolites has become more complex with time, and is told here by Guest Editors Yildirim Dilek and Harald Furnes and their co-authors. We are fortunate to have a perspective by Robert Coleman, one of the convenors of the famous 1972 Penrose field conference where a consensus definition of ophiolite was reached. Also, my colleague Jean Bédard brings his Appalachian perspective.

If, like me, you are not too familiar with the classification of ultramafic rocks, you might find this ternary diagram useful while delving through these articles.

BREAKING NEWS: INCOMING EDITOR 2015–2017

We are thrilled to announce that Bernie Wood has accepted the invitation to join the Elements editorial team, starting in January 2015. He will replace John Valley whose term of office ends on 31 December 2014. We will introduce him more formally at a later date.

ELEMENTS AT GOLDSCHMIDT

Our next editorial meeting will be held in Sacramento, USA, on June 8, immediately prior to the Goldschmidt Conference. This yearly face-to-face meeting is extremely valuable as it gives us an opportunity to discuss in depth various aspects of Elements. Traditionally we invite the incoming editor to attend the meeting as it is a great way to get an overview of how Elements functions. One of our main tasks is discussing the proposals we have received for future issues of the magazine.

The Goldschmidt Conference will feature a two-day union session entitled “Elements: 10 Years Old” on Monday and Tuesday, June 9 and 10. This session will cover the three fields reflected by the magazine over its 10 years of activity, geochemistry, mineralogy, and petrology, and will also include contributions dedicated to societal/cultural aspects. The talks will illustrate the great diversity of topics treated over the years and will emphasize major progress made since the publication of some of the early themes. This will be done in the philosophy of the magazine, that is, combining cutting-edge research with accessibility to a nonspecialist audience. This session will also be an occasion for delegates to discuss expectations concerning the magazine with the editorial team. The talks (19 of which are keynote lectures) will all be 30 minutes long. Elements will also have a booth (#43) at the conference, so please drop by.

CALL FOR PROPOSALS – THEMATIC TOPICS 2016

You think your area of research would make a great issue of Elements? Consider submitting a proposal. At our editorial meeting, we will discuss all proposals we have on hand and will slate six for 2016. The selected proposals will strike a balance among petrology, mineralogy, and geochemistry, and will be the most exciting and pertinent for Elements’ audience. You can download the proposal form at www.elementsgeoscienceworld.org/proposal.htm.

ELEMENTS AND GEOSCIENCEWORLD

GeoScienceWorld (www.geoscienceworld.org) is an aggregate of society-run Earth science journals. Since its launch in 2005, its number of subscribers has steadily grown and many new journals and features have been added. This past year, it launched OpenGeoSci, a free, public, map-based interface that allows users to search for maps, cross sections, charts, tables, figures, and data from GeoScienceWorld publications. Check it out at www.opengeosci.org.

Elements became part of GeoScienceWorld in December 2007, and it has done very well every year. If your institution subscribes to GSW, make sure you get your students or colleagues to download the articles they need from GSW (www.elements.geoscienceworld.org), as Elements is compensated every time a user from one of the GSW subscribers downloads a PDF or reads an HTML file. If your institution does not subscribe to GSW, encourage your librarian to request a free trial period (www.geoscienceworld.org), so you and your colleagues can try it out—it might be a welcome addition to your online resources. Finally, all the editorial content in Elements (book reviews; editorial, Triple Point, society news, etc.) is posted on GSW and is open access.

Pierrette Tremblay, Executive Editor

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ACADEMIA EUROPaea RECOGNIZES EARTH SCIENTISTS

Four Earth scientists were recently elected as members of the Academia Europaea (www.acadeuro.org). Academia Europaea, founded in 1988, is a European, non-governmental association acting as an academy, and has about 2800 members. It includes leading experts from the physical sciences and technology, Earth and environmental sciences, the biological sciences and medicine, mathematics, the letters and humanities, the social and cognitive sciences, economics and law. In addition to its workshops, conferences, and study groups, the academy provides expert advice on European science-policy matters. Our colleagues will be officially received during the presentation and induction ceremony of the academy in Barcelona, Spain, on July 16–18, 2014, on the occasion of its 26th conference.

Gilberto Artioli is a professor of mineralogy and crystallography in the Department of Geosciences at the University of Padova, Italy. His research interests include the relationships between the structure and properties of minerals and industrial phases, the application of advanced characterization techniques in materials science, and the investigation of cultural-heritage materials. He is currently the director of the CIRCe Centre for the study of cementitious systems.

Gordon Brown is the Kirby Professor of Earth Sciences, the chair of the Department of Geological & Environmental Sciences, and Professor (by courtesy) of Chemical Engineering at Stanford University, as well as Professor of Photon Science at SLAC National Accelerator Lab. His research and teaching focus on environmental chemistry/geochemistry and mineralogy, particularly the chemical behavior of heavy metals and actinides.

Elisabetta Erba is a professor of paleontology in the Department of Earth Sciences, University of Milan, Italy, where she investigates and teaches many aspects of Mesozoic calcareous nanoplankton. Through her research in high-resolution biostratigraphy and paleoecology, she has contributed to improving timescales and understanding biosphere-geosphere interactions, especially in paleogreenhouse worlds. Her studies on nanoplankton evolution and biomineralization have highlighted the role of excess CO$_2$, climate change, oceanic fertility, acidification, and anoxia on marine-ecosystem dynamics.

Alexander Sobolev is a professor of geochemistry and petrology at J. Fourier University, Grenoble, France, and a research fellow at Vernadsky Institute of Geochemistry, Moscow, Russia. His studies of melt inclusions in minerals and the composition of olivine phenocrysts in lavas have helped us to understand the scale, nature, and origin of mantle heterogeneity.

GEOLOGICAL ASSOCIATION OF CANADA AWARDS

The Geological Association of Canada recently announced its 2014 awards, which will be presented during its annual meeting. Among the awardees are several members of *Elements* participating societies.

Brendan Murphy, a professor of structural geology in the Department of Earth Sciences at St. Francis Xavier University, will receive the Ambrose Medal for sustained dedicated service to the Canadian Earth science community. Brendan has served on the University Partnerships in Cooperation and Development Program and on the NSERC Solid Earth Sciences Committee, and he has been chair of APICS and Science Atlantic, president of the Atlantic Geoscience Society, a leader on several IGCP projects, and an Earth science columnist for the *Cape Breton Post*. He is a current editor of *Geoscience Canada* and *Geology* and a past editor of the Geological Society of America Bulletin.

The Hutchison Medal for recent exceptional advances in Canadian Earth science research, will be awarded to Ali Polat of the University of Windsor, Canada. Ali received his BSc (1988) from Istanbul Technical University, MSc (1992) from the University of Houston, and PhD (1998) from the University of Saskatchewan. His main research interests include Archean greenstone belts, anorthosites, ophiolites, and accretionary complexes. He is editor in chief of the *Canadian Journal of Earth Sciences*.

The Duncan R. Derry Medal, the highest award bestowed by the Mineral Deposits Division of the association, is awarded annually to an economic geologist who has made significant contributions to the science of economic geology in Canada. The 2014 winner is Barbara H. Scott Smith of Scott-Smith Petrology Inc., North Vancouver, BC. After receiving her PhD in the UK and working for De Beers in South Africa, Barbara has been based in Canada as an independent consultant to worldwide diamond projects. In the last two decades she consulting increasingly focused on Canada during the emergence of its diamond industry. Barbara continues to share her expertise and undertake research through her own professional school of kimberlite petrology and as an adjunct professor at the University of British Columbia.

The Logan Medal, the highest award of the Geological Association of Canada, will be presented to Andrew Miall for sustained distinguished achievement in Canadian Earth science. Andrew has been a professor of geology at the University of Toronto since 1979. He specializes in sedimentary and petroleum geology and is the author of the book *Principles of Sedimentary Basin Analysis*. Andrew is a fellow of the Royal Society of Canada and served as president of the Academy of Science in 2007–2009.
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THE OPHIOLITE CONCEPT EVOLVES

Robert G. Coleman*

1811-5209/13/0010-0825$2.50 DOI: 10.2113/gselements.10.2.82

In 1949, little did I realize, as I began my PhD studies at Stanford University on the mineralogy of the New Idria serpentinite body in the Diablo Range of central California, that the ideas in my thesis (Coleman 1957) would become anachronistic. At the time I began my field work in New Idria, the Johns Manville and Union Carbide companies had begun open pit mining for short-fiber asbestos. Their operations exposed numerous tectonic inclusions of blueschist metamorphic rocks containing jadeite and glaucophane as well as small ophiolitic fragments. With these new exposures it became obvious that the New Idria serpentinite massif was not an igneous intrusion but instead consisted mostly of highly sheared mélangé within an elongate, diapiric dome protruding into an anticlinal fold in Mesozoic sediments! Today, this famous serpentinite massif is better described as the end product of tectonically destroyed ophiolite.

I was invited as a U.S. Geological Survey petrologist to spend a year with the New Zealand Geological Survey (1961–1962) to investigate numerous serpentinite bodies in that country, which are similar in many ways to those in California. The New Zealand field geologists at this time were actively pursuing 1:250,000-scale mapping of the country, and all rock identification studies were carried out by a small group of petrologists. Along some of the contacts of the serpentinites we found fine-grained, dense rocks (rodingites) resembling chilled igneous contacts; however, thin section studies revealed the presence of low-temperature calcium silicates, which were formed from calcium-rich, high-pH (11.5) fluids produced during the serpentinization of the peridotites. These relationships later reinforced my idea that serpentinites along continental margins could be tectonically transported and emplaced within suture zones.

In the decade (1960–1970) following my return to the USGS in Menlo Park, California, the plate tectonic revolution gained momentum and eager young professors and students of the various campuses of the University of California and Stanford produced new interpretations of California geology. The term ophiolite had been used to describe serpentinite associations in Europe and became the descriptor for tectonic fragments of oceanic crust found in California orogenic zones.

The papers in this issue of Elements are a demonstration of how Earth science research has benefited from the explosive high-tech revolution in geochemistry and geophysics. Each year brings new publications on field and laboratory studies of ophiolites from all parts of the world, leading to new facts and observations that modify prior interpretations.

The article by Dilek and Furnes (2014) includes a notable collection of current ideas concerning the ophiolite paradigm, which has developed into an essential element of plate tectonics. They describe variations in the internal structure, magma generation, geochemical fingerprints, and emplacement tectonics. They also attempt to produce a classification that extends beyond the original Penrose ophiolite field conference definition. They speculate on global tectonics and its effects on the generation and recycling of material in the upper mantle.

The lowest part of the mantle section is mostly tectonized ultramafic rocks consisting mainly of harzburgites, dunites, lherzolites, and minor chromitite. In most cases these rocks have deformational fabrics that distinguish them from the overlying layered mafic and ultramafic rocks. These deformed ultramafic rocks are generally considered the residue of partial melting and the source of the overlying layered rocks; however, there are instances where they are not related. The transition to the layered sequence is referred to as the Moho discontinuity and is easily located by geophysical means. These layered sequences are complex, with layered mafic and ultramafic rocks intruded by later magmas.

A sheeted dike complex characterized by subvertical diabase dikes with igneous textures overlies the plutonic sequence. Extrusive rocks in ophiolites consist of pillow lavas, pillow breccias, and massive lava flows, which range in composition from basalt and basaltic andesite at the bottom to andesite, dacite, and rhyolite at the top. Pelagic sedimentary rocks cover these volcanic rocks, and through their stratigraphy, they reveal their travel history within the oceanic lithosphere from ridge to trench.

Dilek and Furnes emphasize that basal tectonized peridotites are depleted mantle residues that have undergone various degrees and episodes of melt extraction from the original primitive mantle. They conclude that the mineralogy and geochemical compositions of crustal and mantle sequences in most ophiolites do not represent a simple melt–residue relationship.

Ophiolites are classified to the first order as subduction-related and subduction-unrelated types. Those ophiolites whose magmatic construction was not affected by subduction processes include continental margin, mid-ocean ridge, and plume-type ophiolites. They display large variations on the Th/Yb-Ta/Yb discrimination diagram. Subduction-influenced ophiolites include suprasubduction zone (SSZ) and volcanic arc (VA) ophiolites. Specific tectonic settings of SSZ oceanic-crust formation include the forearc, backarc, and incipient arc. The magmatic and geochemical evolution of SSZ and VA ophiolites may be controlled by the mode and nature of melting in the mantle and by dehydration of the subducting slab and the element flux from it into the overlying mantle.

The emplacement mechanisms of ophiolites are discussed using simple cross sections with possible geodynamic scenarios. Ophiolites are incorporated into continental margins through complex interactions of lithospheric plates. The age, thickness, and thermal state of oceanic lithosphere to be emplaced, the nature and geometry of plate boundaries involved, and the size and character (e.g. oceanic versus continental) of the interacting plates are among the most important factors controlling the dynamics of ophiolite emplacement mechanisms. Regardless of the nature of the tectonic setting of its magmatic development, subduction zone tectonics is an essential driver for incorporating preexisting oceanic lithosphere into continental margins. Detailed tectonic settings and examples of location are given: continental margin, Ligurian (Italy); mid-ocean ridge, Macquarie Island (New Zealand–Southern Ocean); suprasubduction zone, Oman; volcanic arc, Magnitogorsk, Urals. A north-polar projection showing the global distribution of Phanerozoic orogenic belts clearly shows that ophiolites are critical to understanding plate tectonic evolution. It seems that Pandora’s Ophiolite Box has not yet reached the bottom.

Goodenough and others (2014) show that the Oman–United Arab Emirates (UAE) ophiolite is the largest well-exposed ophiolite on Earth and perhaps the most studied. It has been divided into 12 separate, fault-bounded blocks; the northern three lie mostly within the UAE. The ophiolite in the UAE preserves clear evidence for two stages of magmatism. The earliest episode formed at a spreading center (Phase 1), and a later episode is associated with the onset of subduction (Phase 2). Similar two-stage magmatism has been recognized in the Oman sector, but the UAE contains the most voluminous suprasubduction zone mag-

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The IBM forearc illustrate a similar pattern: FAB erupted from a subduction zone within the southern Tethys. Recent results from more than 2000 km long belt and that it involved the simultaneous initiation of Cretaceous Tethyan SSZ ophiolites was nearly coeval along the more basalts predate boninitic rocks. The age distribution, combined with other authors to suggest that subduction of Arabian continental crust and buoyant uplift took place before ophiolite emplacement. These diverse opinions indicate that a generalized scenario may not be useful for the entire Oman ophiolite.

Ishizuka and others (2014) provide a comprehensive study of the Izu-Bonin-Mariana (IBM) forearc, an area measuring 300 km by 3000 km, and confirm its suprasubduction formation as oceanic crust developed in the initial stages of an island arc. The first volcanic products of the IBM arc are represented by forearc basalts (FAB), consisting mainly of pillow lavas and hyaloclastites. The central Mariana forearc shows a progression from FAB-like lavas at the bottom to nearly boninitic lavas on top, linking these two lava types in time and space. Sheeted dikes in the IBM show that some of the magmatism developed in an extensional stress field. These observations indicate that the first magmatic activity in the IBM arc was associated with sea-floor spreading. The peridotites at the lowest stratigraphic level of the IBM forearc section are dominated by harzburgite with dunite veins. Two distinct dunites in equilibrium with two distinct melts produced boninitic and mid-ocean ridge basalt (MORB). FABs from the Bonin forearc were dated at between 48 and 52 Ma by 40Ar/39Ar. The boninites and differentiates ranged from 46 to 48 Ma, and the arc tholeiites ranged from 35 to 47 Ma.

FABs were generated from clinopyroxene-impoverished residual mantle left after an earlier stage of decompression melting. Most FABs lack enrichment in large-ion lithophile elements (such as Ba, Sr, Pb) compared to rare earth elements and high-field-strength elements, implying that, like MORB, they have received little or no input of slab-derived material. Transitional and boninitic lavas share some geochemical characteristics with the FAB, such as low Ti, low HFSE contents, and very low Ti/V ratios. These geochemical features indicate a depleted mantle source for the magmas of the boninites and transitional lavas.

The boninites and related lavas within suprasubduction zone ophiolites in other worldwide locations are not uniform, and in general MORB-like basalts predate boninitic rocks. The age distribution, combined with their geochemical fingerprints, suggests that the development of the Cretaceous Tethyan SSZ ophiolites was nearly coeval along the more than 2000 km long belt and that it involved the simultaneous initiation of a subduction zone within the southern Tethys. Recent results from the IBM forearc illustrate a similar pattern: FAB erupted first, followed by transitional and then boninitic lavas.

To have been involved in the plate tectonic revolution was a learning experience on how to give up accepted ideas learned as a student.

Pearce's early studies produced a way of fingerprinting ophiolites, first using the immobile elements, namely Ti, Zr, Y, Nb, Cr, and V, and later using the elements Th, Ta, Hf, and Sc. New analytical methods (ICP-MS) have allowed analysis of the full spectrum of immobile elements, providing a powerful tool for estimating the magmatic and tectonic setting of ophiolites. In this issue, Pearce (2014) carefully presents the system he uses to geochemically classify ancient ophiolite magmas. He describes in detail the use of discriminant diagrams to fingerprint magmatic and possible tectonic settings. He first selects the least altered magmatic rocks (volcanic glass if possible) from each location and classifies them petrologically. Then ICP-MS analyses are done to identify the amount of each immobile element, and the results are plotted on discriminant diagrams. He shows that by examining the plotted patterns and comparing them to subduction proxies, one can distinguish between mid-ocean ridge and suprasubduction magmas. In addition, using a plume proxy, one can also define the setting of the mid-ocean ridge ophiolite.

Pearce emphasizes that immobile element fingerprinting of ancient ophiolites is fraught with difficulties as these rocks may have experienced intense alteration and important tectonic events, which may not be recorded in their magmatic history.

To have been involved in the plate tectonic revolution was a learning experience on how to give up accepted ideas learned as a student. Earth science research has a long history of evolving. Geologic mapping, satellite imagery, and geophysical prosves of the crust and mantle now provide a continuous flow of new factual data. High-tech instruments can rapidly reveal quantitative chemical and isotopic relationships within a single mineral grain. These collected papers illustrate how it is now possible to combine some of these new geotech methods to better understand large and small Earth systems. No longer is it possible for one person to produce all the micro- and megascale data required to advance the concepts of the ophiolite paradigm.

My studies of ophiolites have allowed me to carry out field investigations in many parts of the world and learn different approaches from other geologists. I organized the first Penrose Conference on ophiolites in 1972, some 180 years after European geologists introduced the term. Renewed interest in ophiolite sequences developed during this time as part of the new plate tectonic paradigm. During the Penrose Conference, there was no total agreement among the participants, who were divided between those who had studied North American ophiolites and those who had studied European ones within the ancient Tethyan ocean. Nevertheless, at the end of the meeting, the participants were able to produce a consensus definition for ophiolite that has been useful in providing guidelines for ongoing research. Most ophiolite occurrences are within active or ancient continental margins (sutures). The similarity of these allochthonous ophiolite bodies to oceanic crust stratigraphy was further confirmed by drilling and seismic imaging of the oceanic crust.

I introduced the term obduction to describe ophiolite emplacement in New Caledonia, Papua New Guinea, and Oman associated with older blueschist metamorphism. Recent studies in Oman show that the Saih Hatat ophiolite was thrust over older continental margin crust containing eclogites and blueschists, whose isotopic ages are older than the ophiolite rocks.

Recent reports of diamond and other ultrahigh-pressure minerals occurring as inclusions within Tibetan ophiolitic podiform chromitite with crustal isotope signatures have opened up a completely new aspect on the evolution of ophiolite mantle rocks within the lithosphere.
Direct evidence of crustal recycling of ophiolitic peridotites by subduction into the mantle will provide challenging research opportunities for the Earth science community. When did the Earth's oceans first develop ophiolite-like crust? Indeed it is probable that relict Archean oceanic crust is preserved in granite–greenstone–komatiite terrains or other Archean tectonic settings, but a complete Penrose-type Archean ophiolite has not yet been recognized as evidence for when subduction tectonics began. The presence of ophiolite mélanges with blueschist metamorphic rocks or UHP metamorphic rocks is necessary evidence.

Another unsolved problem concerns the evolution of new oceanic crust within rift setting passive margins. During my field mapping with the U.S. Geological Survey in Saudi Arabia, we discovered an igneous complex of sheeted dikes, layered gabbro, granophyre, and basaltic–rhyolitic lava on the southeast margin of the Red Sea, which we called the Tihama Asir complex. These rocks were intruded parallel to the present-day axis of the Red Sea and were related to early Tertiary (20–24 Ma) continental extension. Tholeitic magma intruded along faults and fractures in rifted continental crust, forming extensive dike swarms and layered gabbroic plutons, along with associated silicic intrusive bodies derived from partial melting of the continental crust. During the Pliocene to Miocene, evaporite deposits up to 3 km thick accumulated on the extended Red Sea Basin and are coeval with the Mediterranean salinity crisis. A major unconformity in the basin at 5 Ma marks the end of salt deposition and the beginning of axial seafloor spreading, and listric faulting along the axial trough was accompanied by the deposition of thick continental clastics. The Tihama Asir complex has MORB affinities similar to oceanic crust except that it was injected into old continental crust. More work needs to be done to understand the transition from continental to oceanic crust. The problem that remains is what geochemical and/or structural criteria can be used to distinguish between oceanic ridge and continental margin settings of ophiolites.

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Robert G. Coleman is Professor Emeritus of Geological & Environmental Sciences at Stanford University, where he was previously a professor (1982–1993). Earlier, he was a geologist at the U.S. Geological Survey in Menlo Park, California (1954–1982). Bob earned his BS (1948) and MS (1950) degrees in geology at Oregon State University and his PhD in geology at Stanford University (1957). His PhD thesis (Mineralogy and Petrology of the New Idria District) is now considered a classic and involved a detailed field and laboratory study of the New Idria serpentinite massif and its tectonic inclusions. Bob's thesis work showed that serpentinites are not igneous intrusives but instead are tectonically emplaced pieces of ocean lithosphere. This work also laid the groundwork for his seminal studies of ophiolites.

Bob’s research interests include blueschist and eclogite metamorphism of high-pressure/low-temperature terrains, the petrology of ophiolites, and the tectonics of accreted terrains. He has worked in China, western North America, Oman, and Mongolia. He has also served as a consultant in environmental geology and has been involved in environmental studies on the asbestos Superfund site at New Idria, California. Bob was elected to the U.S. National Academy of Sciences in 1980.
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Ophiolites: Perspectives from Fieldwork in the Appalachians

Jean H. Bédard*

1811-5209/13/0010-087$2.50 DOI: 10.2113/gselements.10.2.87

I love ophiolites. They contain a huge variety of rocks, preserved and arrayed on a scale that makes every outcrop a possible discovery site! Had I the option, I would spend the rest of my career investigating the Bay of Islands Complex in Newfoundland, where the rocks wait for someone who has the patience to listen to their story.

Oceanic crust formed by seafloor spreading covers about 75% of Earth’s surface but is difficult to access. Submersible expeditions and ocean drilling yield valuable but expensive and necessarily limited views. Ophiolites preserve oceanic lithosphere on land, which allows a more complete perspective to be developed as the rocks can be mapped and examined in the field. The Canadian Appalachians are richly endowed with Ordovician ophiolites preserved by the closure of the Iapetus Ocean. Research on these rocks not only helps us to understand how Earth’s biggest magmatic system operates, but contributed to the development of plate tectonic theory by providing unambiguous evidence of the existence of ocean basins destroyed by subduction. Since ophiolites represent the only record of pre-180-million-year-old oceanic crust, their presence in the deep past is eagerly sought, as recognition of oceanic lithosphere formed by seafloor spreading could constrain when plate tectonics began on Earth.

Ophiolites are challenging to work on because a huge diversity of geological expertise is required. Every facet of igneous petrology and geochemistry is needed to understand how magma is expelled from the mantle source (melting reactions, melt-segregation physics), how it passes through the crust (intrusive mechanisms), how it differentiates there (fractional crystallization, host assimilation, cumulate processes, crystal/melt segregation mechanisms), to finally erupt on the seafloor where geochemists can sample and analyze the lavas so as to better understand mantle and bulk-Earth evolution. But structural and metamorphic geology are necessarily equal, since ridge magmatism is necessarily synkinematic. The brittle carapace is dissected by multiple generations of faults, which act as conduits for circulating seawater (Alt and Teagle 2000), locally generating economic Cu-Zn-Pb sulfide deposits. The faults root into the deeper crust as ductile and brittle-ductile shear zones, which facilitate penetration of seawater into the deep crust (Schroetter et al. 2003) but which also guide movement of magma, providing opportunities for the assimilation and/or reheating of hydrothermally altered host rocks (Fig. 1; Bédard et al. 2000; Koepke et al. 2007). The ductile plutonic crust of some ophiolites is plastically deformed, generating textures that are more akin to metamorphic granulites than they are to continental layered-intrusion cumulates (Fig. 1; Nicolas and Poliakov 2001). Oobduction- and post-obduction-related structures also need to be recognized and understood (e.g. Schroetter et al. 2005), otherwise the geometry of pre-obduction rocks and fabrics cannot be reconstructed. Associated sedimentary rocks provide age and paleogeographical constraints (e.g. Robertson 2002), and may be the only record of nearby eroded terrains. In some ophiolites the sedimentary rocks record obduction and erosion of the very ophiolite upon which they were deposited, forming piggyback basins! It is the integration of these different disciplines that makes the study of ophiolites so powerful, yet oh so challenging!

Ophiolites come in various styles, reflecting variations of magma type, relative rates of magma delivery versus tectonic extension, and a fluctuating and heterogeneous crustal rheology (e.g. Harper 1985). Although many well-studied ophiolites formed from tholeiitic melts, yielding cumulates with a typical olivine-plagioclase-clinopyroxene sequence of crystallization (= dunite–troctolite–olivine gabbro), others formed largely from boninitic melts (Kim and Jacobi 2002) with an olivine-pyroxene-plagioclase crystallization sequence, yielding different cumulate parageneses (= dunite–wehrlite/harzburgite–websterite–gabbrodiorite); boninitic melts are responsible for many chromitite deposits. Church (1977) called these boninite-dominated ophiolites “oceanic crust of Betts Cove type.” Mixed types are common: Thetford Mines boninitic lavas overlie tholeiites (Schroetter et al. 2003), Bay of Islands tholeiitic gabbros are underplated by boninitic cumulates (Bédard 1991, 1993), and Betts Cove tholeiitic lavas overlie boninites (Bédard 1999).

Because a given segment of crust typically requires many thousands of years to drift away from the axial melt-delivery zone, it experiences multiple magmatic/deformation/hydrothermal events. As long as it is above the axial zone, new magma is constantly arriving from below to rejuvenate the system, which is cooled by seawater circulation through the brittle carapace. Ophiolites formed at slow-spreaing ridges or through episodic magmatism typically show intense and deeply penetrating hydrothermal overprints (Fig. 1), since ephemeral melt delivery from the mantle allows complete crustal rigidification between melt pulses. In contrast, higher and more constant melt delivery to fast-spreaing ophiolites like Oman (Nicolas et al. 2003) may limit water penetration and keep parts of the lower crust at near-solidus temperatures for much longer, until the ridge segment has drifted away from the axial melt-delivery zone.

Where multiple intrusive and deformation events are preserved, older metamorphosed relics adjoin less-perturbed younger intrusions. At Annieopsquotch (central Newfoundland), the undeformed sheeted gabbroic sills of the middle crust are the cumulate counterpart of the lavas (Lissenberg et al. 2004), but are underlain by a heterogeneous domain where strongly deformed older rocks, some with a boninitic parentage, occur as basalt-metasomatized enclaves embedded in undeformed tholeiitic gabbros (Bédard 2014). The study of such complex ophiolites becomes much like the study of an orogen, with relative chronologies needing to be developed for the different intrusive and deformation events.

Geochronological studies of oceanic basalts are much used to infer mantle composition and evolution, yet few oceanic-ridge basalts are in equilibrium with plausible mantle compositions, requiring a correction for intracrystal differentiation. Ideal fractional crystallization is implicit in most such inversions. The study of ophiolitic magma chambers provides a sobering wake-up call here. The Bay of Islands plutonic crust records pervasive reworking of older cumulates by younger melt pulses; this results in the common development of hybrids between host gabbros...
and intrusive olivine-saturated magmas and of monomineralic anorthositic, chromitite, pyroxenite) at intrusive contacts, as Bowen’s reaction series column, with melts mixing, reacting, and equilibrating with older host cumulates en route to the surface. This implies that lava chemistry cannot be inverted unambiguously since differentiation paths are non-unique.

How mantle melts differentiate within the oceanic crust is much debated. Some believe that ascending primary melt pools below the brittle—rupture points to form the middle and lower crust (Nicolas et al. 2009). Another class of models posits mixing, reacting, and equilibrating with older host cumulates en route to the surface. This implies that lava chemistry cannot be inverted unambiguously since differentiation paths are non-unique.

In the lower ophiolite crust, boundaries between igneous, metamorphic, and structural geology necessarily blur, and cross-fertilization between disciplines is the name of the game. The variety and dynamic nature of Earth materials is what makes ophiolites such superb natural laboratories. They will undoubtedly yield many more important and surprising discoveries about the processes by which oceanic lithosphere is formed, deformed, and preserved. 

Jean Bédard has been studying ophiolites since 1988, the year he joined the Geological Survey of Canada. He works on magmatic differentiation processes, trace elements, large igneous provinces, and Archean tectonics.

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Yildirim Dilek is a professor of geology at Miami University and the vice president of the International Union of Geosciences (IUGS). He received his PhD from the University of California in structural geology and tectonics. He has worked extensively on the structure, geochemistry, and tectonics of the Phanerozoic ophiolites in the Alpine–Himalayan, North American Cordilleran, and Caledonian orogenic belts and of the modern oceanic lithosphere under the Mid-Atlantic Ridge and the Costa Rica Rift. His other research interests include Precambrian tectonics, mantle dynamics, and magmatism in collisional orogenic belts. Recently, he has been spending much time in Tibet and China exploring their fascinating geological landscapes.

Harald Furnes has been a professor in the Department of Earth Science, University of Bergen, Norway, since 1985. He received his D Phil from Oxford University, UK, in 1978. His main research involves the physical volcanology, geochemistry, and petrology of basaltic rocks in ophiolites, island arcs, oceanic islands, and continental flood basalts provinces ranging in age from recent to Archean. During the last 12 years his main research efforts have focused on Precambrian greenstones, in particular those in the Paleoarchean Barberton greenstone belt. In addition, he has been investigating the alteration of volcanic glass, specifically the microbial alteration of submarine basaltic volcanic rocks and the traces of early life.

Kathryn M. Goodenough is a senior geologist at the British Geological Survey. After completing a PhD in igneous petrology and geochemistry in 1997, she broadened her research into the field of crustal evolution. She was part of a BGS team that mapped the Oman–UAE ophiolite in the United Arab Emirates (UAE) between 2002 and 2006 and has continued to work in the UAE and Oman since. Her research investigates the role of subduction in a range of processes, including the formation of the early continental crust, the generation of alkaline magmatism and associated mineralization, and the initiation of subduction zones as recorded in ophiolites.

Osamu Ishizuka is a senior researcher at the Geological Survey of Japan/AIST and an invited researcher at IFREE, JAMSTEC. He completed a master’s degree and a PhD at the University of Tokyo, Japan, in economic geology, geochemistry, and marine geology, and then held a post-doctoral position at the University of Southampton. His specialties are Ar/Ar geochronology and igneous geochemistry. He is currently working on subduction-initiation processes along the Izu-Bonin-Mariana arc system. He is also interested in magma transport within the crust in active island arc volcanoes. He will serve as a cochief scientist for the IODP (International Ocean Discovery program) Expedition 351 in 2014.

Chris MacLeod is professor of geology in the Cardiff University School of Earth and Ocean Sciences (UK). His principal scientific interests deal with the formation and deformation of ocean lithosphere at submarine spreading centers and on the mechanisms of intraoceanic subduction initiation. He investigates these processes by conducting observation-based, multidisciplinary, mesoscale geological studies of ophiolite complexes and the modern ocean floor. For his PhD, under Ian Gass at the Open University, he undertook some of the primary investigations of the southern Troodos transform fault zone in the Troodos ophiolite of Cyprus. For the subsequent 25 years he has worked on the Oman ophiolite.

Julian Pearce is a professor of geochemistry in the School of Earth and Ocean Sciences at Cardiff University. He received a BA in mineralogy and petrology from the University of Cambridge and a PhD from the University of East Anglia. His current work includes the development of new methodologies for the geochemical fingerprinting of rocks and the application of these methodologies to topological problems such as the understanding of Archean tectonic environments. This work has also led to a continuing interest in dredging and drilling the ocean floor, and he will be cochief scientist on the upcoming IODP Expedition 352 to the Izu-Bonin-Mariana forearc.

Mark K. Reagan is a professor in the Department of Earth & Environmental Sciences at the University of Iowa, USA. He received his PhD from the University of California, Santa Cruz, in 1987. His primary research involves the use of field relations, petrology, and geochemistry to investigate the origin and evolution of subduction-related magmas. One research focus since the 1980s has been on collecting and analyzing rocks from the Izu-Bonin-Mariana forearc islands and ocean floor to investigate subduction initiation and the early development of the arc system. He also uses U-series nuclide abundances to investigate the rates and timescales of magma generation, differentiation, and degassing in different tectonic settings.

Paul T. Robinson is an honorary professor at the Chinese Academy of Geological Sciences, Beijing, and the China University of Geosciences (Wuhan). He received a PhD from the University of California, Berkeley. He was a professor at Oregon State University and the University of California, Riverside, before moving to Dalhousie University, Halifax, Canada. He is a fellow of the Geological Society of America and recipient of the Michael J. Keen Medal of the Geological Association of Canada. His major interests include the origin and evolution of oceanic lithosphere. He has worked on many ophiolites, and on the wide variety of unexpected minerals in them.

David I. Schofield is a principal geologist and chief geologist for Wales at the British Geological Survey. He is also a key member of the team that mapped the northern section of the Oman–UAE ophiolite in the UAE between 2002 and 2006 and is now involved in extending that research into Oman. His wider research focuses on investigating accretionary processes and paleogeographic evolution, particularly relating to Rodinia dispersal and Pangea assembly. He has worked on a range of major international projects in collisional tectonic zones, such as the Pan-African (Mauritania, Madagascar). He is currently science editor for the Geological Society of America Bulletin.

Mark Smits is a postdoctoral fellow at Hasselt University, Belgium. He received an MSc in biology and a PhD in soil science and geology from Wageningen University (the Netherlands). He did his PhD on “rock-eating” mycorrhizal fungi. Thereafter, at the University of Sheffield (UK) and Lund University (Sweden), he continued working on fungus-induced weathering on scales ranging from nanometer fungus–mineral interactions to plant and ecosystem processes. Currently he is working on the role of mycorrhizal fungi in soil carbon dynamics.
Hubert Staudigel is a senior scientist at the Institute for Geophysics and Planetary Physics of Scripps Institution of Oceanography at the University of California in San Diego. His current research focuses on seamount science and the geomicrobiology and geochemistry of water–rock interaction.

Michael T. Styles is a principal geologist at the British Geological Survey. After completing a PhD at Manchester University and postdoctoral research at Oslo University, he joined the Mineralogy and Petrology Group at BGS. He has longstanding research interests in mafic and ultramafic rocks and their mineralization. He has studied many ophiolites, including those in the UK, and during the last 10 years has worked on regional mapping and economic geology applications in the Oman–UAE ophiolite. He led the UAE mapping project carried out by the BGS between 2002 and 2006. He is currently involved in studies of the carbonation of ultramafic rocks as a possible method of CO₂ sequestration.

Kenichiro Tani is a researcher at the Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology (JAMSTEC). He received a BS in geology and a MS in Earth and planetary science from the University of Tokyo and a PhD in geosciences from the Yokohama National University. Since joining JAMSTEC in 2002, he has collaborated with Osamu Ishizuka in sampling and surveying the islands and ocean floor of the western Pacific. In this project, he focuses on determining the precise timing of tectonomagmatic processes in the intraoceanic Izu-Bonin-Mariana arc system using zircon U–Pb geochronology measured with a sensitive high-resolution ion microprobe (SHRIMP).

Robert J. Thomas is a principal geologist at the British Geological Survey. After obtaining his PhD in 1978, he worked at the Council for Geoscience, South Africa, until 2003. In this period he worked extensively on large mapping and research projects in South Africa, Antarctica, the Falkland Islands, Gabon, Morocco, Mozambique, and the UAE, including work on the Mesoproterozoic Tugela ophiolite in southern Africa and part of the Oman–UAE ophiolite. In 2002 he joined BGS to manage several regional mapping projects in East Africa and was a member of the team that mapped the UAE part of the UAE–Oman ophiolite in great detail.

Jingsui Yang is a professor at the Institute of Geology, Chinese Academy of Geological Sciences, in Beijing. He received his PhD from Dalhousie University, Canada, in 1992. He has been working on ophiolites for many years, particularly on high-pressure minerals in mantle rocks, as well as on ultrahigh-pressure metamorphic rocks in paleo-subduction zones on the Tibetan plateau and in other orogenic belts. He is a recipient of the Award of Scientific and Technological Process from the HLHL foundation in Hongkong and the LiShiguang Award in China. He is a fellow of the Mineralogical Society of America and the Geological Society of America.

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Ophiolites and Their Origins

Yildirim Dilek¹ and Harald Furnes²

INTRODUCTION

Ophiolites are the remnants of ancient oceanic crust and upper mantle that were tectonically emplaced into continental margins. They display the only evidence for magmatic, tectonic, and hydrothermal processes associated with seafloor spreading prior to 170 Ma because no oceanic lithosphere older than this age is preserved in the modern oceans. The occurrence of sheeted dikes, side-by-side tabular intrusions of magma, is the primary evidence for the seafloor spreading origin of ophiolites. Ophiolites are therefore the best archives of the evolutionary history of ocean basins from their rift–drift and seafloor spreading stages to subduction initiation and final closure. Their recognition as structural analogues for oceanic crust played a significant role in the advancement of the plate tectonic theory in the 1960s, and geoscientists have used ophiolites in investigating the nature of mid-ocean ridge processes, mantle chemistry, the paleogeography of ancient ocean basins, and the tectonic evolution of orogenic belts.

Brongniart’s (1821) early definition of an ophiolite was based on a suite of ultramafic, gabbroic, diabasic, and volcanic rocks in the Italian Apennines. Subsequently, Steinmann (1927) noted the common occurrence of serpentinite, basalt, and chert (“Steinmann’s Trinity”) in the Mediterranean mountains, and interpreted their origin as differentiated, ocean-floor magmatic units. The Dutch geologist de Roever (1957) and then the Swiss geologist Vuagnat (1964) argued that the association of these rocks was a result of mantle melting, which produced basaltic rocks on top and residual peridotites at the bottom.

By the mid-1960s, the recognition of sheeted dike complexes, fossil magma chambers in plutonic sequences, and refractory harzburgites in mantle units was instrumental in formulating a model for the formation of ophiolite within the framework of the plate tectonic theory. The ophiolite–oceanic crust analogy was confirmed at the first Penrose Conference on ophiolites (Anonymous 1972). However, Miyashiro (1973) questioned the ruling model of a mid-ocean ridge setting for the genesis of ophiolite and proposed, based on geochemical interpretations, that the Troodos oceanic crust on Cyprus was a product of island arc magmatism. This was a revolutionary but controversial development in the ophiolite concept and led to the definition of suprasubduction zone ophiolites in the early 1980s. Observations of in situ oceanic crust in spreading environments within the upper plates of subduction zones in the western Pacific during the 1980s and 1990s were particularly important for demonstrating the influence of subduction on the magmatic evolution of ophiolites. Thus, this remarkable transformation in the scientific understanding of ophiolites since 1821 has contributed significantly to major advances in various Earth science disciplines.

Ophiolites have also been indispensable for human cultures and civilizations because of the wealth of mineral and ore deposits they host. The precious metals gold, silver, and platinum-group elements (PGEs), the ferrous metals chromium, manganese, and titanium, and the base metals cobalt, copper, and nickel occur widely in the ultramafic–mafic rocks of ophiolites. The discovery of copper in the Troodos ophiolite contributed to the development of the Bronze Age (~2400 BC) and triggered a critical era in human history during which the use of bronze brought about drastic changes in farming, hunting, and warfare. Nonmetallic chrysotile asbestos and jade are mainly found in serpentinitized peridotites. Asbestos, in the form of various serpentine minerals, was widely used as an effective insulator because of its resistance to fire, heat, and electrical damage; this changed when asbestos was recognized as a human carcinogen. Jade is an important

Keywords: suprasubduction zone ophiolite, boninite, mid-ocean ridge ophiolite, plume-type ophiolite, continental margin ophiolite, ophiolite pulse

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Sheeted dikes, up to 1.5 km in total thickness, are vertical, deformation bands in the gabbros (Dilek and Eddy 1992). In some ophiolites (i.e. Troodos, Cyprus; Penrose Conference, an ophiolite sequence consists, from bottom to top, of upper mantle peridotites, layered ultramafic–mafic rocks, layered to isotropic gabbros, sheeted dikes, extrusive rocks, and a sedimentary cover (Fig. 1; Anonymous 1972). The upper mantle peridotites commonly include layers of lherzolite and harzburgite and lenses of dunite with chromitite (Fig. 1, units A, B). Harzburgitic rocks (Fig. 1, photos A, B) are characterized near the absence of primary clinopyroxene; they are interpreted to be restites that experienced high degrees of partial melting beyond the stability of clinopyroxene, and therefore represent refractory mantle. They commonly display high-temperature deformation fabrics.

Layered ultramafic and mafic rocks form a transitional mantle–crust section (Fig. 1, unit and photo C), which corresponds to the petrological Moho (after Andrija Mohorovičić, 1857–1936) in the fast-spreading, modern oceanic lithosphere (Dilek and Furnes 2011). The overlying layered gabbro (Fig. 1, unit and photo D) consists mainly of olivine gabbro and gabbro, with subordinate trachyolite, anorthosite, and wehrlite layers. Modal variations of olivine, plagioclase, and clinopyroxene define the layering in these rocks. Isotropic gabbros above the layered gabbro have heterogeneous textures and grain sizes (hence the term varietextured gabbro; Fig. 1, unit and photo E) and include pegmatitic gabbro veins and plagiogranite dikes near the top.

Mutually intrusive relationships (Fig. 1, photo F) may define the boundary between the isotropic gabbros–plagiogranites of the plutonic sequence and the overlying sheeted dike complex. However, this boundary is not always magmatic in nature; in some ophiolites (i.e. Troodos, Cyprus: Kızıldag, Turkey) it is locally defined by low-angle normal faults (detachment surfaces) with mylonitic to cataclastic deformation bands in the gabbros (Dilek and Eddy 1992). Sheeted dikes, up to 1.5 km in total thickness, are vertical, subvertical (Fig. 1, photo G), or variously inclined, and are commonly cut by dike-parallel extensional faults, some of which acquire low-angle dips with depth (listric geometry). Rotation of sheeted dikes in the hanging wall of these listric normal faults during amagmatic extension causes the dikes to tilt.

The extrusive rocks in ophiolites consist of pillow lavas, pillow breccias, and massive lava flows (Fig. 1, units and photos H–J), which range in composition from basalt and basaltic andesite at the bottom to andesite, dacite, and rhyolite at the top. In some ophiolites, boninitic (high-Mg, high-SiO₂ andesite) dikes and lavas represent the latest stages of magmatism, as they crosscut and overlie other ophiolitic subunits (Fig. 1). Extrusive rocks are typically overlain by pelagic (Fig. 1, photos K), hemipelagic, and clastic sedimentary rocks; these rocks represent the ocean plate stratigraphy, recording the travel history of the oceanic lithosphere from ridge to trench.

**MANTLE HETEROGENEITIES IN OPHIOLITES**

Both ophiolites and in situ oceanic lithosphere show compositional and geochemical heterogeneities at various scales that are not consistent with steady-state magmatic accretion at a spreading center. Ophiolitic peridotites are depleted mantle residues resulting from various degrees and episodes of melt extraction from the primitive mantle. It is widely thought that systematic covariations of major and trace element distributions in ophiolitic peridotites are a result of partial melting processes. Yet, the bulk composition and the mineral chemistry of some ophiolitic peridotites are incompatible, and hence the assumption of a simple liquid line of descent for a parental melt that evolved via fractional crystallization does not work. This discrepancy may have resulted from postcumulus infiltration by melts, which reacted and reequilibrated with the depleted host peridotites, causing their refertilization by crystallization of interstitial mineral phases (plagioclase and clinopyroxene) (e.g. Dijkstra et al. 2001). Hence the observed mineralogy, textures, and compositions of upper mantle peridotites in some ophiolites are not primary. Likewise, the removal of a melt fraction after melt–peridotite reactions and the intrusion of this melt into the lower crust may produce late ultramafic–mafic intrusions in the layered gabbros (Fig. 1). Residual peridotites may react with slab-derived fluids in a mantle wedge and may interact with asthenospheric melts at shallow depths. These processes result in the modification or total obliteration of the primary structures, whole-rock chemistry, and mineralogical compositions of oceanic peridotites (O’Driscoll et al. 2012). Therefore, the mineralogy and geochemical compositions of crustal and mantle sequences in most ophiolites do not represent a simple melt–residua relationship.

**OPHIOLOTE TYPES AND THEIR MELT EVOLUTION**

The magmatic construction mechanisms of ophiolites depend on the geodynamic settings of their formation. Their emplacement mechanisms are also different (see below). Therefore, the occurrence and the types of ophiolites are the result of two important factors: (1) the tectonic, magmatic, and geochemical processes of ophiolite formation, and (2) the preservation of ophiolites as a result of different emplacement mechanisms.

The magmatic-structural architecture and geochemical signature of ophiolites are affected by several factors: the spreading rate and geometry in their igneous environment of formation; the proximity of this environment to mantle plumes or trenches (hence to subducting slabs); the composition, fertility, and temperature of the mantle beneath their spreading centers; the availability of fluids and recycled crustal material to the melt column(s) beneath these spreading centers; and the magnitude and nature of mantle melting and magmatic differentiation patterns (Dilek and Furnes 2011). An ophiolite is, therefore, a suite of temporally and spatially associated ultramafic, mafic, and felsic rocks that formed as the products of multiple mantle melting events and magmatic differentiation processes in a particular tectonic environment.
Ophiolites can be classified to the first order as subduction-related and subduction-unrelated types. Ophiolites whose magmatic construction was not affected by subduction processes include continental margin (CM), mid-ocean ridge (MOR), and plume-type (P) ophiolites (Table 1). These types correspond to the ophiolites developed at "normal" mid-ocean, plume-related mid-ocean, continental margin, and subducted ridges, as defined by Pearce (2014 this issue). Subduction-related ophiolites include suprasubduction zone (SSZ) and volcanic arc (VA) ophiolites (Table 1). The SSZ type encompasses ophiolites formed in subduction-initiation (forearc) and backarc basin settings.

**Subduction-Unrelated Ophiolites**

Tectonic extension and rifting may lead to continental breakup and development of an incipient ocean. Magmatic activity associated with this breakup and embryonic oceanic crust formation produces an ocean–continent transition (OCT) zone, where the subcontinental lithospheric mantle lherzolite is directly overlain by basaltic lavas and intruded by small gabbroic plutons and mafic dikes (Fig. 2A1; Manatschal and Müntener 2009). Formation of these crustal rocks, all with mid-ocean ridge basalt (MORB) compositions, involves small degrees of partial melting of little-depleted lithospheric mantle and slowly upwelling asthenosphere. This OCT lithosphere may be preserved in orogenic belts as CM ophiolites.

Continued lithospheric extension and magmatism in the aftermath of continental breakup lead to seafloor spreading, and new oceanic crust forms by decompression melting of uprisng asthenosphere. Variations in magma supply rates and the thermal structure beneath the spreading axes control the mode of magmatic accretion and the architecture of oceanic crust produced (Fig. 2A2). In fast-spreading ridges (e.g. East Pacific Rise), where magma supply is robust, continuous magmatism keeps pace with plate separation, and synchronous extension and diking produce a Penrose-type oceanic crust with a transitional Moho (Fig. 2A2). In intermediate-spreading ridges (e.g. Costa Rica Rift), oceanic crust has a thinner volcanic sequence but a thicker sheeted dike complex in comparison to fast-spreading crust (Fig. 2A2). In slow-spreading ridges (e.g. Mid-Atlantic Ridge, SW Indian Ridge), extensional faulting and crustal attenuation may outpace magmatism episodically, resulting in the exhumation of serpentinitized upper mantle peridotites and gabbros on the seafloor (Dilek and Furnes 2011). Slow-spreading oceanic crust may, therefore,
be thin and deformed, and the Moho may be represented by an alteration front or a detachment fault. Pillow lavas locally rest directly on exhumed, serpentinized peridotites and gabbros. Thus, MOR ophiolites may show major variations in their structural architecture and crustal thickness, depending on the spreading rate of the lithosphere (Fig. 2a,2).

All MOR ophiolites plot along the mantle array in a Ta/Yb versus Th/Yb diagram and may display N-MORB (e.g. Masirah ophiolite) or E-MORB (e.g. Macquarie ophiolite) geochemistry (Fig. 2a,2). The trench-proximal Taitao ophiolite in southern Chile (Le Moigne et al. 1996) is geochemically transitional between N-MORB and E-MORB (Fig. 2a,2) and also shows slight crustal contamination, representing a C-MORB affinity (Pearce 2014).

P-type ophiolites form at plume-proximal oceanic ridges or as part of oceanic plateaus, and they contain massive lava flows with minor pillow ed lavas, mostly picritic basalt in composition. Gabbroic to ultramafic plutons and sills are intrusive into a thick volcanic sequence (Fig. 2a,3). Pillow breccias, hyaloclastites, and chert–shale layers are intercalated with basaltic lava flows at higher stratigraphic levels. P-type ophiolites display geochemical variations between N-MORB and ocean island basalt (OIB; Fig. 2a,3).

The subduction-unrelated ophiolites display large variations in the Th/Yb versus Ta/Yb discrimination diagram (Fig. 2a). Their multielement patterns (Lu through Cs) vary from nearly flat, as shown by the CM Ligurian and the MOR Masirah ophiolites, to steep, as defined by the Macquarie ophiolite (Fig. 2a). These variations in incompatible element behavior are related to the degree of partial melting and the mantle temperature and fertility.

Subduction-Related Ophiolites

Suprasubduction zone (SSZ) ophiolites represent oceanic lithosphere formed in the extended upper plates of subduction zones, analogous to the modern Izu-Bonin-Mariana and Tonga-Kermadec arc–trench rollback systems (Stern and Bloomer 1992; Ishizuka et al. 2014; Pearce 2014). Specific tectonic settings of SSZ oceanic crust formation include the forearc, the backarc, and the incipient arc. Backarc tectonic environments may evolve as trench-proximal or trench-distal spreading centers showing variable subduction influence (Dilek and Furnes 2011). Extrusive and dike rocks of forearc ophiolites show time-progressive compositional and geochemical variations, from the oldest mid-ocean ridge–like (MORB-like) to the island arc tholeiite (IAT), and to the youngest boninitic affinities (Fig. 2c; Dilek et al. 2008; Dilek and Thy 2009; Ishizuka et al. 2014).

The earlier, MORB-like rocks are the products of decompressional melting of deep and fertile lherzolitic mantle and show no subduction influence. IAT magmas are strongly influenced by slab-dehydration-driven mantle metasomatism, repeated episodes of partial melting of peridotites in the mantle wedge, melting of subducted sediments, and mixing of highly enriched liquids from the lower fertile source with refractory melts in the melt column. Shallow partial melting of ultrarefractory harzburgites produces hydrous, Si- and Mg-rich boninitic magmas in the latest stages. In a multielement diagram (Lu through Cs), the first-produced basalts display a relatively flat pattern, and the younger IAT and boninitic rocks show a progressive depletion (relative to the first-produced basalts) in Lu–Nd and Ce–Ta, and a strong enrichment in Pb, Th, and Cs (Fig. 2n,1).

A volcanic arc (VA) ophiolite contains a middle crust with dioritic, tonalitic, and granodioritic intrusions (Nakajima and Arita 1998) and an uppermost crust with abundant andesitic to rhyolitic lavas and pyroclastic rocks (Fig. 2c,2). The diorite–tonalitic middle crust is produced by partial melting of the hydrated, earlier-formed mafic crust as a result of the infiltration of arc magmas. In the Th/Yb-Ta/Yb diagram, these ophiolites straddle the boundary between the IAT and calc-alkaline (CA) fields, and in the multielement diagram, the element concentrations are higher than those in SSZ ophiolites (Fig. 2n,2).

The magmatic and geochemical evolution of SSZ and VA ophiolites is controlled, therefore, by the mode and nature of (1) partial melting of the mantle above the subduction zone, and (2) the dehydration of and element flux from the subducted slab into the overlying mantle. Repeated episodes of partial melting cause a progressive change in the composition of the mantle, from fertile lherzolite to ultrarefractory harzburgite, and consequently the mantle source and the magmas derived from it become depleted in incompatible elements. In the meantime, dehydration of the subducting oceanic slab and partial melting of subducted sediments lead to the incorporation of the light rare earth elements (LREEs) and the mobile elements Cs, Pb, Ba, Th, and U into the mantle wedge (Hawkesworth et al. 1997; Pearce 2014). The conservative elements Nb, Ti, Y, and the heavy REEs (HREEs) are largely unaffected by this process and hence become progressively depleted in

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BABB = back-arc basin basalt; CA = calc-alkaline; C-MORB = contaminated MORB; DMM = depleted MORB mantle; E-MORB = enriched MORB; FAB = forearc basalt; IAT = island arc tholeiite; MORB = mid-ocean ridge basalt; N-MORB = normal MORB; P-MORB = plume-influenced MORB.
the mantle source during the repeated episodes of melting. However, the solidus of the wedge peridotites is lowered considerably due to the input of slab-derived fluids, facilitating further partial melting, and the depleted mantle becomes progressively enriched in highly mobile incompatible elements. The sharp increase in the incompatible element concentration, the marked positive Pb anomaly, and the negative Nb anomaly displayed by VA ophiolites in comparison to SSZ ophiolites (Fig. 2b) are mostly time-dependent phenomena because of the prolonged subduction history (~20–30 My) of VA ophiolites as opposed to the relatively shorter subduction history (<10 My) of SSZ ophiolites (Dilek and Furnes 2011).

**OPHIOLOITE EMPLACEMENT MECHANISMS**

Among the most important factors controlling the mechanisms of ophiolite emplacement are (1) the age, thickness, and thermal state of oceanic lithosphere to be emplaced, (2) the nature and geometry of plate boundaries involved, and (3) the size and character (e.g. oceanic versus continental) of the interacting plates (Wakabayashi and Dilek 2003). Subduction zone tectonics is an essential driver for incorporating preexisting oceanic lithosphere into continental margins. The oceanic lithosphere of MOR- and P-type ophiolites is tectionally transferred from a downgoing plate to the upper plate via subduction-accretion. The oceanic lithosphere in SSZ and VA ophiolites is always part of the upper plate of a subduction system, but it gets emplaced into a continental margin in a downgoing plate via collisional processes. We examine here the emplacement mechanisms of some subduction-unrelated and subduction-related ophiolites through subduction-accretion and collisional processes (Fig. 3).
Continental Margin Ophiolites: Ligurian Ophiolites

The Middle Jurassic ophiolites in the northern Apennines and the western Alps formed during and following the rifting of Adria (or Apulia) and Africa from Europe that led to the opening of the Piemont-Liguria ocean (Manatschal and Müntener 2009). These CM ophiolites were subsequently imbricated with trench deposits (“schistes lustrés” in the Alps/Apennines) and telescoped along west-vergent thrust faults in the late Cretaceous as a result of regional shortening associated with a newly developed subduction zone near the Adria continental margin (Fig. 3a). In the western Alps, a ribbon continent (the Sesia-Margna extensional allochthon) and the OCT zone crust were partly subducted beneath the Adria margin, metamorphosed to eclogite facies, and exhumed later following the continent–continent collision (Alpine orogeny).

Mid-Ocean Ridge Ophiolites: Macquarie and Taitao Ophiolites

The Macquarie ophiolite in the Southern Ocean (Fig. 3b) and the Taitao ophiolite in southern Chile (Fig. 3c) are two young MOR ophiolites that experienced different processes of tectonic displacement and emplacement. The Macquarie ophiolite (11.5–9.7 Ma) is exposed along the transform fault boundary between the Australian and Pacific plates (Meckel et al. 2003). Transpression across this boundary during the last 6 million years has resulted in the tectonic displacement and uplift of the MOR crust (Fig. 3a). The transpressional, transform plate boundary here connects along-strike, to the north and south, with two active trenches and is thus in the process of being converted into an intraoceanic subduction zone (Meckel et al. 2003). The late Miocene Taitao ophiolite in southern Chile was emplaced into the active margin of South America as a result of ridge–trench interaction (Fig. 3c; Le Moigne et al. 1996). Subduction of an oceanic ridge may result in the emplacement of a piece of young and buoyant oceanic lithosphere as an ophiolite in the upper plate (Van den Beukel and Wortel 1992). As the Chile Rise collided with the Peru-Chile Trench around 5.6 Ma, a slice of hot oceanic lithosphere was decoupled from the downgoing oceanic slab and was incorporated into the South American continental margin as a MOR ophiolite.

Plume-Type Ophiolites: Western Colombia

The Cretaceous peri-Caribbean ophiolites, exposed in Venezuela, western Colombia, Costa Rica, Hispaniola, and Puerto Rico, represent fragments of the Caribbean oceanic plateau (Kerr et al. 1998). The thick (~20 km) oceanic crust of this plateau was formed on the Farallon plate above the Galapagos mantle plume during 100–89 Ma (Hastie and Kerr 2010). This thick and buoyant oceanic crust resisted subduction and was decoupled from its lithospheric mantle,
which continued to subduct, and tectonic slices of basaltic lavas, gabbros, and ultramafic rocks were accreted into the upper-plate continental margin (Hastie and Kerr 2010). In western Colombia, basaltic, doleritic, and gabbroic rocks are tectonically intercalated with metasedimentary rocks of the accretionary prism of the northern margin of South America (Fig. 3a).

**Suprasubduction Zone Forearc Ophiolites: Oman Ophiolite**

The ~15 km thick Oman ophiolite is a remnant of the Tethyan oceanic lithosphere (Goodenough et al. 2014 this issue); it forms the uppermost tectonic nappe in an imbricated stack of oceanic rocks in the southeastern part of the Arabian Peninsula (Figs. 3e, 4). The Oman ophiolite rests tectonically on a discontinuously exposed metamorphic sole or a subophiolitic melange. The metamorphic sole beneath the ophiolite shows inverted temperature and pressure gradients, indicating that it is a composite of rock slices formed at different depths and juxtaposed later by thrust faulting (Hacker et al. 1996). Pressure–temperature data suggest high-temperature metamorphism at the inception of oceanic subduction beneath the hot subophiolitic mantle in the upper plate. The forearc oceanic lithosphere of the Tethyan Ocean was displaced from its tectonic setting above this new subduction zone and was emplaced onto the Arabian margin during the continent–trench collision.

**Volcanic Arc Ophiolites: Magnitogorsk Arc**

The Magnitogorsk island arc system in the Urals consists of an early Devonian subduction-initiation-related volcanic complex, which is composed of high-Mg basalt, basaltic andesite, picrite, boninitic lavas and dikes, and volcaniclastic rocks. These units are overlain by early to middle Devonian calc-alkaline volcanic rocks. This volcanic complex is tectonically underlain by an accretionary prism (Fig. 3f), which includes west-vergent thrust sheets composed of metapelitic rocks, serpentinite-matrix mélangé, and blueschist to eclogitic rocks (Brown et al. 2006). The protoliths of these high-pressure rocks were the passive margin units of the partially subducted East European continental margin. The emplacement of the Magnitogorsk arc system onto the East European continent was facilitated by the partial subduction of the continental margin rocks beneath the forearc (Fig. 3f).

**GLOBAL DISTRIBUTION OF OPHIOLITES AND OPHIOLITE PULSES**

**Figure 4** shows the global distribution of Phanerozoic orogenic belts, along with representative examples of various ophiolite types (marked in different colors) and their ages. The evolution of orogenic belts of accretionary origin involved the tectonic amalgamation of oceanic terranes, such as seamounts, oceanic plateaus, and volcanic arcs, into long-lived, active continental margins facing large oceans. Important examples include the Central Asian Orogenic Belt, the North American Cordillera (including the Aleutians), the Andes, the peri-Caribbean belt, and the Japanese islands (Fig. 4). The Cordilleran, western Pacific, and peri-Caribbean orogenic belts mainly include scraped-off fragments of MOR- and P-type ophiolites that are commonly associated with accretionary prism and high-pressure metamorphic rocks (Kerr et al. 1998). The tectonic history of collisional orogenic belts involved multiple collisions between microcontinents, intraoceanic arc–trench systems, and continents following the closures of ocean basins. Examples are the Mesozoic Alpine–Himalayan and the Paleozoic Appalachian–Caledonian–Uralian orogenic belts. Collisional orogenic belts commonly display a record of rift–drift, seafloor spreading, and subduction typical of the Wilson cycle. Therefore, it is not uncommon to see CM, MOR, and SSZ ophiolites nested along and across the suture zones in these belts.

The distribution of certain ophiolite types during particular time periods coincides with major tectonic and magmatic events in Earth history. For example, the formation of the late Paleozoic and Jurassic CM ophiolites was coeval with the dismantling and riftiing of the northern edge of western Gondwana. The development of the Jurassic–Cretaceous P-type ophiolites overlapped in time with the emplacement of giant dike swarms and the formation of large igneous provinces (LIPs) (Kerr et al. 1998; Vaughan and Scarrow 2003) and with the breakup of Pangea through discrete episodes of continental rifting (Dalziel et al. 2000).

The main ophiolite pulses—that is, peak times of ophiolite genesis and emplacement—in the early Paleozoic, the late Jurassic, and the Cretaceous reflect the timing of SSZ ophiolite formation, which was contemporaneous with the
Although there appear to be spatial–temporal relationships between the formation and distribution of ophiolite types and major tectonic and magmatic events, the relative abundances of these various ophiolite types do not reflect the proportions of the different types of oceanic lithosphere that were generated. Rather, these abundances are a result of ophiolite formation, emplacement, and preservation, as discussed earlier. For example, the vast majority of MOR-generated oceanic lithosphere has been subducted. Hence, MOR ophiolites are scarce (in comparison to other ophiolite types) in the rock record, even though MOR crust is the most common type in the modern ocean system.

ACKNOWLEDGMENTS
We thank the authors for their contributions to this issue of Elements, and John Valley and Pierrerette Tremblay for their editorial support. Thorough reviews by Y. Ogawa, P. Thy, J. Wakabayashi, and B. F. Windley helped us improve this paper.

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Much of our understanding of ocean ridges has come from the collection and analysis of glasses recovered from ridge axes. However, applying the resulting methodologies to ophiolite complexes is not straightforward because ophiolites typically experience intense alteration during their passage from ridge to subduction zone to mountain belt. Instead, immobile element proxies for fractionation indices, alkalinities, mantle temperature, mantle flow and subduction addition may be used to classify ophiolite lavas and fingerprint the precise setting of the ridge at which an ophiolite formed. The results can help us recognise and interpret past spreading centres and so make plate tectonic reconstructions.

Key words: ophiolites, volcanic rocks, trace elements, ridges, subduction zones

INTRODUCTION

Ophiolite complexes represent fragments of oceanic crust and upper mantle which formed at ocean ridges and were then emplaced on land. They commonly carry the only record we have of the nature and composition of the crust and upper mantle of former oceans, so they are important in making past plate reconstructions. Extracting the maximum information from ophiolitic rocks requires the use of geochemistry to name the rock types, identify the tectonic setting and interpret fully their origin. All parts of the ophiolite are important for doing this, from the mantle peridotites at the base, through the plutonic complex, to the lavas and dykes and finally sediments. For reasons of space, I shall focus here on the lavas and dykes and on how geochemical fingerprinting can be used to determine the type of ocean ridge at which they formed.

A particular problem with studying ophiolite lavas and dykes is that very few contain fresh glasses. Immediately following intrusion or eruption, the transfer of heat from the underlying magma chamber to the overlying ocean by hydrothermal circulation generally transforms the lavas and dykes, both mineralogically and geochemically. Thereafter, lower-temperature alteration continues as the oceanic crust moves further away from the ridge. Further modification then takes place as the crust accretes at an active margin and becomes involved in orogenic processes – as occurred in many of the Alpine ophiolites. In extreme cases, ophiolite lavas may be subducted to depths of over 100 km (resulting in eclogite facies metamorphism) or raised to the melting point at the peak temperature of an orogenic cycle (amphibolite and granulite facies metamorphism), in which case few, if any, mineralogical or structural relics of their original ocean-floor history may be preserved.

The consequence is that most of the well-established geochemical methods of interpreting volcanic rocks cannot be applied to comparable rocks in ophiolite complexes. Instead, a new branch of geochemistry, informally known as immobile element geochemistry, has developed over the past forty years to enable altered oceanic lavas to be assigned to their most probable tectonic setting. Here, I summarize the principles of immobile element geochemistry and examine how it may optimally be used to investigate ophiolitic lavas and dykes.

SETTINGS OF OPHIOLITE FORMATION

When ophiolites were first defined formally, they were assumed to represent lithosphere formed at mid-ocean ridges. Almost immediately, this assertion was contested (Miyashiro 1973), and there followed a sometimes acrimonious debate about their precise setting of formation which is now well documented in the literature (e.g. Pearce and Robinson 2010; Dilek and Furnes 2014 this issue). With improving knowledge of the ocean floor, especially in marginal basins and at continental margins, it became apparent that sea-floor spreading could take place in a number of settings, not just at ridges in the centres of large ocean basins. The challenge then switched from answering the question of whether or not ophiolites formed at ocean ridges to determining the precise nature and setting of the ridges at which they formed. The various options have recently been defined and described in detail by Dilek and Furnes (2011, 2014). For the purpose of this paper, I have focused on the six types of ridges that might reasonably be distinguished geochemically on the basis of their petrogenetic differences. These differences are fundamental to the application of immobile element geochemistry, so are summarized briefly below and illustrated in Figure 1.

‘Normal’ Mid-Ocean Ridges (Fig. 1a)

These ridges form once an ocean has opened sufficiently for steady-state spreading to be established and, by definition, are unaffected by plumes or the influence of subduction zones. There is a small degree of deep melting, but most melting takes place as a result of decompression at shallow depths (<60 km) as the mantle rises beneath the ridge in response to plate separation (e.g. Langmuir et al. 1992). The dominant magma type is known as normal mid-ocean
ridge basalt (N-MORB). Its mantle source is depleted with respect to average mantle and is often termed depleted MORB mantle (DMM).

Plume-Related Mid-Ocean Ridges (Fig. 1b)
These ridges are located within the detectable influence of mantle plumes. Plume mantle is hotter than mantle beneath normal ridges. This leads to melting columns in which melting begins at greater depth than at plume-distal ridges. As a result, more melting takes place within the deeper garnet facies compared to the shallower spinel facies, and the overall degree of melting is higher. Unlike DMM, plume mantle is typically undepleted or, if depleted, becomes so by mixing and by loss of small volumes of melt at depth as residual plume mantle moves laterally to the ridge, a process known as plume–ridge interaction (e.g. Niu and Hékinian 2004). The magma type in this setting may be termed P(plume)-MORB (Dilek and Furnes 2014).

Continental Margin Ridges (Fig. 1c)
These ridges form when continents break up and evolve from a ‘rifting’ to a ‘drifting’ stage, and before a steady-state spreading regime has developed. At volcanic-rifted margins, driven by plume-associated extension, the lavas may be of P-MORB character. More distinctive are the non-volcanic rifted margins (e.g. Whitmarsh et al. 2001), where the lavas are more typically E(enriched)-MORB. Here, the presence of cool continental lithosphere and non-infinite extension (compared to the situation once spreading is established) typically leads to cooler, shorter melting columns and hence less melting, which may, in part at least, be responsible for the E-MORB character. Locally, the involvement of trapped, relict continental lithosphere can lead to distinctive, C(contaminated)-MORB compositions, not unlike those found in subducted ridge settings (Fig. 1f).

Subduction-Initiation Ridges (Fig. 1d)
A relatively recent development in ophiolite studies has been the recognition of the importance of intra-oceanic subduction-initiation processes in ophiolite genesis (e.g. Stern and Bloomer 1992). In the Stern-Bloomer model, the ophiolites form immediately after the start of convergence during an extensional event that accompanies the roll-back and sinking of the newly subducting plate. In this setting, mantle flows into the nascent mantle wedge and interacts with a small and variable contribution of fluids from the sinking plate. Melting induced by the fluid augments that resulting from decompression, leading to a higher degree of melting than at mid-ocean ridges (e.g. Langmuir et al. 2006). Subduction-influenced lavas originating in this setting have been termed forearc basalts (FAB) by Reagan et al. (2010). The ophiolite-forming spreading event is typically followed by the first products of arc volcanism. These are commonly boninites, a distinctive Mg,Si-rich lava formed by the melting of depleted mantle under shallow, hydrous conditions (Ishizuka et al. 2006, 2014 this issue). The presence of boninites at the top of a FAB lava sequence is a major indicator of a subduction-initiation setting.

Back-Arc Basin Ridges (Fig. 1e)
These are located, as the term implies, behind island arcs. They originate by rifting, as in Figure 1c, but of arcs rather than continental lithosphere. They can then develop into fully fledged spreading axes (Fig. 1e). If the axis is...
sufficiently far behind the arc, the lavas resemble those from mid-ocean ridges. If it is closer to the arc, its underlying mantle incorporates a fluid-rich component from the subducting plate below, as in ridges in subduction-initiation settings. Subduction-influenced lavas from this setting are termed back-arc basin basaltas (BABB). The geochemical differences between BABB and FAB are subtle and mostly beyond the scope of this paper. Essentially, BABB erupt much further from the trench than FAB. This means that they typically carry a deep, rather than shallow, subduction signal (low H/Th, as indicated in Fig. 1c); they also lack the up-sequence transition into boninites described in the preceding paragraph.

**Subducted Ridges (Fig. 1c)**

Ophiolites can form where ridges subduct. Mantle continues to upwell as it did before subduction, but now the melting column is shortened because of the overlying lithosphere of the forearc in the overriding plate. Guivel et al. (1999) carried out a detailed geochemical study of the best example (the Taitao ophiolite in southern Chile) and revealed the co-existence of a number of magma types and a complicated petrogenetic scenario. The melting column produces both N-MORB and E-MORB compositions, commonly with a subduction component. The magma composition depends particularly on the height of the melting column (which decreases as subduction proceeds) and the mantle flow pattern (whether flow is from outboard or inboard of the trench). That magma may then interact with forearc continental lithosphere giving a C(contaminated)-MORB composition.

**Other Considerations**

This list will likely be refined and extended in the future. The most notable omission is likely to be slab-edge ridges. At these, mantle flows around the slab edge and into an extensional regime above the edge of a retreating subducting plate. Slab-edge ridges can be viewed as having characteristics of both back-arc and subduction-initiation ridges. If the mantle outboard of the slab edge is plume-influenced, as in their type area of the Samoa-influenced northern Lau Basin, they can also have some characteristics of P-MORB. Future and ongoing work should define their characteristics more precisely and allow them to be fingerprinted in their own right.

It is important to note, too, that geochemistry is unlikely ever to be able to define a setting uniquely. This is because the ridge-crest variables, such as temperature and mantle composition, do not just vary between tectonic settings, as depicted above, they also vary within any one setting in response to differences in, for example, spreading rate and the nature of ridge segmentation. With this caveat, it is apparent from the different scenarios in Figure 1 that different types of ridges are generally characterised by systematic (if sometimes overlapping) differences in mantle compositions, mantle temperatures and subduction components. Using elements unaffected by alteration to recognise these is the goal of immobile element fingerprinting. To achieve this goal, we need to formally identify the immobile elements and define immobile element proxies for the discriminating ridge variables.

**IMMOBILE ELEMENT GEOCHEMISTRY**

**Identification of Immobile Elements**

The concept of immobile element geochemistry in an ophiolite context may be traced back to Cann (1970). He used what was then the new technique of X-ray fluorescence (XRF) to analyse a range of MORB samples, some fresh, some weathered, some metamorphosed to green-

![Figure 2](image-url) Methodology for identifying immobile elements (based on Cann 1970). (A) Immobile, incompatible elements such as Ti and Zr exhibit highly significant (at 95% confidence level), positive correlation coefficients (r) in cogenetic lavas, even when altered or metamorphosed. (B) When a mobile element such as K is substituted for Ti, the correlation is no longer significant. Theoretical vectors show the co-variation expected as a result of 50% crystallization (f = 0.5) of the assemblage olivine (20%) + plagioclase (50%) + clinopyroxene (20%) from basic magma.
This study led to the first ophiolite fingerprinting using the immobile elements thus identified, namely Ti, Zr, Y and Nb (Pearce and Cann 1971). Pearce (1975) and Shervais (1982), respectively, added two other elements analysable by XRF to that list: the compatible element Cr and the moderately incompatible element V.

Meanwhile, the rare earth elements (REEs) were being applied to ophiolite fingerprinting, though with less success. Moreover, the analytical method (isotope dilution, ID) was time-consuming. However, the development of instrumental neutron activation analysis (INAA) not only provided a quicker method of analysing REEs, but critically added the elements Th, Ta, Hf and Sc to the list. Ta–Nb, Y–Ho and Hf–Zr are immobile element pairs with similar behaviour, so there was effective overlap between the XRF and INAA analyses, but, nonetheless, full immobile element fingerprinting initially required more than one analytical instrument. Subsequently, the development of inductively coupled plasma mass spectrometry (ICP–MS) provided the opportunity to analyse the full spectrum of immobile elements in a single run. ICP–MS also highlighted other immobile elements, such as Ga, though these have yet to find an application in interpreting ophiolite lavas.

Interestingly, elements identified as immobile in ophiolites are also those long known to be the least mobile during rock weathering: they are all characterised by intermediate charge/radius (Z/r) ratios, such that they do not readily form soluble hydrated cations (low Z/r), complex anions (high Z/r) or chloride complexes in fluids. A number of authors have, however, published examples of ‘immobile elements’ exhibiting clear mobility (e.g. Hynes 1980). Many of these involve shear zones, which are characterised by high fluid/rock ratios and where fluids commonly carry complexing agents such as carbonate species. Alternatively, they involve rocks raised to temperatures approaching the melting points of either the metamorphosed lavas themselves or their surrounding sediments. A number of key elements (e.g. Th, Nb, Zr) may be mobile under these conditions.

Using the Cann (1970) correlation-based method (Fig. 2) to confirm which elements are immobile is therefore a wise precaution. To do this, one needs to identify rocks which might have a similar crystallization history, as for example in a single lava unit. A bivariate plot can then be drawn for each pair of potentially immobile elements and a theoretical crystallization vector drawn. For a plot of two elements, A and B, the gradient of this vector in logarithmic space is given by \((D_A - 1)/(D_B - 1)\), where D is the bulk distribution coefficient (a measure of the partitioning of the element in question between the crystallizing magma and the solid crystals). The samples can then be plotted with different symbols according to the type and intensity of alteration. If the elements in question are immobile, all samples should follow significantly correlated trends that run subparallel to the theoretical crystallization vector.

**Immobile Element Patterns**

The full suite of immobile element can be represented as geochemical patterns, though it is usual not to include elements that are more incompatible than the heavy REEs (Fig. 3). These resemble the patterns used to characterise modern lavas, but avoid the mobile elements Rb, Ba, Cs, U, K, Sr, P and Pb. N-MORB is the normalising factor of choice as the resulting flat N-MORB pattern is a useful tectonic reference. As with the full patterns, the elements are ordered according to their average incompatible mobility during mantle melting. Similarly behaving elements (such as Nb–Ta and Hf–Zr) are usually plotted separately, but I have plotted an average here just to aid clarity. All the REEs have been plotted except Eu (which can be mobile) and Lu (which is unnecessary); La is included but its immobility often needs careful checking. Cr is not plotted but it is sensible to choose samples with Cr as close to 275 ppm as possible: this is equivalent to choosing samples with compositions close to 8 wt% MgO, in keeping with most studies of ocean ridge glasses.

**FIGURE 3** Incompatible, immobile element patterns for lavas from present-day settings (A, B) together with some typical ophiolites for comparison (C). For data sources, see Pearce (2008) and references in the text. Key indices used as proxies in Figures 4 and 5 are highlighted. T8 = TiO2 at MgO = 8 wt%. Normalisation is to N-MORB (Sun and McDonough 1989). Patterns such as these can give a quick indication of magma type and tectonic setting for ophiolites of unknown affinities. SZ = subduction zone; SSZ = suprasubduction zone; for all other abbreviations, see caption of figure 1.
FIGURE 3 shows some typical patterns for lavas from the modern analogue settings depicted in Figure 1, subdivided into mid-ocean ridge (non-subduction) settings in Figure 3a and suprasubduction zone settings in Figure 3b. Some of the key geochemical indices have been highlighted, and these will be discussed in more detail as the basis of the diagrams used in Figures 4 and 5. Note, in particular: the overall high gradients of some patterns (high Nb/Yb), which is an indicator of the alkalinity of the magma; the positive and negative slopes in the right-hand part of the patterns (high and low Ti/Yb) in Figure 3a, which indicate settings associated with mantle plumes; and the negative Nb anomalies (high Th/Nb) and low Ti8 (TiO2 for magmas with 8 wt% MgO) in Figure 3b, which indicate settings associated with subduction zones.

For ophiolite lavas, simple inspection of geochemical patterns gives a first indication of the setting of the ridge. Figure 3c contains patterns from some well-characterised ophiolites, for which the immobile element geochemistry has been integrated with other information to provide a confident interpretation. These are: parts of the Corsican ophiolite, which represent steady-state spreading axes in a newly established Jurassic Alpine ocean (setting of Fig. 1a; Saccani et al. 2008b); the Nicoya ophiolite in Costa Rica, which represents volcanism at the edge of a mantle plume (setting of Fig. 1b; Hauff et al. 2000); the Jormova ophiolite in Finland, which represents a Proterozoic continental margin ophiolite (setting of Fig. 1c; Peltonen et al. 1996); the Troodos ophiolite, which formed just after a mid-Cretaceous subduction-initiation event (setting of Fig. 1d; Rautenschlein et al. 1985); the Guevgueli ophiolite in Greece, which formed by back-arc extension in a partly ensialic basin with coeval arc volcanism (setting of Fig. 1e; Saccani et al. 2008a); and the Taitao ophiolite in Chile, the classic ridge-subduction ophiolite still preserved in its setting of formation (setting of Fig. 1f; Guivel et al. 1999). Comparison of the ophiolite patterns in Figure 3c with ophiolite analogue patterns in Figure 3a, b supports the inferences made by the authors cited above. In addition, the suite of patterns highlights the wide range of settings in which ophiolites can be formed.

However, although ophiolites can be interpreted by direct comparison with type patterns of this sort either visually or using pattern-recognition methodologies, it is generally more effective to use diagrams based on immobile element proxies. This is because suites of lavas commonly include more than one magma type and the petrogenetic interpretations of proxy diagrams commonly yield additional information necessary for a full interpretation of the data.

IMMOBILE ELEMENT PROXIES

Proxies for Rock Classification

Immobile element proxies are combinations of immobile elements that represent either a mobile element index or a geological process. For classification, a principal goal is to provide an immobile element equivalent to the recognised classification diagram. For ophiolites, the first step is to identify rocks of the boninite series. Boninites are unusual – having high silica and high MgO resulting from shallow, wet melting – and are strongly indicative (as already noted) of subduction initiation. In altered rocks, we have to use a second characteristic of boninites, low TiO2, specifically Ti8 < 0.5 wt%, which would normally be observed using a plot of TiO2 against MgO (Pearce and Robinson 2010). Mg is highly mobile, so Cr can be used as an immobile element proxy for MgO. Ti275 (TiO2 at 275 ppm Cr) is approximately equal to Ti8. Any boninitic series should follow a trend which has <0.5 wt% TiO2 at 275 ppm Cr.

Ophiolite lavas that are not of boninitic affinity would, if fresh, be classified by the IUGS total alkali–silica (TAS) diagram (Fig. 4a; Le Bas and Streckeisen 1991). The elements making up that diagram (K, Na and Si) are all highly mobile. Floyd and Winchester (1975) devised an immobile element equivalent with Nb/Y as a proxy for total alkalis (Na2O + K2O) and Zr/Ti as a proxy for SiO2. Because of the limited data set available in 1975 and the fact that Floyd and Winchester did not include lavas from convergent margins, I subsequently revised their diagram using >10,000 data points and a wider range of tectonic settings (Pearce 1996). The resulting TAS proxy diagram (Fig. 4b) loses some detail compared with its IUGS equivalent, but does permit the proper classification of altered rocks.

To illustrate the need for a TAS proxy diagram, I have used two data sets. The first is from a drill core (CY2a) from the Troodos Deep Drilling project, which penetrated the high-temperature alteration zone beneath the Agrokopia B massive sulfide deposit within the upper unit (Unit III) of the lower lavas of the Troodos ophiolite of Cyprus (Paul Robinson, pers. comm.). Glasses recovered along

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**Figure 4** Classification of ophiolite lavas from the Troodos (Cyprus) and Semial (Oman) ophiolites using (A) the IUGS-recommended TAS diagram of Le Bas and Streckeisen (1991) and (B) an immobile element–based TAS proxy diagram (from Pearce 1996, after Floyd and Winchester 1975). In particular, Si addition to Troodos lavas and Na addition to Semial lavas by hydrothermal fluids lead to wide dispersion on the IUGS TAS diagram and multiple misidentifications. The proxy diagram gives tight clusters dominated by tholeiitic basalts for both groups in (A), Pic Bas = picrite basalt, TrBas = trachybasalt, BA = basic, andesite, BTA = basaltic trachyandesite.
strike within this unit are high-silica basalts (Pearce and Robinson 2010). Si metasomatism of the lavas from the drill core results in a spread of data from picrite basalts to dacites, with only some 35% of the lavas classifying as basalts (Fig. 4A). In contrast, the lavas form a tight cluster at the upper end of the basalt field on the TAS proxy diagram (Fig. 4A). Both diagrams classify the rocks as tholeiitic, though alkali metasomatism has resulted in more scatter on the TAS diagram. The second example, from the lower (Geotimes) lava unit of the Semail (Oman) ophiolite (Alabaster et al. 1982), illustrates the other problem, that of alkali element metasomatism. Albitisation of feldspars has resulted, in particular, in a large increase in Na2O at the expense of CaO in the Geotimes unit. In consequence, the TAS diagram in Figure 4A misclassifies the lavas as alkalic (trachybasalts and trachyandesites). The Floyd–Winchester proxy diagram, however, sees through the Na addition and classifies the rocks as basic to intermediate members of the basalt–andesite–dacite–ryholite series (Fig. 4A).

It may seem an academic exercise to classify the rocks correctly but, in fact, it is important in fingerprinting tectonic setting. Historically, it was the misclassification of Troodos lavas using conventional classification diagrams that made many appear to be evolved lavas from arc shield volcanoes (Miyashiro 1973) and contributed to the heated debate on the setting of the Troodos ophiolite in the 1970s. Moreover, data plotted on immobile element-based discriminant diagrams need to be filtered on the basis of rock type. For example, the discriminant diagrams shown in Figure 5B, C only apply to basic rocks. This is because crystallization of magnetite or ilmenite at more fractionated compositions causes Ti to be depleted, which can lead to misclassification. Figure 5A is more robust, but crystallization of iron oxides can also deplete Nb to some extent and so it is still advisable to restrict its use to basic rocks if possible.

Proxies for Fingerprinting Magma Type and Tectonic Setting

The final goal is to recognise magma types, which, in turn, provides information on tectonic setting. Essentially, these divide into suprasubduction types (boninite, forearc basalt and back-arc basin basalt) and mid-ocean ridge types (N-MORB, E-MORB, P-MORB, and C-MORB). The rationale for the choice of proxies is easiest to understand by reference to the multielement patterns in Figure 3A, B. Three proxies (or types of proxy) are needed.

Th/Nb (proxy for subduction/crustal input) Th and Nb are both highly incompatible elements which retain an almost-constant ratio during mantle melting. Otherwise, however, Th (Z = 4; r = 94 pm, where pm = picometres) and Nb (Z = 5; r = 64 pm) have significantly different properties which cause them to be decoupled during subduction: Th is subduction-mobile and Nb is subduction-immobile in most arc systems, with the result that the vast majority of suprasubduction zone lavas have high Th/Nb. Moreover, because continental crust is, at least in part, derived by subduction, it too has high Th/Nb. Therefore, magma that has assimilated continental crust also has high Th/Nb. Ta (also Z = 5; r = 64 pm) behaves in a very similar way to Nb, such that Th/Ta and Th/Nb are essentially equivalent for this purpose.

Many discrimination diagrams in the literature are based on the Th/Nb proxy. The original was the Th–Ta–Hf triangular diagram of Wood et al. (1979). My adaptation of this is the plot of Th/Yb versus Nb/Yb (Fig. 5A; Pearce 2008), which is easier to interpret petrogenetically. On this projection, lavas from non-subduction settings plot along a MORB-OIB array which includes virtually all mid-ocean ridge and most ocean island basalts. Lavas derived from mantle modified by subduction-derived fluids and melts are displaced from that array to higher Th/Yb ratios. Lavas modified by assimilation of continental crust form diagonal lines in which both Th and Nb are modified. Usually, assimilation does not apply to ophiolites but, as noted earlier, lavas erupted in ridge-subduction and, rarely, continental margin settings can have these characteristics.

Applying the Th/Yb versus Nb/Yb diagram to the six ophiolites represented in Figure 3C is straightforward. The three from the mid-ocean ridge ophiolite subgroup (Corsica, Nicoya and Jormua) plot within the MORB-OIB array in Figure 5A. In contrast, the three from the suprasubduction zone subgroup (Troodos, Guevgueli and Taitao) are variably displaced from the MORB-OIB array to higher Th/Yb. Particularly important is the dispersion of the data, which can define the magma type better than individual analyses. For example, the Guevgueli samples form a trend that extend from the MORB-OIB array into the island arc field. Given that samples from modern-day back-arc basins can do the same on quite small (<1 km) length scales, this is in itself a diagnostic feature. The high dispersion and diagonal trends formed by Taitao lavas are distinctive and controversial, and involvement of continental crust, subcontinental lithospheric mantle and slab melt have all been considered by Guivel et al. (1999) for what is a complex tectonic setting.

Ti/Yb (proxy for plume melting) The key to this proxy is that, whereas Ti and Yb are partitioned similarly into melt during shallow melting (i.e. of spinel peridotites), they are decoupled for deep melting (i.e. of garnet peridotites) where only Yb is partitioned significantly into garnet. The retention of Yb in residual garnet, but not residual spinel, means that Ti/Yb is high only in the products of deep melting where garnet is stable. Conversely, in mantle previously depleted by deep melting, Ti/Yb is low. As deep melting is usually a consequence of high mantle temperatures, the decoupling of Ti and Yb is typically associated with mantle plumes where high-temperature mantle advects to shallow depth.

Historically, many discriminant diagrams use this type of proxy, including the original Ti–Zr–Y triangular plot (Pearce and Cann 1971). Figure 5B shows its updated equivalent, Ti/Yb versus Nb/Yb (Pearce 2008), which separates ocean island basalts (ocean-ridge melt, so high Ti/Yb) from MORB (shallow melting, so low Ti/Yb). N-MORB and E-MORB form a near-horizontal trend in the MORB field, whereas plume-related magmas typically plot along a diagonal trend into the OIB field. Note that Ti may be viewed as a major or a trace element, and so is plotted on some diagrams (including Figure 5B) as wt% of the oxide and on others (including Ti–Zr–Y) as parts per million (ppm) of the metal, where 1 wt% TiO2 = 6000 ppm Ti. Note also that Zr/Y has been used successfully as a proxy for plume influence, for example, in the Fitton et al. (1997) projection of Nb/Y–Zr/Y. The latter may prove a more effective plume indicator, but its interpretation is currently less clear.

Taking the three ophiolites that plotted in the MORB-OIB array in Figure 5A, it is evident from Figure 5A that the Corsica lavas plot as N-MORB, consistent with the inference that they represent oceanic crust from an established spreading centre, albeit in a small ocean. The Jormua ophiolites are E-MORB in character, fitting their continental margin interpretation. Nicoya is distinct in that its basalt–andesite–dacite–ryholite series (F. 4A)
**V/Ti (proxy for suprasubduction zone melting)** As illustrated in Figure 3b, Ti8 is a key parameter for investigating subduction-influenced ridges. Notably, subduction-derived water increases the degree of partial melting. Ti, being an incompatible element, is then increasingly depleted in the melt as the degree of partial melting increases. This degree of depletion has been quantified (e.g. Kelley et al. 2006). For example, adding 0.2 wt% of water (a moderately high value) to mantle that would otherwise undergo 10% melting should approximately double the amount of melt and halve the concentration of Ti in the resulting melt. A second process that leads to reduction in Ti8 is the loss of small degrees of melt as mantle flows towards the trench, a process described as mantle preconditioning (McCulloch and Gamble 1991). This process is believed to be the basis for boninites having such low contents of titanium. Using Cr, an immobile, compatible element, as a proxy for MgO gives plots of the type Ti versus Cr and Y versus Cr, which have long been used to distinguish MORB from suprasubduction zone lavas (e.g. Pearce 1975).

Shervais (1982) pioneered the combined use of vanadium and titanium. Vanadium is unique in that it has three oxidation states, all of them immobile: V\textsuperscript{III}, V\textsuperscript{IV} and V\textsuperscript{V}. Melting of the mantle in the presence of water makes the melting process more oxidising and that in turn increases the proportion of vanadium in the higher oxidation states. Because V is more incompatible in the higher oxidation states, this causes more vanadium to be partitioned into the magma. Thus, subducted water leads to a melting regime that produces magmas not just with lower Ti but also with higher V, in other words high V/Ti.

The V/Ti proxy is different from the Th/Nb proxy in that only the latter identifies subduction zone influence independent of mantle temperature and mantle depletion. In contrast, V/Ti is influenced by two processes, Ti depletion and V enrichment. Of these, only the second is subduction-specific. Thus I prefer to use the Ti/Cr or V/Ti proxy specifically to define the melting regime of lavas already known to have a suprasubduction zone setting. On Shervais’s V–Ti diagram (Fig. 5c), lava compositions shift from low V/Ti in MORB lavas through intermediate V/Ti in island arc tholeiite (IAT) compositions to high V/Ti in boninites. Of particular importance in fingerprinting ophiolites is the fact that subduction-initiation ophiolites commonly form a distinct time trend on this diagram: from more MORB-like when subduction begins, to more IAT-like as subduction influence increases, to more boninite-like as the slab subducts far enough to act as a barrier to mantle flow (Fig. 1d).

The V–Ti plot in Figure 5c provides the extra information needed to improve the fingerprinting of the three ophiolites identified as having suprasubduction zone origins. The Taitao ophiolite predictably plots in the MORB field as its mantle source lies below the subduction zone (Fig. 1s) and

**Figure 5** Use of discriminant diagrams to fingerprint tectonic settings. The examples used to illustrate their application are from the ophiolites described in the text; representative samples from them are drawn as patterns in Figure 3c. (A) The Th/Nb proxy is used to distinguish suprasubduction zone (SSZ) from mid-ocean ridge ophiolites. (B) The Ti/Yb plume-melting proxy distinguishes N(normal), E(enriched), P(plume-influenced) and C(contaminated)-MORB. (C) The V/Ti subduction-melting proxy is useful to distinguish MORB, island arc tholeiite (IAT) and boninite magma types. Diagonal lines are from Shervais (1982) and Pearce (2008). Note the importance of the volcanic stratigraphy (lower [L] tholeiites overlain by upper [U] boninites) for identifying the subduction-initiation setting of the Troodos Massif. See captions of Figures 1 and 2 for abbreviations.
so melts without the addition of subduction-derived fluid. The Guéguen ophiolite extends from the IAT field to the centre of the MORB field in Figure 5C. This is consistent with the fact that the samples also span the MORB-OIB array and volcanic arc fields in Figure 5A. The lower Troodos lavas plot as island arc tholeiites but the upper lavas plot as boninites, a time sequence indicative of subduction initiation. The lower lavas therefore represent forearc basalts (FAB) based on these criteria.

**CONCLUSIONS**

Geochemical fingerprinting of ophiolite lavas follows what is a now a well-established procedure of (1) identifying the elements that are immobile (Fig. 2); (2) examining the immobile element patterns (Fig. 3); (3) classifying the rock type and selecting basic rocks for fingerprinting (Fig. 4); (4) using a subduction-input proxy to distinguish between mid-ocean ridge and supra-subduction zone ophiolites (Fig. 5A); (5) using a plume-melting proxy to further define the setting of the mid-ocean ridge ophiolites (Fig. 5A); and (6) using a subduction-melting proxy to further define the setting of the supra-subduction zone ophiolites (Fig. 5C). This procedure defines the magma type and most probable setting based on immobile element criteria, and the results can then be integrated with other information for a final evaluation of the tectonic setting of the ridge at which the ophiolite formed.

**ACKNOWLEDGMENTS**

I thank Joe Cann, Fred Vine, Euan Nisbet and Mike Bickle for their various contributions to the birth of this research field, Paul Robinson for some of the Troodos data, Harald Furnes and Jean Bédard for their helpful comments on the manuscript, and Yildirim Dilek and John Valley for providing excellent editorial support.

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**Records of Ocean Growth and Destruction in the Oman–UAE Ophiolite**

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INTRODUCTION

The Oman–UAE ophiolite is the largest piece of oceanic crust exposed on land, yet debate continues about its origin. It has been variously considered as an ideal analogue for a fast-spreading mid-ocean ridge and as a typical suprasubduction zone ophiolite. A resolution to this conundrum comes from the recognition of at least two different phases of magmatism, with the second phase being most voluminous in the northern blocks of the ophiolite. The first phase was formed at an oceanic spreading centre; petrological and geochemical evidence clearly shows that the second phase was formed above a subduction zone.

**KEYWORDS:** Oman–UAE ophiolite, suprasubduction zone, Moho Transition Zone, multi-phase magmatism

However, work in the northern blocks of the ophiolite (Lippard et al. 1986; Styles et al. 2006) has led to the recognition of much greater complexity, notably the presence of large volumes of younger magmatic rocks which cross-cut, and clearly post-date, the standard ophiolite succession and which have island arc–type geochemical characteristics. Such characteristics have also been recognised in the earlier, spreading centre magmatic suite, and this led some authors to suggest that the Oman–UAE ophiolite formed in a suprasubduction zone (SSZ) setting (Alabaster et al. 1982). This different perspective has led to continuing debate over the geodynamic setting of the ophiolite. Some authors downplay the significance of the later magmatism and continue to interpret the Oman–UAE ophiolite as having formed at a fast-spreading mid-ocean ridge (Nicolas and Boudier 2011).

Over the past decade, our work has focused on the less well-known northern section of the ophiolite in the UAE. We have systematically mapped the two northernmost blocks in detail and we have studied their petrography, mineralogy, geochemistry and geochronology (Styles et al. 2006; Goodenough et al. 2010). The northern part of the ophiolite contains voluminous later magmatic phases, making it a crucial area for deciphering the origin and evolution of the Neo-Tethyan oceanic crust. This paper reviews the findings from our work in the UAE and considers what they tell us about the history of the Oman–UAE ophiolite as a whole.

**MAGMATIC HISTORY IN THE NORTHERN BLOCKS OF THE OMAN–UAE OPHIOLITE**

The two most northerly segments of the ophiolite, the Khor Fakkhan and Aswad blocks, lie within the UAE (Fig. 1). Easy access and excellent exposure in three dimensions have allowed detailed study of the earlier, sea-floor spreading–related magmatism, which we term Phase 1, and the relationships and internal features of widespread cross-cutting intrusions, which are collectively described as...
Phase 2 magmatism. These respectively correlate with the V1 and V2 episodes recognised in the volcanic succession further south in Oman (Alabaster et al. 1982; Ernewein et al. 1988). Some of the key features of the two phases are described in Table 1.

The Khor Fakkan and Aswad blocks each contain large volumes of mantle rocks, made up of variably serpentinised harzburgite and dunite (Fig. 2a). The dunite occurs as networks of veins up to about 1 m wide within the harzburgite; these veins represent melt channels within the mantle that were exploited by both Phase 1 and Phase 2 magmas (Kelemen et al. 1995). The mantle rocks pass upwards into the Moho Transition Zone (MTZ), a region of gradational change between the mantle and the crust (Boudier and Nicolas 1995). It typically consists of massive dunite at the base, overlain by a ‘Mixed Unit’ comprising variable quantities of dunite, wehrlite, pyroxenite, and gabbro (Benn et al. 1988; Goodenough et al. 2010). In the UAE, the MTZ is a major part of the sequence, being locally over 1000 m thick (Fig. 2a). Wehlrites and pyroxenites are abundant, intruding and clearly post-dating Phase 1 crustal gabbros; these ultramafic intrusions are consequently ascribed to Phase 2 magmatism.

The MTZ is overlain by a Phase 1 crustal sequence, in which layered gabbros pass upwards into high-level gabbros, a sheeted dyke complex, and pillow lavas. The layered gabbros vary in thickness from ~500 m to over 1000 m, and are characterised by centimetre- to metre-scale rhythmic igneous layering. They grade upwards into massive high-level gabbros that range from strongly foliated to ‘varitextured’ (showing significant grain size and textural heterogeneity on the centimetre to metre scale). Mafic dykes become more abundant in the upper parts of the high-level gabbro, merging into a classic sheeted dyke complex, which fed the overlying pillow lavas.

However, the key feature highlighted in this paper is the presence of the voluminous Phase 2 intrusive suite. In the Aswad block, these later intrusions include wehrlite and pyroxenite in the MTZ and the lower part of the crust, together with a complex network of gabbro, microgabbro, diorite, basalt and tonalite intrusions that cut across the entire Phase 1 crustal suite and locally intrude the mantle rocks (Fig. 2a). Together, Phase 2 intrusions make up around half of all crustal exposure in the UAE, a far higher proportion than has been recognised elsewhere (Goodenough et al. 2010). The Phase 2 gabbros and dikes are very heterogeneous, but in many areas they are characterised by a generally finer grain size and a more felsic composition than the Phase 1 gabbros, even where they cut across the MTZ and mantle rocks. Pegmatitic gabbro and diorite are also common within Phase 2, and they are typically associated with tonalites and hybrid intrusions that show magma mingling textures. The Phase 2 intrusions take the form of dykes, sills and irregular bodies up to several kilometres across (Fig. 3). They are commonly associated with syn-intrusion faults and ductile shear zones, suggesting that their distribution and emplacement were structurally controlled.

The Phase 1 and Phase 2 lithologies show some clear mineralogical and textural differences that indicate contrasting environments of formation. The Phase 1 layered and high-level gabbros are mineralogically similar to each other, with early formed euhedral olivine and plagioclase laths, the latter having a parallel orientation in layered gabbro. Clinopyroxene may also form euhedral crystals, but commonly occurs as large grains poikilitically enclosing olivine and plagioclase. These textures indicate a crystallisation sequence of olivine–plagioclase–clinopyroxene, a sequence that is typically found in near-anhydrous magmas and is commonly seen in mid-ocean ridge basalts (MORBs). Hornblende is found locally in these gabbros. In contrast, many of the Phase 2 rock types show evidence of formation from different magmas. Wehlrites in the MTZ and the lower parts of the crustal section are typically poikilitic, with clinopyroxene forming large plates up to several centimetres across enclosing rounded crystals of olivine. Plagioclase, where present, is generally interstitial. These textures indicate an olivine–clinopyroxene–plagioclase crystallisation sequence, indicative of hydrous magmas containing around 5 wt% water (Koepeke et al. 2009). The more-evolved intrusions emplaced into the crustal section are very variable in composition, ranging from gabbros to tonalites. Some gabbros are similar in mineralogy to Phase 1 gabbros, but primary amphibole and/or orthopyroxene are present in many areas whilst olivine is rare, again indicating a more hydrous magma. The gabbros grade into more felsic rocks with increasing amounts of quartz and plagioclase. It is notable that, in the UAE, all the felsic lithologies, such as tonalites, belong to Phase 2 magmatism.

The gabbros and other coarse-grained rocks of the crustal section have textures that indicate a cumulate origin, and their bulk geochemistry has been affected by those cumulate processes. However, the compositions of volcanic rocks and dikes are closer to those of primary magma, and so their bulk-rock geochemistry can be used to interpret source composition and tectonic setting. In the UAE, Phase 1 dykes and pillow basalts have MORB-like geochemistry, but with small negative Nb and Ta anomalies (Fig. 4) that could point towards formation in a marginal basin setting. In contrast, Phase 2 dykes have features, such as significant negative Nb and Ta anomalies and light rare earth element depletion (Fig. 4), that are characteristic of magmas formed in a suprasubduction zone (SSZ) setting (Goodenough et al. 2010). The geochemistry of chrome spinels in the mantle harzburgites and dunites can also be used to distinguish between MOR and SSZ settings. The analysis of spinels from
the Oman–UAE ophiolite has provided evidence for spatial and temporal changes from an anhydrous MOR setting to a hydrous SSZ setting (Python et al. 2008; Rollinson and Adetunji 2013).

Based on the evidence from the UAE discussed above, we propose that Phase 1 magmatism occurred at a spreading centre, which may have been at a mid-ocean ridge but was more likely in a marginal basin above a newly initiated subduction zone (MacLeod et al. 2013). Phase 2 magmas were hydrous and record the initial stages of arc magmatism. Now, we turn our attention further south to Oman and investigate whether this model holds true for the whole Oman–UAE ophiolite.

**IS THE MAGMATIC HISTORY CONSISTENT ALONG THE LENGTH OF THE OPHIOLITE?**

The structural blocks of the Oman–UAE ophiolite can be divided into three main groups, with the blocks within each group showing similar characteristics but also differences from the other groups. The northern blocks include Khor Fakkan and Aswad in the UAE, as well as the Fizh and Salahi blocks in northern Oman; the central blocks around Jebel Akhdar include the Sarami, Haylayn and Rustaq blocks; and the south-eastern blocks, to the east of the Semail Gap, are Semail and Wadi Tayin (Fig. 1).

The proportion of Phase 2 magmatic rocks varies significantly along the length of the ophiolite, although in some areas Phase 2 gabbros may not have been recognised. The two gabbro phases commonly look similar at the outcrop scale; and mapping of the intrusive relations on a wider scale is needed to clearly identify the second-phase gabbros.

The distribution of Phase 2 indicated on the map (Fig. 1) is based on comparison of our own maps of the UAE with the national geological maps of Oman. It is clear from these maps that there is a close correlation between Phase 2 magmatism (as described above) and the Late Magmatic Units mapped in Oman, both of which are ascribed to formation from hydrous magmas. The Late Magmatic Units are thus considered here to be part of Phase 2, and are shown as such on Figure 1. Whilst there is some debate about the origin of these later magmas (Koga et al. 2001), they are typically hydrous in nature, and we consider it likely that they are related to the second magmatic phase throughout the ophiolite. Their origin is worthy of further investigation.

Large amounts of Phase 2 magma are found in the MTZ, which shows notable lateral thickness variations (Boudier and Nicolas 1985). In the north, the MTZ is locally over 1000 m in thickness, but in the central blocks it is typically around 10 m thick (Benn et al. 1988), although some discrete large masses of wehrlite, locally forming 20–40% of the plutonic section, have been identified (Juteau et al. 1988). At the south-eastern end of the ophiolite, in the Maqsad area of the Semail block, an area of thick MTZ (500–750 m) is considered to have formed at a zone of mantle upwelling and is known as the Maqsad Diapir. The current interpretation is that this sequence formed beneath a mid-ocean ridge (Boudier and Nicolas 1995). Within the Maqsad Diapir, the MTZ is locally made up of dunite with gabbro lenses, although large areas of wehrlite are present around the edges of the diapir and are suggestive of Phase 2 magmatism (Clénet et al. 2010). The absence of wehrlite within the diapir itself provides evidence for it being formed during the Phase 1 magmatic episode.

Late intrusive complexes have been identified in all the northern and central blocks of the ophiolite, although they are less voluminous in Oman than in the UAE (Lippar et al. 1986; Adachi and Miyashita 2003). These intrusions include wehrlite, gabbro, diorite and tonalite, are locally orthopyroxene-bearing, and are commonly associated with faults; we equate them to the Phase 2 plutonic rocks in the UAE. Study of the mineral chemistry in some of these Phase 2 intrusive complexes has shown that the later gabbroic intrusions typically have more calcic plagioclase at any given Mg# [i.e. atomic Mg/(Mg + Fe)] of olivine and clinopyroxene, whereas the early crustal gabbros have more sodic plagioclase (Yamasaki et al. 2006). Similarly, the clinopyroxenes of Phase 2 magmas are lower in TiO<sub>2</sub>, NaO and Al<sub>2</sub>O<sub>3</sub> (Adachi and Miyashita 2003; Goodenough et al. 2010). All these features are compatible with crystallisation from hydrous magmas in a SSZ setting (Yamasaki et al. 2006).

The central and northern blocks of the ophiolite have a thick sequence of extrusive volcanic rocks (basalts and andesites) containing several distinct units that can be correlated over a considerable distance (Alabaster et al. 1982). The basal Geotimes unit, also termed V1 (Ernewein et al. 1988), has the geochemical characteristics of lavas formed at a spreading centre, potentially in a marginal basin setting (Alabaster et al. 1982). This unit is overlain by the Lasail, Alley and Cpx-phyric units (collectively termed V2), which include boninitic rocks and are geochemically akin to island arc lavas (Alabaster et al. 1982; Lippar et al. 1986; Ishikawa et al. 2002), although some authors have suggested that parts of the V2 sequence formed by second-stage melting of the spreading centre mantle source (Ernewein et al. 1988; Godard et al. 2006). As with Phase 2 gabbros, clinopyroxenes in the Lasail, Alley and Cpx-phyric units are lower in TiO<sub>2</sub> and Na<sub>2</sub>O than in the Geotimes unit, and they are thus considered to be the extrusive equivalents of Phase 2 intrusions. The uppermost Salahi
unit post-dates the main episodes of ocean crust formation and has a within-plate geochemistry; it is not discussed further here.

It is clear that Phase 2 magmatism is an important part of all the northern and central blocks of the Oman–UAE ophiolite, although there appears to be a general southwards decrease in volume. By contrast, in the south-eastern blocks, Phase 2 magmatism is much less abundant. No large, late, intrusive bodies have been described, although areas of wehrlite and pyroxenite have been mapped (Fig. 1). The volcanic succession in the south-eastern blocks is thin and poorly preserved, and Phase 2 volcanic units have not been identified there. Furthermore, a study of chrome spinels in mantle dykes along the length of the ophiolite has indicated clear spatial variations in magma type; the SSZ (Cr-rich) component decreases from the north to the south-east, and MORB-type compositions are particularly common in a zone centred on the Maqsad Diapir (Python et al. 2008). The evidence indicates that the south-eastern blocks have not been affected by Phase 2 magmatism to the same extent as the central and northern blocks.

**TIMING OF PHASE 2 MAGMATISM**

Considering the wealth of research that has been carried out on the Oman–UAE ophiolite, few high-precision radiometric ages had been obtained until very recently. The general age of the ophiolite was originally established by U–Pb dating of zircon grains in ‘plagiogranites’, the most evolved magmas and hence those with the highest zircon contents. A number of samples from along the length of the
ophiolite gave ages ranging from around 93.5 to 97.9 Ma, which were considered at the time to represent the time of formation of the ophiolite crust (Tilton et al. 1981). More recently, U–Pb dating of zircon grains from several tonalite and trondhjemite intrusions along the length of the ophiolite has been carried out using modern methods (ID-TIMS), producing more precise results (Warren et al. 2005; Goodenough et al. 2010; Rioux et al. 2012, 2013). All these intrusions were dated at between 94 and 96.1 Ma, and notably, the majority of tonalites and trondhjemites along the length of the ophiolite fall within a narrow age range of 95.3 ± 0.5 Ma. Since the tonalites and trondhjemites typically represent the last part of the ophiolitic crust and are considered to be part of Phase 2, this age constraints the last stages of crustal formation. Distinctly earlier tonalite and trondhjemite ages (96.1–95.8 Ma) came from the southernmost Wadi Tayin block, which has little Phase 2 magmatism, and these ages are associated with Phase 1 (Rioux et al. 2012).

Recently published U–Pb ages for gabbros also cover much of the length of the ophiolite. Phase 2 gabbros in the northernmost blocks give ages of 96.40 ± 0.29 Ma (the Khor Fakkan block) and 95.74 ± 0.32 Ma (the Aswad block) (Goodenough et al. 2010). Gabbro ages in the central blocks are from ~96.2 to 95.4 Ma (Rioux et al. 2013); these ages are considered to represent Phase 1 magmatism, but they overlap with the ages for Phase 2 magmatism in the northern blocks. In the southern Wadi Tayin and Semail blocks, several samples of Phase 1 gabbro have similar ages in the range 96.4–95.5 Ma (Rioux et al. 2012, 2013). Ar–Ar ages have also been obtained from hornblende-bearing gabbros and tonalites in Oman, again likely to be part of the Phase 2 magmatism, and these rocks range in age from 93.6 ± 0.5 Ma to 96.3 ± 1.3 Ma (Hacker et al. 1996). Overall, the crust of the Oman–UAE ophiolite was largely formed in the 96.4 to 95 Ma period. The transition from Phase 1 to Phase 2 magmatism occurred during this time, and may have begun first in the northern blocks of the ophiolite.

A number of workers have discussed the timing of ophiolite obduction. Both Ar–Ar and U–Pb dating of rocks in the metamorphic sole below the ophiolite indicate an early, rapid phase of intraoceanic thrusting at ~95–93 Ma (Hacker et al. 1996; Warren et al. 2005; Stylès et al. 2006; Rioux et al. 2013). These ages overlap with the latter parts of Phase 2 magmatism. The timing of subsequent translation onto the continental crust remains controversial. Metamorphism and melting in continental rocks in the UAE are considered to be associated with ophiolite emplacement onto the continental margin and have been dated at ~93–92 Ma (Stylès et al. 2006). However, in the Saih Hatat area at the southeastern end of the ophiolite, eclogites are thought to have formed during subduction of continental crust associated with overthrusting of the ophiolite. Zircon grains in these rocks have been dated at ~82–79 Ma (Warren et al. 2005). These ages indicate that subduction continued along the southern Oman part of the Arabian margin long after it ceased further north in the UAE. This might mean that the northern and central blocks of the Oman–UAE ophiolite were emplaced onto the continental margin significantly earlier than the south-eastern blocks.

**ORIGIN OF PHASE 2 MAGMATISM**

The northern and central blocks of the Oman–UAE ophiolite are characterised by spreading centre–type Phase 1 magmatism overprinted by voluminous Phase 2 magmatism (Table 1). The amount of Phase 2 magmatism decreases southwards along the ophiolite. Petrological criteria indicate that the Phase 2 magmas were more hydrous than the basaltic, MORB-like magmas of Phase 1. However, the source of the hydrous fluids in these magmas continues to be debated.

A number of geochemical criteria – including the whole-rock geochemistry of volcanic rocks and dykes, and the chemistry of clinopyroxenes in gabbros and chrome spinels in the mantle peridotites – indicate a suprasubduction zone origin for the Phase 2 magmas. Despite this, some authors argue for the formation of both magmatic phases at a mid-ocean ridge (or possibly a spreading ridge in a large marginal basin). Whilst it is generally agreed that Phase 2 magmas were hydrous, it has been suggested that this could be due to seawater penetrating into a mid-ocean ridge magma chamber from above, rather than to fluids released from a subducting slab below (Boudier et al. 2000), with the geochemistry of Phase 2 magmas explained by melting of an already depleted mantle (Godard et al. 2006). This model does not easily explain the large volumes of Phase 2 magmatic rocks in the northern blocks, nor why their equivalents are not found at modern mid-ocean ridges. In addition, the evidence from chrome spinels indicates that the hydrous magmas were derived from beneath the Moho Transition Zone.

We conclude, therefore, that Phase 1 crust in the Oman–UAE ophiolite was formed at a spreading centre, probably in a marginal basin above an infant subduction zone (MacLeod et al. 2013). Phase 2 magmas were emplaced as that subduction zone developed (Fig. 5), and the influence of fluids from the subducting slab increased both with time and towards the north within the ophiolite. Compression above the subduction zone led to intraoceanic thrusting at the time of Phase 2 magmatism, with magmas being emplaced into the crust along shear zones. When these suprasubduction zone magmas were being emplaced in the northern part of the ophiolite, the southern part was continuing to form at a spreading centre.

**Table 1** SOME OF THE KEY FEATURES OF PHASE 1 AND PHASE 2 MAGMATISM

<table>
<thead>
<tr>
<th>Phase 1 magmatism</th>
<th>Phase 2 magmatism</th>
</tr>
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<tbody>
<tr>
<td>Classic ophiolite sequence with a clear ‘stratigraphy’</td>
<td>Cross-cutting magmatism, forming irregular, heterogeneous igneous bodies on all scales</td>
</tr>
<tr>
<td>Cross-cut by faults and shear zones</td>
<td>Associated with faults and shear zones</td>
</tr>
<tr>
<td>Harzburgite, dunite, layered to isotropic gabbro, microgabbro, basalt</td>
<td>Dunite, wehrlite, clinopyroxene, very heterogeneous gabbro, tonalite and trondhjemite, mafic–felsic mingled magmas</td>
</tr>
<tr>
<td>Mineralogy dominated by plagioclase, clinopyroxene and olivine</td>
<td>Mineralogy dominated by plagioclase and clinopyroxene, with variable amounts of olivine, orthopyroxene, hornblende and quartz</td>
</tr>
<tr>
<td>Olivine–plagioclase–clinopyroxene crystallisation sequence (anhydrous magmas)</td>
<td>Olivine–clinopyroxene–plagioclase crystallisation sequence (hydrous magmas)</td>
</tr>
<tr>
<td>MORB-like magma geochemistry</td>
<td>SSZ-type magma geochemistry with depletion in Nb, Ta and light rare earth elements</td>
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<td>MORB signatures in associated mantle spinels</td>
<td>SSZ signatures in associated mantle spinels</td>
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**ACKNOWLEDGMENTS**

A large number of papers have been written about the Oman–UAE ophiolite, but because of space constraints, we refer only to a small selection of them here; we therefore acknowledge the work of many authors beyond those mentioned in the reference list. Marguerite Godard, Harald Furnes and Sumio Miyashita are thanked for their constructive comments on an earlier version. Yildirim Dilek and John Valley are thanked for their editorial handling. This paper is published with the permission of the Executive Director of the British Geological Survey. ++

**Figure 5** Generalised model for the genesis of Phase 2 magmas above a developing subduction zone at ~95 Ma.
Recent geological and geophysical surveys in the Izu-Bonin-Mariana forearc have revealed the occurrence on the seafloor of oceanic crust generated in the initial stages of subduction and the earliest stage of island arc formation. The earliest magmatism after subduction initiation generated forearc basalts, and subsequently, boninitic and tholeiitic to calc-alkaline lavas were produced. Collectively, these rocks make up the extrusive sequence of the Izu-Bonin-Mariana forearc oceanic crust. This volcanic stratigraphy and its time-progressive development are analogous to those documented from many suprasubduction zone ophiolites. Most suprasubduction zone ophiolites may be on-land fragments of forearc oceanic crust, produced during the initiation of subduction and the early stages of island arc development.

**SUBDUCTION INITIATION AND FOREARCS**

The initiation of subduction and the subsequent birth and early development of island arcs are still poorly understood (e.g. Stern 2004). Exposed “naked forearcs,” where neither accretion of material from the subducting plate nor volcanism or sedimentation after the earliest stage of arc formation occurred to cover the basement lithologies, are particularly valuable for understanding how subduction zones start (Stern et al. 2012). The Izu-Bonin-Mariana (IBM) forearc (Fig. 1) is an archetypal example with widespread exposures of early-arc lavas, and it is thus an excellent location for investigating subduction initiation and subsequent island arc evolution. Understanding the igneous stratigraphy of the IBM forearc has been slow because most outcrops of intraoceanic forearcs are deeply submerged and are difficult to study directly. In recent years, we have examined the forearc crustal section of the IBM along the trench slope via submersible observations and extensive sampling (Ishizuka et al. 2006, 2011a; Reagan et al. 2010). We have discovered that the basement lithologies here represent magmatism associated with subduction initiation and that this magmatism occurred nearly synchronously along a zone that is up to 300 km wide and 3000 km long (Stern and Bloomer 1992; Bloomer et al. 1995).

**FOREARC STRATIGRAPHY OF THE IZU-BONIN-MARIANA ARC**

The Bonin Islands (Fig. 1) expose an intact record of magmatism produced early in the history of the IBM arc. These islands are known as the type locality for boninite, a high-Mg andesite lacking plagioclase phenocrysts and with exceedingly low concentrations of titanium and rare earth elements (REEs). Geochronological studies have revealed that the eruption of boninites in the IBM arc lasted for 3 to 4 million years after starting at ~48 Ma. These boninitic lavas, therefore, constitute the oldest volcanic sequence exposed on the islands (Ishizuka et al. 2006, 2011a). The Mariana section of the IBM arc also has a forearc high between the Mariana Trench and the volcanic front (Fig. 1); this high includes the islands of Guam, Rota, Rugen, and Saipan.

**KEYWORDS**: Izu-Bonin-Mariana arc, subduction initiation, forearc stratigraphy, suprasubduction zone ophiolite, boninite, geochronology
Tinian, and Saipan. The early-arc rocks here are transitional between boninite and tholeiitic arc lavas and have ages of ~44 Ma (e.g. Reagan et al. 2008). In both sections, tholeiitic to calc-alkaline lavas with relatively normal major and trace element compositions have ages of 44–45 Ma.

In addition to these subaerially exposed sections, submarine portions of the forearc highs have been investigated during the past several years (Fig. 1; Ishizuka et al. 2006, 2011a; Reagan et al. 2010). The investigations in the Izu-Bonin section started with bathymetric surveys and rock sampling by dredging, with the purpose of documenting the structure and stratigraphy of the forearc crust. Direct observations of the crustal section along the trenchward slope of the forearc highs using both a manned submersible (Shinkai 6500) and a remotely operated vehicle (Kaiko), which are capable of diving to depths of 6500 m and 7000 m, respectively, followed the initial bathymetric surveys (Ishizuka et al. 2011a). The southern Mariana forearc was also extensively surveyed by early dredging and drilling, followed by Shinkai 6500 dives (Reagan et al. 2010). The observed geological sections of the Izu-Bonin and Mariana forearcs are nearly identical. The stratigraphic section of the forearc crust overlaying the peridotites comprises, from bottom to top (Fig. 2), (1) gabbroic rocks, (2) a sheeted dike complex (Fig. 3a), (3) basaltic lava flows (Fig. 3a), (4) lavas and dikes of boninite and their differentiates (Fig. 3c, d), (5) transitional high-Mg andesites, at (6) tholeiitic and calc-alkaline arc lavas.

The oldest volcanic products of the IBM arc are forearc basalts (FABs), consisting mainly of pillow lavas and hyaloclastites (Fig. 2; Reagan et al. 2010). The lavas encountered in DSDP (Deep Sea Drilling Project) sites 458 and 459 in the central Mariana forearc show a progression from FAB-like lavas at the bottom to nearly boninitic lavas on top, linking these two lava types in time and space (Reagan et al. 2010).

The sheeted dikes occur at the same or lower stratigraphic levels relative to the FAB lavas, and they have mineral assemblages and chemical compositions identical to those of the FAB lavas. The formation of sheeted dikes in the IBM arc–trench system illustrates that magmatism occurred in an extensional stress field; in addition, these dikes are key evidence for seafloor spreading and ocean crust production in a forearc tectonic setting (e.g. Umino et al. 2008). These observations indicate that the first magmatic activity in the IBM arc was associated with seafloor spreading.

The sequence underlying the FABs in the Bonin Islands area consists of medium-grained, undeformed, orthopyroxene-bearing gabbros, predominantly composed of plagioclase, clinopyroxene, and orthopyroxene, with accessory magnetite, apatite, and zircon. The gabbros encountered in the Mariana forearc have little or no orthopyroxene, but are otherwise similar in texture and composition to gabbros from the Bonin Islands area.

The peridotites at the lowest stratigraphic level of the IBM forearc section are dominated by harzburgite with dunite veins (Morishita et al. 2011a). Two different dunites are present: dunite bearing spinels with high atomic Cr/(Cr+Al) ratios (i.e. chromium number, Cr#, greater than 0.8), and dunite containing spinels with medium Cr# values (0.4–0.6) (Morishita et al. 2011a). These two types of dunite were in equilibrium with two distinctive melts—boninitic melt and mid-ocean ridge basalt (MORB)–like melts. This interpretation is consistent with the volcanic stratigraphy observed in the IBM forearc, where FABs and boninitic lavas progressively overlie the peridotites. From this observation, we infer that the magmas produced in the earliest phase of arc formation were derived from and interacted with the upper mantle in the forearc basement.

**AGE CONSTRAINTS**

FABs from the Bonin forearc were dated at between 48 and 52 Ma by 40Ar/39Ar techniques (Fig. 4; Ishizuka et al. 2011a). These ages are older than the oldest age for the boninites (48.2 Ma; Ishizuka et al. 2006), confirming that FAB predated boninite eruption. These age relationships mean that the oldest magmatic activity in the IBM arc dates back to ~52 Ma, which closely matches the timing of the change in the Pacific Plate motion (~50 Ma; Sharp and Clague 2006). The available U–Pb ages of zircon from Bonin forearc gabbros are 51.6 and 51.7 Ma, indicating that these intrusive rocks formed contemporaneously with the forearc basalt (Fig. 4; Ishizuka et al. 2011a). Boninites from the Bonin Islands have 40Ar/39Ar ages of 46.0–48.2 Ma, and the overlying transitional high-Mg andesites have ages of 44.3–44.74 Ma (Fig. 4). The uppermost sections consist of tholeiitic and calc-alkaline arc lavas, and these are younger than 44 Ma (Ishizuka et al. 2006).

FABs from the Mariana forearc also yielded a 40Ar/39Ar age of 51.1 Ma (Ishizuka et al. 2011a), indicating that volcanism associated with subduction initiation occurred contemporaneously along the entire length of the IBM arc. Lavas recovered from DSDP sites 458 and 459, with transitional compositions between FAB and boninite, were dated at 49 Ma (Cosca et al. 1998), and lavas transitional between boninite and tholeiitic arc lavas on Guam were dated at about 44 Ma (Meijer et al. 1998). The eruption of high-silica rhyolite on Saipan (45.1 Ma; Reagan et al. 2008) marked the first appearance of arc volcanism with relatively normal trace element compositions. Tholeiitic to calc-alkaline arc lavas on Rota, Saipan, and Guam erupted...
after 42 Ma (Fig. 4; Reagan et al. 2008). These age relationships suggest that the crustal section exposed between the trench and the forearc high along most or all of the IBM system was generated over approximately 7–8 million years while the area transitioned from mantle upwelling and near-trench extension immediately after subduction initiation to normal mantle counterflow.

MAGMATIC EVOLUTION

The geochemical characteristics of FABs are compatible with their being generated from clinopyroxene-impoverished residual mantle. This mantle was left over from an earlier stage of decompression melting of possibly depleted asthenospheric mantle that upwelled when the Pacific Plate began to subduct beneath the Philippine Sea Plate (Reagan et al. 2010). FABs have light REE (LREE)–depleted patterns like MORB, but have lower concentrations of REEs and high-field-strength elements (HFSEs), such as Nb, Ta, and Zr (Fig. 5a, b). For example, FABs have significantly lower Ti concentrations and Ti/V ratios compared to basalts from the Philippine Sea Basin (Fig. 5c; Reagan et al. 2010; Ishizuka et al. 2011a), and they generally have lower LREE/HREE (heavy REE) ratios compared to N-MORB (normal MORB) and backarc basin basalts from the Philippine Sea Basin (e.g. Hickey-Vargas 1998; Ishizuka et al. 2009).

Most FABs lack a clear enrichment in large-ion lithophile elements (LILEs, such as Ba, Sr, Pb) compared to REEs and HFSEs, implying that, like MORB, they received little or no input from slab-derived material (Fig. 5a). Nevertheless, transitional FAB glasses recovered from DSDP sites 458 and 459 are clearly enriched in LILEs as a result of the modification of their melt source by subduction-derived fluids (Reagan et al. 2010).

Boninite was formed by partial melting of depleted harzburgite that was hydrated by slab-derived fluids. Heat was supplied by an upwelling asthenosphere associated with the sinking slab. Transitional and boninitic lavas share some geochemical characteristics with FABs, such as low Ti, low HFSE contents, and very low Ti/V ratios (Fig. 5a, b). These geochemical features indicate a depleted mantle source for the magmas of the boninites and transitional lavas. There also are some clear differences between the two magma types in terms of their melt sources. For example, boninites have a compositional signature indicative of slab-derived material, such as high concentrations of alkali metals, alkaline earths, and U compared to REE concentrations (Fig. 5a, b).

Boninitic rocks have been found in the same stratigraphic position at several sites along the entire ~3000 km length of the IBM forearc, suggesting that boninite volcanism occurred contemporaneously along the entire forearc, beginning at about 48 Ma (Fig. 4). The wide distribution of boninitic rocks rules out the possibility of a point heat source for the genesis of their magmas, and is consistent with a model of boninite magma genesis involving high temperatures at shallow depths along the length of the IBM arc.

Following boninite magmatism, transitional high-Mg andesite (Taylor et al. 1994; Ishizuka et al. 2006; Reagan et al. 2008) and then tholeiitic to calc-alkaline arc magmas started to erupt after ~44 Ma. This activity marked the beginning of steady-state subduction and convection in the mantle wedge. The transitional suites lavas from Guam, with compositions similar to those of the high-Mg andesite lavas from the Bonin Ridge, erupted at about 44 Ma (Fig. 4). This observation means that the eruption of high-Mg andesites (transitional suites) with REE and TiO$_2$ concentrations

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**Figure 3** Photos of samples and outcrops of the IBM forearc. Locations of the dive sites are shown in Figure 1. 
(A) Sheeted dike outcrop at 5555 meters below sea level (mbsl) (Shinkai 6500 dive 6K1154). (B) Aphyric pillow basalt in the Mariana forearc at 6015 mbsl (Shinkai 6500 dive 6K1093). (C) Boninite dike swarm along the east coast of Chichijima Island, Bonin Islands. The total height of the lava outcrop is over 50 m. (D) Boninite pillow lavas on the coast of Chichijima Island.
higher than those of boninites from the Bonin Ridge was also coeval along the entire length of the arc. After 44 Ma, tholeiitic to calc-alkaline arc magmas formed, and these share many geochemical characteristics with the later arc magmas. Note, however, that transitional boninites erupted at the same time as tholeiitic to calc-alkaline arc lavas erupted in different sections of the IBM arc between 45 and 43 Ma. We interpret these relationships to mean that there was an ~2-million-year time period during which mantle counterflow replaced the upwelling mantle regime and that this switch in the convection regimes occurred at different times in different portions of the arc.

The arc lavas that began erupting after 44 Ma have higher TiO₂, Zr, Hf, and REE concentrations than the older boninitic lavas (Fig. 5a). These geochemical features imply that the mantle involved in the younger IBM arc magmatism was less depleted than the mantle sources of the magmas older than 44 Ma. This phenomenon can be explained by a change from simple upwelling to counterflow of the asthenosphere in the newly established mantle wedge, causing partial melting to move deeper into the mantle (Ishizuka et al. 2006). During this process, the magmatic axis of the arc retreated from the trench, which in turn facilitated cooling of the forearc mantle by continuous subduction.

**DISCUSSION AND LINKS TO SUPRASUBDUCTION ZONE OPHIOLITES**

A possible analogy between western Pacific forearc oceanic crust and supraduction zone (SSZ) ophiolites has been discussed for more than 20 years (e.g. Bloomer et al. 1995; Stern et al. 2012). These discussions were based on the understanding of forearc oceanic crust derived from ODP (Ocean Drilling Project) and DSDP boresoles and dredge sampling in the IBM and Tonga forearcs (Bloomer et al. 1995). New key observations obtained from the IBM forearc during the last several years include the following:

1. MORB-like tholeiitic basalts (FABs) with compositions that differ from nearby backarc lavas have been found underlying the boninitic lavas.
2. Sheeted dikes, clear evidence of seafloor spreading, have been found.
3. Lavas transitional between FABs and boninites have been recognized, linking these two magma types in time and space.
4. Precise geochronology of forearc sections along the IBM arc has documented the timing, duration, and scale of each of the magmatic events related to subduction initiation and early arc development.

One of the most important characteristics linking SSZ ophiolites and forearc ocean crust is the occurrence of boninites and arc volcanic suites overlying or accompanying MORB-like basaltic lavas (Fig. 2; Dilek and Furnes 2014 this issue). These spatial and temporal relationships imply that boninite magmatism, which involves fluids derived from a sinking oceanic slab, occurred contemporaneously with or immediately after decompression melting that was associated with seafloor spreading during the evolution of the IBM forearc crust and the SSZ ophiolites.

There are, however, some differences in detail between the forearc stratigraphy of the IBM arc and the internal structure and stratigraphy of SSZ ophiolites. For example, it appears that all volcanic rocks in the Troodos ophiolite (Cyprus) show the influence of subduction. The lower pillow lava unit (LPL), which represents the first volcanic sequence in the Troodos extrusive section, is composed of tholeiitic basalt and andesite with LILE enrichment caused by slab-derived fluids (Fig. 5a; Bednarz and Schmincke 1994). This extrusive section shows increasing LILE/HFSE and LILE/REE ratios and decreasing HFSE and REE contents over time, implying an increasing contribution of slab-derived fluids and depletion of the mantle source through time (Bednarz and Schmincke 1994). Thus, although the Troodos extrusive rocks are similar to the IBM forearc lavas at DSDP sites 458 and 459, they lack FABs with minimal slab influence, as are found at IBM dive sites.

The FAB-like basalt in the Semail (Oman) ophiolite (Geotimes Formation) is topped by low-Ti, depleted basaltic rocks that are free of slab-derived components (Fig. 2; Godard et al. 2006). These younger basaltic rocks are the products of a highly depleted mantle source, and their formation appears to have been followed by the eruption of lavas with subduction-affected compositions similar to those recovered from DSDP sites 458 and 459 (e.g. Reagan et al. 2010; Goodenough et al. 2014 this issue). Ishikawa et al. (2005) postulated that fluids released by the dehydration of an amphibolitic crust, with a different composition from that of fluids associated with a mature arc (for example, lower Ba/Bb, lower Pb), were added to the shallow mantle source where the boninitic magmas of the Semail ophiolite were produced. We infer that this magmatism likely
occurred in an immature, hot, shallow subduction-zone, analogous to the subduction initiation rock record along an oceanic plate boundary (Reagan et al. 2010). Dilek and Thy (2009) reported the occurrence of sheeted dikes and extrusive rocks in the Kizildag ophiolite in southern Turkey with a geochemical signature characteristic of a depleted mantle source modified by slab-derived fluids. Boninitic magmas, produced by a high degree of melting of an ultradeppleted mantle, appear to have formed contemporaneously with or shortly after the seafloor spreading-related magmas of the sheeted dikes and extrusive rocks in this ophiolite (Dilek and Thy 2009); this relationship is reminiscent of the IBM forearc crust. These observations from ophiolites formed along the Tethyan margin point to a magmatic evolutionary path that is similar to that of IBM forearc crust. Decompressional melting of a depleted MORB-type mantle was followed by melting of an even more depleted mantle to which slab-derived fluid/melt was added. The temporal relationships among MORB-like, boninitic, and arc magmatism may vary in detail, but the formation of MORB-like FAB almost always predates the other types of early-arc magmatism in SSZ-type Tethyan ophiolites (Dilek and Furnes 2009, 2011). The temporal relationships between boninites and other subduction-related rocks in SSZ ophiolites are variable, but in general, MORB-like basalts predate boninitic rocks, which predate and/or are coeval with arc tholeiites and calc-alkaline lavas (Dilek and Furnes 2009, 2011). Recent results from the IBM forearc illustrate a similar pattern. FAB erupted first, followed by transitional and then boninitic lavas. Thereafter, transitional high-Mg andesites erupted simultaneously with relatively normal arc lavas in different parts of the arc. This period was followed by the eruption of entirely subduction-related tholeiitic and calc-alkaline lavas. At a given location in the IBM forearc, the magmatic progression is generally from MORB-like basalt to boninite to arc tholeiites and calc-alkaline lavas. There is no evidence for a significant time gap between the eruptions of any of these magma types in the IBM system. A similar progression of magmatism in the Tethyan ophiolites and the IBM forearc implies that SSZ oceanic crust formation in both modern and ancient examples was associated with subduction initiation in a forearc environment (Reagan et al. 2010; Dilek and Furnes 2011, 2014).

Similarities between the oceanic lithosphere of forearc settings and SSZ ophiolites also extend to the upper mantle units, which are composed of extremely depleted peridotites. For example, peridotites underlying gabbroic and basaltic rocks in the Papuan Ultramafic Belt (PUB) in Papua New Guinea consist mainly of refractory harzburgites (Jaques and Chappell 1980). Depleted harzburgites have also been reported from many ophiolites (e.g. Dilek and Furnes 2009, 2011; Morishita et al. 2011b). The geochemically depleted characteristics of ophiolitic peridotites compared to upper mantle rocks from mid-ocean ridges might be caused by: (1) additional melt extraction during subduction initiation from an already depleted mantle; (2) a high degree of melting, aided by fluid flux from a subducting slab; and (3) interaction between depleted basaltic/boninitic melt and the peridotites (Dilek and Furnes 2014). Ophiolitic peridotites vary in the extent of their depletion, from extremely depleted harzburgite– dunite assemblages to moderately...
depleted clinopyroxene-bearing harzburgites, which are associated with boninitic and MORB-type magmatism, respectively (e.g. Dilek and Thy 2009; Morishita et al. 2011a, b).

In Tethyan ophiolites, the crystallization ages of plagio-granite and dolerite dikes in seafloor-spread-related oceanic crust plot within a narrow time window during the early–late Cretaceous (for example, 95.3 Ma for the Semali ophiolite [Warren et al. 2005]; 90–92 Ma for the Troodos ophiolite [Mukasa and Ludden 1987]; 91.8–91.6 Ma for the Kizildag ophiolite [Dilek and Thy 2009]; and 90–92 Ma for the Tauride ophiolite [Dilek et al. 1999]). This age distribution, combined with their geochemical fingerprints, suggests that the development of the Tethyan SSZ ophiolites during the Cretaceous was nearly coeval along the more than 2000 km long belt and that it involved the simultaneous initiation of a subduction zone within the southern Tethys Ocean.

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Volcanic glass from pillow lavas and hyaloclastites displays distinctive alteration textures that suggest the activity of boring microbes. Analogous textures are common in volcanic sections of the seafloor, in ophiolites, and in greenstone belts up to 3.5 Ga in age. While the origin of such trace fossils remains poorly understood, they offer much potential for investigating processes in the present-day, deep-ocean, crustal biosphere and their role in biogeochemical cycles.

Keywords: glass bioalteration, deep oceanic biosphere, geomicrobiology, oligotrophic volcanic ecosystem

INTRODUCTION

The study of ophiolites has been central to our understanding of how Earth works as a dynamic physical and chemical system. This includes much of what we know about the lower oceanic crust, and the tectonic processes that form it (Dilek and Furnes 2014 this issue). Ophiolites and greenstone belts have also yielded observations of distinct glass alteration textures in pillow lavas and hyaloclastites that are interpreted as microbially excavated tunnels and cavities (Furnes et al. 1996; Staudigel et al. 2008) similar to microbial tunneling in carbonates (Golubic et al. 2005) and soil feldspars (Jongmans et al. 1997). Such potential trace fossils offer an opportunity to constrain the presence and functioning of a deep-ocean crustal biosphere back through geological time. So far, the results are very promising: interpreted microbial trace fossils in volcanic glass are common, making up about 80% of glass alteration in the upper 300 m of the Phanerozoic oceanic crust (Staudigel et al. 2008). The largest variety of trace fossils so far have been found in the Troodos ophiolite (Furnes et al. 2008; McLoughlin et al. 2009), and studies of greenstone belts have allowed us to infer the presence of a deep biosphere as early as 3.5 Ga, among the earliest observable physical evidence for life on Earth (Furnes et al. 2008). While a direct linkage remains to be established between specific microbes and particular trace fossils in volcanic glass, the increasingly known detail in textural data continues to support their biogenicity (McLoughlin et al. 2009).

The study of possible trace fossils in volcanic glass from ophiolites has much potential for revealing the activity of microbes in ancient ocean crust and how their activity depends on the hydrothermal–volcanic boundary conditions. Ophiolites have the advantage over relatively young ocean floor rocks of allowing us to look further back in time. In addition, ophiolites provide better access than the one-dimensional and typically poorly recovered drill cores from present-day ocean crust. However, the interpretation of these trace fossils is not without caveats. Key issues include the fact that no specific microbes have been directly linked to these textures in volcanic glass and that the biogenicity of the fossil evidence for microbial life is difficult to verify in the laboratory. Hence any description of such trace fossils has to be accompanied by a critical evaluation of their possible biogenicity. We describe the evidence for microbial activity in volcanic sections of ophiolites, we provide models for the origin of various trace fossil types, and we discuss their significance and biogenicity. We focus on textural arguments because they offer the most powerful biological evidence, and we refer to previous chemical and molecular biological studies (e.g. Furnes et al. 2008; Staudigel et al. 2008).

MICROBIAL DISSOLUTION OF ROCKS AND MINERALS

Trace fossils distinguish themselves from fossils in that they do not offer a record of the organism itself but preserve the traces they left behind, such as borings and imprints. As such, trace fossils not only indicate life at a given place and geological time, but they also reveal how a particular organism interacted with its environment. For microbial trace fossils, such interactions may include the creation of shelter from predators, the extraction of nutrients from rocks in a symbiotic relationship with the root systems of trees, or, for an autotrophic organism (one that produces its own food), the fixation of carbon in an oligotrophic (nutrient-poor) setting. Hence, microbial trace fossils have the potential to reveal important details about biological activity in a local ecosystem, its role in large-scale geochemical fluxes, and its relationship to the overall food web. Excellent microbial microfossils occur in marine mollusk shells, where they can be beautifully visualized using a resin microcasting technique. An example was reported at 3000 m water depth in the Red Sea, well below the depths at which photosynthesis is possible (Radtke and Golubic 2005). Most of the fossils identified are tubular, but some display very complex shapes that mirror the distinct shapes of particular fungi found in the same setting. This unique similarity in shape allowed identification of a specific fungus as the likely producer of these cavities. This correlation also underscores how increasing detail of

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delicate morphological features offers improved capabilities to support biogenicity and, in fact, ultimately identify the organism that created the trace fossils.

Microbial etching of carbonates is chemically easily accomplished as microbial metabolism produces many organic acids that are very effective at this. In particular, calcium carbonate dissolution may also be an integral part of the respiration–photosynthesis cycle: Garcia-Pichel et al. (2010) showed that cyanobacteria may dissolve carbonate using direct chemical uptake of Ca\(^{2+}\) using certain types of enzymes. While little is known about whether such microbial processes may work outside the respiration–photosynthesis cycle, it is clear that carbonates can play an important role in biochemical reactions between microbes and their local (calcium carbonate) environment.

Tunneling trace fossils have also been observed in soil feldspars and physically linked to the activity of fungal hyphae that are capable of producing oxalic acid to extract potassium from these feldspars (Jongmans et al. 1997). These microborings are commonly 5–10 \(\mu\)m in diameter and they can be up to 50 \(\mu\)m long. In some cases, these tunnels bifurcate (Fig. 1A). Smits (2006) studied tunneling of feldspars in soils on postglacial dunes of variable age, revealing relationships between biological activity of tunneling and time (Fig. 1B). There are important relationships between the age of the soil on a given dune and the physical extent of tunneling: (1) no tunneling is observed at least during the first 1500 years of soil formation, (2) all feldspars show increasing upper bounds of cumulative tunneling length as the soil age increases, and (3) plagioclase is preferentially tunneled over K-feldspars. These data suggest that tunneling is a slow process that occurs over geological time and that there is a preference for one substrate over another. Other extremely slow biological processes have been observed in sedimentary sequences (D'Hondt et al. 2002) and reflect an effective adaptation to oligotrophic geological environments. The quantification of current fungal colonization of these minerals in the same samples revealed a fungal distribution similar to the tunnels, underpinning the fungal origin of these tunnels. In short, these studies offer powerful arguments that microbes do interact with their environment by boring into mineral substrates, even though this process is too slow to be reproduced in the laboratory.

TRACE FOSSILS IN SUBMARINE VOLCANIC ROCKS

Microbial trace fossils in volcanic rocks have predominantly been found in volcanic glass and are expressed as tubular or granular microcavities. These trace fossils were formally described as ichnofossil genera that highlight the systematic differences between different types (McLoughlin et al. 2009; photomicrographs in Figs. 2–5). It is important to note that ichnofossil genera do not refer to particular organism genera as in the common usage of the term; rather, the classification criteria for ichnofossil genera use morphological similarities only as a first step towards identifying the actual organisms. Most of these trace fossil cavities are about 1 \(\mu\)m in diameter and are excavated into fresh volcanic glass; tubular cavities may reach lengths exceeding 100 \(\mu\)m. While a biogenic origin for these glass alteration textures is most likely, the exact mechanisms used for excavation and the reason for excavation remain largely speculative. Hence, the specific microbes remain to be identified, and models for the biogenicity of these textures must be carefully evaluated. We describe two groups of trace fossils and their varieties, based on their shapes, similarity of appearance, and possible origin. 

Granular Textures

Granular glass alteration textures (Fig. 2) were originally identified and interpreted as trace fossils by Thorseth et al. (1992); they were named "Granulohyalichnus vulgaris" by McLoughlin et al. (2009). Granular textures are by far the most common trace fossils in volcanic glass. They consist of single or multiple, 0.5–2 \(\mu\)m sized (Furnes et al. 2008), near-spherical cavities that may be void or filled by smectite. Their physical appearance and genetic model are shown in Fig. 2A–C. Cavities on fresh glass surfaces have sharp edges, distinct from the flaring openings that would be expected from surface pitting during abiogenic dissolution. Cavities of granular alteration may form clusters that resemble bacterial cultures on an agar plate, or they may form continuous bands along the surface of the glass. Thorseth et al. (1992) proposed that these cavities are formed during the colonization of glass surfaces by micron-sized microbes; these organisms exude organic acids that dissolve the glass. Additional cavities are excavated when microbial cells divide, ultimately creating a sponge-like texture (Fig. 2A). These textures may reach into the glass by expanding from single cavities at the surface of the glass to multiple coalescing cavities. These microcavities are commonly accompanied by deposition of authigenic minerals, which are deposited within the spherical voids. This process dramatically reduces access to circulating hydrothermal solutions; eventually, access is cut off and the granular alteration process terminates (Fig. 2C).
Colonizing microbes could gain energy for metabolic activity by oxidizing reduced chemical components in the glass [e.g. Fe(II)] and could also obtain nutrients (e.g. P) from it. However, so far no specific microbes have been linked to the formation of these textures.

**Tubular Textures**

Simple tubular alteration textures (Fig. 3) in volcanic glass (called "Tubulohyalechinus simplus"; McLoughlin et al. 2009) are an order of magnitude less abundant than granular alteration features. They consist of tubes 0.5–3 µm in diameter and 10–100 µm in length (Furnes et al. 2008) (Fig. 3a, b, c); they may have straight or slightly irregularly shaped walls against the fresh glass. Staudigel et al. (2008) proposed that tubular textures are most likely drilled chemically by cell extensions (Fig. 3n), as has been suggested for the tunneling into soil feldspars by fungi (Jongmans et al. 1997; Smits 2006). Such filamentous growth gives microorganisms a unique ability to link spatially separated resources (Klein and Paschke 2004). Filamentous cell extensions of microorganisms colonizing rock surfaces may reach deep into a crack, connecting the rock interior with circulating hydrothermal solutions. These two environments provide different, and likely complementary, nutrient resources. While it appears likely that tunnels are caused by organisms with a filamentous morphology, such as fungal hyphae, it is not clear what type of microbe and metabolism are involved. However, filamentous growing cell extensions such as hyphae, pili, or filagella, could play a role in the development of tubular alteration textures. They have been shown to be linked to important nutrient-uptake mechanisms, and they have been observed in association with fungi and bacteria. Bacteria involved in glass alteration (such as Actinobacteria) have been shown to produce abundant filaments (Cockell et al. 2009), but little is known about their role in nutrient uptake or their ability to dissolve rocks, in particular under oligotrophic conditions.

**Varieties of tubular textures**

Some tubular textures show very complex features, such as branching forms, coils, and regular annulated forms (Fig. 4A–C). These features are probably caused by processes similar to those resulting in plain tubular textures, but their complexities could reveal clues for identifying specific microorganisms or processes. Notably, the bifurcating tunnels (Fig. 4C) resemble the complex networks formed by fungal mycelia in soil environments. Incubation of biotite and chlorite surfaces in soil microcosms and in the field produces mineral-surface alterations with bifurcating shapes that fit the size and morphology of the fungal mycelia colonizing these minerals (Saccone et al. 2012). These observations, in combination with evidence of fungal alterations in soil
and nutrient uptake from soil minerals (e.g. Jongmans et al. 1997), support our view that the study and classification of marine trace fossils will eventually lead to the identification of specific microbes linked to the biogenesis of distinct ichnofossil genera (Fig. 4). The complex shapes of corrosion textures also serve as powerful evidence for the biogenicity of these features, as it is impossible to excavate such cavities in an isotropic medium by abiotic processes. Such complex shapes include, in particular, the tubular helical types. We still have a long way to go before we are able to match particular complex trace fossil morphologies with the drilling activity of any specific organism, but we are confident that they are of biotic origin, especially since many examples of microbial drilling have been well documented in other settings.

**Fossilized tubular texture** Tubular alteration textures in old rocks may be fossilized by titanite inclusions that show remarkable textural similarities to tubular alteration found in young, well-preserved glass (Fig. 5; Furnes et al. 2008). Features interpreted as titanite tube replacements have been found in undeformed, greenschist-grade metamorphosed glass in pillow margins and hyaloclastites of the Archean greenstone belts in the Barberton Mountains in South Africa and the Pilbara Craton in Western Australia (Furnes et al. 2008). These possible trace fossils may have been shielded from tectonic shear that would otherwise destroy the delicate, hair-sized tubular textures within a chlorite matrix. Figure 5 illustrates a young tubular texture in unmetamorphosed glass (Fig. 5a) and an ancient, metamorphosed texture preserved by titanite in a fine-grained chlorite matrix (Fig. 5e). In our model, bioalteration begins with granular alteration that is replaced by secondary clays; this is followed by tubular alteration (stage 1 in Fig. 5c). Once microbial activity ceases, all textures tend to be replaced by smectite, with the potential formation of some precursor phase to titanite; this process is initiated by the passive accumulation of Ti as other elements are leached from the glass during tube formation (stage 2). Due to the relatively low concentration of Ti in glass, passive accumulation is not sufficient to provide enough Ti to allow the tube replacements shown in Fig. 5f, and hence complete replacement requires a third stage. In this stage, greenschist metamorphism transforms the glass mainly into chlorite and mobilizes Ti, which accretes to the initial Ti-enrichment site, effectively replacing the tubular textures (stage 3). The somewhat larger diameter of Ti tubes suggests that this process may expand the sizes of the tubes slightly beyond the original size.

It is possible to date the time of titanite formation by laser ICP–MS U–Pb techniques (see references in Furnes et al. 2008). These ages date the metamorphism during which the titanites formed and hence provide a minimum age for the formation of the tubes. Dating the likely tube-replacing titanites from Barberton and Pilbara yielded Archean ages, which places these alteration textures among the oldest potential fossil microbial textures on Earth.

**DISTRIBUTION IN SPACE AND TIME**

The distribution and abundance of fossils in the rock record offer insights into the role of organisms in the evolution of life on Earth, the living conditions of the organisms, and their potential role in biogeochemical cycles. Hence the distribution of bioalteration textures in space and time may increase our understanding of the controls that support their growth and of their role in how Earth works as a dynamic biological, chemical, and physical system.

The search for bioalteration textures in seafloor volcanic rocks, ophiolites, and greenstone belts has been extremely successful. Bioalteration textures have been found in the volcanic rocks of every ocean drill hole in which residual glass is present and in little-deformed and minimally metamorphosed ophiolites and greenstone belts (Furnes et al. 2008). Bioalteration preserved by titanite mineralization in greenstone belts is much rarer, but it is common in low-grade metamorphic and undeformed greenstone belts. Examples include the Barberton and Pilbara greenstone belts, where cherts host the oldest-reported physical microbial fossils (3.5 Ga); interbedded with the cherts are pillow lavas that contain titanite-preserved trace fossils (Furnes et al. 2008; McLoughlin et al. 2012). We searched for such textures in the 3.8 Ga Isua supracrustal belt in Greenland, but our search failed, probably due to the more metamorphosed and deformed character of the rocks. Hence, there is no preserved textural evidence for life in the Isua volcanic rocks. These results suggest that glass bioalteration textures are among the oldest and physically best-preserved fossil evidence of life in the geological record. This fuels speculation about the role of these trace fossils in the origin of life, as well as their role in preserving life (within the crust) at a time when the planet’s exterior was being repeatedly sterilized by major meteorite impacts.

A detailed quantitative study of the relative abundance of bioalteration and abiotic alteration at Ocean Drilling sites 417D, 418A, and 504B (Fig. 6; Staudigel et al. 2008) offers insights into the relative importance of biotic and abiotic processes and their controlling factors. At all three sites, the upper 300 m of crust display glass alteration features that are about 75% biotic, decreasing to near zero at about 500 m depth. Tubular alteration overall comprises less than 10% of all bioalteration textures but shows a maximum at about 150–200 m depth. Bioalteration, and in particular the characteristic tubular alteration, decreases in abundance below and above ca 150 m. This suggests that conditions for tunneling by microbes are best at 150–200 m depth and for
granular alteration above 300 m. At all sites the abundance of bioalteration textures correlates with high ocean-crust porosity, which suggests that bioalteration is linked to the intensity of water circulation through the system. At Site 504B, the abundance of bioalteration textures may be compared with in situ measured temperature, whereby the most intense bioalteration is found at temperatures below 60 °C, whereas some may occur at temperatures up to the limit at which life can exist. The frequency of biotextures is much reduced at temperatures above 80 °C. This shows that microbial activity is much more important at temperatures less than 60 °C and under conditions of more intense water circulation (Fig. 6).

**THE BIOGENICITY OF TUBULAR AND GRANULAR TEXTURES**

The biogenicity of these textures may be called into question as it has not been possible, to date, to identify specific processes or organisms that can be uniquely associated with the formation of bioalteration textures. There have been observations of corrosion damage from colonization by microbes in the laboratory (Staudigel et al. 2008), but none of these experiments resulted in tubular textures. Tube formation may be impossible in the laboratory, or it is at least very difficult for three reasons: (1) tubular textures are relatively rare, making up only 10% of the trace fossils found; (2) they are most abundant at about 100–250 m depth in oceanic crust; and (3) their growth is so slow that it is unlikely that the active process can be observed in the laboratory or in nature. At our current level of understanding, the strongest evidence for biogenicity comes from the textures themselves. In the following we provide a brief discussion of this reasoning; for more detail, see Staudigel et al. (2008).

Arguments in favor of biogenicity are of three types: (1) the features do not readily fit known abiotic processes; (2) many of the textures resemble uniquely biological features; and (3) tubes and granules contain chemical components and/or DNA that can be explained by life having been present in those locations. These arguments have different strengths and weaknesses. Abiotic glass alteration is well understood (e.g. Stroncik and Schmincke 2001). Glass is a noncrystalline, anisotropic material with only minor fractions of dissolved volatiles. Glass either dissolves congruently or hydrates concentrically from the outside in. Glass alteration is commonly accompanied by the precipitation of hydrous secondary minerals that take up more volume than the original glass, increasing access of water to a glass-rich formation and finally sealing it. This type of behavior cannot account for the formation of tunnels with parallel walls. It is also unlikely that such tunneling occurs along some hypothetical weakness in the glass. Such weaknesses are likely to be symmetric and to cross cooling cracks that form well after the glass solidifies, but this type of behavior is not displayed in tubular alteration features.

Tubular alteration has many morphological features that point towards biotic processes, in particular shapes that are common in the biotic world. These include the helical forms of “*Tubulohyalolichnus spiralis*” (Fig. 4A) or annulated...
forms (Fig. 4a). Furthermore, tunneling bioalteration features have been found in carbonates and silicate minerals (Gohubic et al. 2005; Smits 2006) and hence it should not be surprising to find such features in volcanic glass.

Many tubular and granular textures carry chemical signatures (C, N, P), and some even show fluorescence characteristics that indicate the presence of residual DNA. This evidence strongly suggests the former presence of microbes in these cavities, but does not prove that microbes have actually produced these textures (Staudigel et al. 2008).

Taken together, these arguments for biogenicity, particularly with respect to Phanerozoic samples, are convincing, despite the fact that the actual microbes remain elusive.

**OPIOOLITES AND GREENSTONE BELTS AS NATURAL LABORATORIES FOR EXPLORING THE DEEP BIOSPHERE**

The investigation of microbial trace fossils in volcanic glass has shown that bioalteration may be relevant in terms of the total biomass involved, its effects on geochemical fluxes, and its possible role in the origin of life. Most samples studied for glass bioalteration were recovered by drilling the present seafloor and few came from ophiolites or greenstone belts (Staudigel et al. 2008). Yet, potential microbial trace fossils in ancient glass from ophiolites and optimally preserved greenstone belts offer much potential for advancing our understanding of the deep biosphere. There are three reasons for this. (1) Ophiolites and greenstone belts date back beyond the earliest evidence for life, far exceeding the age window of in situ seafloor (0–170 Ma). Hence, ophiolites and greenstone belts allow us to study the evolution of life in the deep biosphere back through time. (2) Ophiolites and greenstone belts can be studied in two or three dimensions, often over large length scales and at all stratigraphic depths in the oceanic crust, in the context of known hydrothermal vents or other extremes in fluid circulation. Such exposure provides much better structural, chemical, hydrological, and hydrothermal context for bioalteration than drill holes in submerged oceanic crust. (3) Last, ophiolite research has revealed by far the most distinctive and delicate bioalteration features in seafloor rocks (Furnes et al. 2008). Textures such as spirals and annulated tunnels require a specific microbial function that might eventually be simulated in the laboratory, ultimately helping us identify microbes that are capable of producing the bioalteration features observed (Fig. 4). These three factors combined make ophiolites attractive targets for deep-biosphere research, in a context that is reminiscent of the role ophiolites have played in helping us understand plate tectonics (Dilek and Furnes 2014).

**CONCLUSIONS**

Microbial trace fossils in volcanic rocks from the seafloor provide exciting geological evidence that offers much potential for helping us understand the subsurface biosphere. Their wide distribution and abundance relative to abiotic alteration processes suggest that glass bioalteration is an important process. Similar-appearing features in greenstone belts suggest that this deep biosphere has been active since the earliest occurrence of physical fossil evidence for life on earth about 3.5 Gy ago. While we consider the evidence for biogenicity of these textures as strong, it is important to know that no specific organisms have been identified for producing them.

Recent research on trace fossils and the excellent exposure, high abundance, and wide age spectrum of ophiolites suggest that the study of ophiolites will help us understand the importance and function of deep, oligotrophic, volcanic ecosystems.

**ACKNOWLEDGMENTS**

We thank Nicola McLoughlin for many discussions on bioalteration and Jane Ellingsen for her help with the illustrations. Katrina Edwards and John Valley reviewed this manuscript and helped us hone our arguments regarding the biogenicity of the dissolution features. This paper was supported by the US National Science Foundation NSF-0739712 (HS) and by the Norwegian Research Council (HF).

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Diamonds in Ophiolites

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Ophiolites are a newly documented host of diamonds on Earth. Abundant diamonds have indeed been separated from peridotites and chromitites of ophiolites in China, Myanmar, and Russia. In addition, diamond grains have recently been discovered in chromite from the Cretaceous Luobusa ophiolite (Tibet) and the early Paleozoic Ray-Iz ophiolite (polar Urals, Russia). These diamonds are accompanied by a wide range of highly reduced minerals, such as Ni–Mn–Co alloys, Fe–Si and Fe–C phases, and moissanite (SiC); these have been found as either mineral separates or inclusions in diamonds and indicate growth under superreducing conditions. The diamond-bearing chromite grains likely formed near the mantle transition zone and were then brought to shallow levels in the upper mantle to form podiform chromitites in oceanic lithosphere. Because these diamond grains occur widely in peridotites and chromitites of many ophiolites, we refer to them as ophiolite-hosted diamonds. It is possible that such diamonds may be common in the upper oceanic mantle.

KEYWORDS: diamond-bearing chromitites, UHP minerals, podiform chromitites, mantle transition zone, highly reduced minerals

DIAMONDS ON EARTH

Natural diamonds occur in a variety of crustal and mantle rocks, mainly in kimberlites from subcontinental lithosphere, in ultrahigh-pressure (UHP) metamorphic rocks formed by subduction of continental crust, and in meteorites and rocks associated with impact structures. The best-known diamonds and the ones of most commercial importance are from kimberlites and lamproites (Gurney et al. 2010). They are formed mainly where pressure conditions are appropriate for carbon to crystallize as diamond, and they are brought to the surface mainly through the erosion of alkaline magmas that commonly form kimberlites and lamproites. Most such diamonds are of Archean age and many are peridotitic in character. However, the protoliths of younger Proterozoic diamonds were eclogitic, websteritic, or lherzolitic in composition (e.g. Field et al. 2008; Gurney et al. 2010). Most kimberlitic diamonds formed from melts or fluids in the upper mantle at depths of <200 km (e.g. Boyd and Gurney 1986; Liu et al. 2009). However, a few of these diamonds have mineral inclusions suggesting derivation from much greater depths (400–670 km) (Tappert et al. 2005; Walter et al. 2011; Kaminsky 2012).

Less common are microdiamonds in UHP metamorphic rocks formed by deep subduction of crustal material at convergent plate margins (e.g. Sobolev and Shatsky 1990; Xu et al. 1992; Ogasawara 2005). UHP metamorphic diamonds were initially recognized about 20 years ago during detailed study of major orogenic belts. These diamonds commonly occur as very small (0.01 to 0.1 mm) inclusions within metamorphic minerals such as garnet, diopside, phengite, and zircon, or at the mineral grain boundaries (Shertl and Sobolev 2013). The discovery of such microdiamonds suggests that continental slabs can be subducted to depths of 120–150 km or more and returned to the surface by tectonic exhumation (e.g. Liou and Tsujimori 2013).

Meteorites and terrestrial impact craters also contain microdiamonds (Koeberl et al. 1997; Karczemska et al. 2009). The largest-known deposit of impact diamond is the Popigai crater in Siberia. Most of the UHP metamorphic and impact diamonds have little commercial value because they are small and skeletal and generally occur in low concentrations.

DIAMONDS IN OPHIOLITIC PERIDOTITES AND CHROMITITNES

Over the last 30 years there have been a number of reports of diamonds in ophiolitic peridotites (e.g. Bai et al. 1993), but these findings have generally been dismissed as the result of natural or anthropogenic contamination. Our studies of ophiolites in China, Russia, and Myanmar have confirmed the common presence of microdiamonds in both ophiolitic peridotites and podiform chromitites. These occurrences raise many questions regarding the source of carbon, the processes by which the diamonds are formed and incorporated into ophiolitic chromitites, and the petrogenesis of oceanic mantle. Ophiolites are fragments of ancient oceanic lithosphere emplaced onto continental margins, accretionary prisms, or island arcs during plate collisions (Dilek and Furnes 2011). Mantle peridotites in many ophiolites host small bodies of chromite (podiform chromitites), which likely formed from subduction-influenced melts migrating through the mantle above subducting slabs (Zhou et al. 1996; Rollinson and Adetunji 2013).

The Tethyan ophiolites in southern Tibet occur within the ~2000 km long Yarlung–Zangbo suture zone, which marks the plate boundary between India and Eurasia. They include, from east to west, the Luobusa, Zedang, Xigaze, Dangqiong, Purang, and Dongbo massifs (Fig. 1). These massifs, some of which are very large (Xigaze covers ~700 km², Purang ~600 km², and Dongbo ~400 km²), consist mainly of harzburgite,
Gneiss, and garnet, which are 0.2–0.5 mm in diameter, contained in small patches of gneiss. (B) Carbon element map showing small carbon (light green) hosted in chromite (dark blue). (C) Chromium element map showing small chromite grains in the gneiss. (D) Amorphous carbon (light green) hosted in chromite (dark blue). Chromite = chr, Amor C = amorite carbon, Dia = diamond.


deduced from the absence of any Raman pattern and patches are generally 0.5–1 mm across and circular to irregular in shape. These patches are generally 0.5–1 mm across and circular to irregular in shape; they consist mainly of amorphous carbon, as deduced from the absence of any Raman pattern and from element mapping by electron microprobe (Fig. 2c). The amorphous carbon is a solid glass and very hard, and commonly contains small fragments of chromite (Fig. 2d). Several tens of grains of diamond have also been separated from individual samples ranging from 300 to 600 kg in weight from other ophiolitic massifs along the Yarlung–Zangbo suture zone (Yang et al. 2013). These diamonds are yellowish green in color, are about 0.2–0.5 mm in size, and have octahedral and cone-like forms. They are similar to those found in the Luobusa massif, and they commonly contain inclusions of Ni–Mn–Co alloy, a feature that distinguishes them from kimberlitic and metamorphic diamonds. We have also discovered diamonds in podiform chromitites of the Devonian Sartohai ophiolite in western China and in peridotites of the Jurassic Myitkyina ophiolite (Myanmar), which occurs in the southeastern extension of the Bangong–Nujiang suture of central Tibet (Fig. 1).

The chromitites and peridotites of all the ophiolites also contain a wide range of native elements (e.g. Fe, Ni, Ti, Si, Cr, Al), base metal and platinum group element alloys (e.g. FeSi, FeTi, Ni–Mn–Co, OsI), and numerous other minerals such as coesite, kyanite, corundum, zircon, rutile, almandine garnet, olivine, amphibole, chlorite, and sulfides (Table 1 and Appendix 1 as supplementary online material; Bai et al. 2000; Robinson et al. 2004; Yang et al. 2007; Yamamoto et al. 2013). The occurrence of Ni–Mn–Co alloys, Fe–Si and Fe–C phases, and moissanite (SiC) along with these diamonds is significant because it indicates superreducing conditions at extremely low oxygen fugacity in the mantle, where the diamonds crystallized.

PERSPECTIVES

The diamonds from ophiolites of various regions (China, Russia, Myanmar) and ages (early Paleozoic to Cretaceous) show many similarities in their morphology, carbon isotopes (δ13C = –18 to –28‰), trace elements, and mineral inclusions, but they are different in these respects from most diamonds occurring in kimberlites, UHP metamorphic belts, and impact craters (Griffin et al. 2013). The newly discovered in situ diamonds, highly reduced phases, and crustal minerals in chromitites and peridotites of ophiolites require a reevaluation of the petrogenesis of oceanic mantle lithosphere and the formation of diamonds in the lower mantle. The in situ diamonds reported here likely formed at depths of 150–300 km or even deeper (Yang et al. 2007; Yamamoto et al. 2009, 2013). These depths are far greater than the depths where the melts of suprasubduction zone ophiolites evolve (Dilek and Furnes 2011).
The chromite grains and perhaps some small chromitites carrying diamonds appear to have formed at or near the top of the mantle transition zone. The presence of many silicate minerals, such as zircon, corundum, kyanite, and rutile in ophiolitic chromitites and peridotites (Robinson et al. 2011; Yamamoto et al. 2013), suggests recycling of continental crust via subduction into the mantle transition zone. Water, CO$_2$, and other fluids released from subducted rocks become mixed with highly reduced fluids from greater depths, producing numerous native elements, such as diamonds, Si, Al, and Ti (Robinson et al. 2011). The melts and fluids then rise through the mantle to the top of, or above, the transition zone (>300 km depth), where UHP chromite (with dissolved Si) begins to crystallize, encapsulating diamond, moissanite, and other highly reduced phases. With continued upwelling, coesite exsolution lamellae form in the chromite grains and stishovite is replaced by coesite, but the diamonds are preserved as inclusions in chromite grains. All these processes require depths around 300 km or more in the mantle (Fig. 3).

Following their formation, diamond-bearing chromitites had to be transported upward and incorporated into the rising asthenosphere beneath a spreading center and eventually into suprasubduction zone mantle wedges. One effective way to transport these diamond-bearing peridotites and chromitites to shallow mantle depths is by plumes or superplumes (Fig. 3). Then, the diamond-bearing peridotites and chromitites are distributed, as a result of convection, throughout the upper mantle.

Most of the diamond-bearing peridotites and chromitites are subducted back into the lower mantle, but some of them become trapped in suprasubduction zone environments, where they can be modified by hydrous melts and slab-derived fluids and then incorporated into newly formed suprasubduction zone oceanic lithosphere. There is no evidence that the ophiolites themselves were ever subducted; many of the ophiolites described in this study contain unmetamorphosed or weakly metamorphosed gabbros, lavas, and dikes, as well as moderately to extensively serpentinized peridotites. Thus, the continental crust material must have been introduced into the lower mantle by subduction, long before formation of ophiolitic magmas at shallow depths in the upper mantle (cf. Yamamoto et al. 2013). One very important aspect of this model is that podiform chromitites in ophiolites may not always originate at shallow depths in the uppermost mantle, as widely thought. The chromitite formation may initially begin within or near the mantle transition zone.

The spherical shape of most carbon patches in which the in situ diamond grains occur suggests that a C-rich fluid was present during, or shortly after, chromite crystallization. The diamonds appear to have grown from these C-rich fluids (Fig. 3), but the absence of inclusions of magnesiocrossite or Mg-olivine in the diamonds and the fact that not all carbon patches contain UHP minerals suggest that the diamonds crystallized in the fluids before they were encapsulated in the chromitites. The common presence of Ni–Mn–Co alloys in the diamonds suggests that these highly reduced phases were present in the C-rich fluids and may have acted as seeds or catalysts for crystallization of the diamonds. Diamonds and other unusual minerals were preserved in ophiolitic peridotites because they were encapsulated within chromitite grains.

It is unlikely that the carbon patches formed by transformation of diamond to graphite during decompression because this process should have produced pseudomorphs of the diamond grains, as documented in the Beni Bousera and Ronda peridotite massifs of Morocco and Spain (Davies et al. 1993), rather than subcircular patches of amorphous carbon. Also, some of the in situ diamond grains in these carbon patches are euhedral, which argues against formation of the amorphous carbon by alteration. The in situ and separated diamonds are much larger (mostly 0.2–0.5 mm) than those used to grind and polish the samples (<0.04 mm). Thus, it is highly unlikely that the diamonds or amorphous carbon were introduced during preparation of the samples (cf. Dobrzhinetskaya et al. 2013).

The common presence of diamonds and associated UHP minerals in ophiolites suggests that the oceanic mantle is compositionally and isotopically more heterogeneous than previously thought, and it raises many questions regarding mantle processes and the formation of ophiolitic melts.

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**Figure 3** A conceptual model for the formation and occurrence of diamonds and associated ultrahigh-pressure minerals in the oceanic mantle. See text for discussion.
Exactly where and when are the diamonds formed, and how are they introduced into the mantle peridotites and chromitites now exposed in ophiolites? How are diamonds and highly reduced, crustal-type minerals preserved in oceanic mantle peridotites and chromitites? Most podiform chromitites contain evidence of formation at shallow mantle depths in suprasubduction zone environments, making it difficult to understand how UHP and highly reduced phases can be introduced into these enigmatic bodies. Can podiform chromitites and the diamonds they contain be formed in a single tectonomagmatic cycle, or do the peridotites and their chromitites in oceanic lithosphere go through repeated cycles of formation and reformation at various mantle depths prior to their incorporation into ophiolites? We expect that answers to these and other questions will be provided by future interdisciplinary investigations now that diamonds, UHP minerals, and associated crustal minerals have been confirmed as integral features of peridotites in many ophiolites. Clearly, ophiolites still have much to tell us about the nature and evolution of oceanic mantle.

ACKNOWLEDGMENTS
Professor Qingsong Fang (deceased), Xiangzhen Xu, and Fahui Xiong are gratefully acknowledged for their careful work in selecting diamonds from heavy-mineral separates and figure preparation for the manuscript. This research was funded by grants from the NSF China (40930131, 40921001), SinoProbe-05, and the China Geological Survey. The authors acknowledge the Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Germany, for the use of their facilities and for scientific and technical assistance. We thank H. Helmstaedt, J. Valley, and an anonymous reviewer for their insightful and thorough comments on the manuscript, Principal Editor John Valley for his invitation to contribute this article, and Pierrette Tremblay for her rigorous copy editing and layout of our paper.

SUPPLEMENTARY ONLINE MATERIAL
Table 1 and Appendix 1 available as supplementary online material at www.elementsmagazine.org/supplements/.

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BROADENING THE DIVERSITY OF EXCELLENCE

Seemingly we have a long time before the nominations deadline for the Geochemical Society's highest competitive honors (October 15, 2014). The vision and work begin long before, however, as the chair of the Awards Nominations Committee and its members work to establish an outstanding pool of candidates for consideration. Awardees symbolize the highest achievement in our field. They inspire all of us, and especially those at an early-career stage, to do our best science. They become among the most visible spokespersons for our profession. The Geochemical Society needs your help. The past record of winners reflects scientific excellence and achievement of the highest level. The development of a large and competitive pool of excellent nominees is critical to the success of the award competitions. Continue to send in suggestions to the Awards Nomination Committee. Even better, decide to lead the nomination yourself. There can be no more important role in leading and mentoring scientific accomplishments and recognition in the field of geochemistry.

I bring to your attention a second important issue that we can address by mobilizing the collective resources of our community. The record of achievement the Geochemical Society recognizes through awards, plenaries, and keynotes at Goldschmidt has been exemplary. We congratulate this year's winners and are proud of the diversity of our community and the science they reflect. But a quick look at past statistics reveals that historically the awardees and invited speakers have been heavily concentrated in our European and North American membership. This has been the case despite the fact that more than 20% of our membership is drawn from outside these regions and the fact that the community membership reflects a much wider range of diversity of all descriptions (gender, heritage, and discipline). At a recent Goldschmidt, more than 30% of the suggested keynote speakers had been keynote speakers at one of the last few Goldschmidts—a remarkably high repeat rate.

We would like to urge you now to get involved to help ensure all aspects of the Geochemical Society's activities, including awards, fellows, plenaries, and keynotes, reflect the full diversity of scientific excellence and professional achievement in our community. It is a normal human tendency to self-replicate. If I were asked to brainstorm a list of names for recognition of scientific excellence, my initial list would no doubt contain too many groundwater geochemists, likely too many women, and certainly too many Canadians! Those who have studied this issue suggest a simple step can help us broaden our collective perspective. Draw up your initial brainstorming list, then step back and think again—more broadly this time. Consider excellent scientists you know who are significantly different from yourself and from those you studied with, and add their names to your nomination list. Our goal this year is to have no fewer than 5 strong nominees to consider for each award and 30 in the consideration pool for GS fellows.

We can do better in the nominations phase. We need your expert judgment and creative vision. Get involved this year. Make a resolution to continue your involvement annually and nominate one excellent candidate each year for something, whether it is within GS or elsewhere. We continue your involvement annually and nominate one excellent candidate each year for something, whether it is within GS or elsewhere. We are counting on your leadership and vision to ensure we have a conference that reflects scientific excellence drawn from the full spectrum of our diverse community of scholars and researchers, and that continues to provide room for new as well as traditional voices. Your role as a scientific mentor and supporter can change the world.

We gratefully acknowledge the contributions of the following:

**THE GEOCHEMICAL SOCIETY AWARDS**

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

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

**The Clair C. Patterson Award** recognizes an innovative breakthrough of fundamental significance in environmental geochemistry, particularly in the service of society, consisting of either a single outstanding contribution or a short series of papers published within the last decade.

**The Geochemical Society’s Organic Geochemistry Division Alfred Treibs Award** is given for major achievements, over a period of years, in organic geochemistry.

**The Organic Geochemistry Best Paper Award** is presented annually by the Organic Geochemistry Division to the authors of a paper published in the previous year with a significant contribution to organic geochemistry.

**Geochemical Fellows.** In 1996, the Geochemical Society and the European Association of Geochemistry established the honorary title of Geochemistry Fellow, to be bestowed upon outstanding scientists who have, over some years, made a major contribution to the field of geochemistry. Former and new Urey, Goldschmidt, and Treibs medal winners become Fellows automatically.

**Distinguished Service Award.** This award is given at the discretion of the GS Board of Directors. The award recognizes and documents outstanding service to the Geochemical Society and/or the geochemical community that greatly exceeds the normal expectations of voluntary service to the Society. The award does not have to be given each year.

**The F. Earl Ingerson Lecture Series** honors the Geochemical Society’s first president. The recipient is selected annually by the GS Board of Directors to present the Ingerson Lecture at the GSA Annual Meeting and Exposition.

**The Paul W. Gast Lecture Series** honors the Geochemical Society’s first Goldschmidt medalist. The award is made to a mid-career scientist (under 45 years old), and the lecture is presented at the GS/EAG annual Goldschmidt Conference. Lecturer selection alternates between the GS Board of Directors and the EAG Council, depending on the location of the Goldschmidt Conference.
2014 AWARDS TO BE PRESENTED AT GOLDSCHMIDT

GEOCHEMICAL SOCIETY

GOLDSCHMIDT MEDAL: Timothy Grove (Massachusetts Institute of Technology)
PATTERSON MEDAL: Christopher Reddy (Woods Hole Oceanographic Institution)
CLARKE MEDAL: Matthew Jackson (University of California, Santa Barbara)

EUROPEAN ASSOCIATION OF GEOCHEMISTRY

UREY MEDAL: Edward Boyle (Massachusetts Institute of Technology)
SCIENCE INNOVATION AWARD (SAMUEL EPSTEIN MEDAL): James Farquhar (University of Maryland)
HOUTERMANS MEDAL: Liping Qin (University of Science and Technology of China)

GS/EAG

GAST LECTURER: Tim Elliott (University of Bristol)

GS/EAG GEOCHEMICAL SOCIETY OF JAPAN

UREY MEDAL: Edward Boyle (Massachusetts Institute of Technology)
SCIENCE INNOVATION AWARD: Hiroshi Amakawa (National Taiwan University)
SHEN-SU SUN FOUNDATION

SHEN-SU SUN MEDAL: Liping Qin (University of Science and Technology of China)
SHEN-SU SUN AWARD: Peng Peng (Chinese Academy of Sciences)

2014 GS/EAG GEOCHEMICAL FELLOWS

Yuri Amelin (Australian National University)
Marc Hirschmann (University of Minnesota)
Hiroko Nagahara (University of Tokyo)
Rebecca Lange (University of Michigan)
Martin Palmer (University of Southampton)
Adina Paytan (University of California, Santa Cruz)

GS/EAG GEOCHEMICAL FELLOWS BY PATTERSON AND SCIENCE INNOVATION AWARDS

Robert F. Anderson (Columbia University)
Kenneth Bruland (University of California, Santa Cruz)
R. Lawrence Edwards (University of Minnesota)
William F. Fitzgerald (University of Connecticut)
George W. Luther III (University of Delaware)
William Sunda (National Oceanic and Atmospheric Administration)
Jeffrey P. Severinghaus (University of California, San Diego)
Kei Hirose (Tokyo Institute of Technology)
Daniel Sigman (Princeton University)

The GS and EAG are also pleased to announce that all current and future recipients of the Geochemical Society’s C.C. Patterson Award and the EAG’s Science Innovation Award will also be named GS/EAG Geochemical Fellows. Past recipients who have not yet been named Geochemical Fellow will be presented with the honor during a ceremony at the Goldschmidt2014 conference. These honorees are:
ORGANIZING A GOLDSCHMIDT

The Goldschmidt Conferences™ were started 25 years ago by the Geochemical Society to provide a forum for its members to discuss their latest research. The European Association of Geochemistry became involved early on, and since then the conference has also benefitted from the involvement of other societies, notably the Geochemical Society of Japan, the European Mineralogical Union and the Mineralogical Society of America. By 1996 the conference had grown to 1000 delegates, and in 2013 the meeting attracted over 4000 delegates.

The goal of this piece is to provide a look at the details of the hard work that is done each year. Typically this work goes on seamlessly and so much behind the scenes that our community is largely unaware of it. For instance, many may not realize that the standard pattern now is that odd-year meetings are organized by the EAG at European venues, while even-year conferences are organized by the GS at venues elsewhere in the world; so after Sacramento this year we will visit Prague (2015) and Yokohama (2016).

From previous years’ experience, we have learned that to make a great conference we need to choose a great scientist to lead it, book an appropriate venue, employ a good conference administrator, and arrange an outstanding science program. An organizing committee is appointed to make all the key decisions on the arrangements for the meeting, and a science committee manages the conference program. The Goldschmidt Conferences have been fortunate to have had a succession of senior scientists willing to serve on these committees. Even with the most effective support provided by a professional conference-management company, these roles still take up a significant amount of time in the run-up to the conference. Now that Goldschmidt works to a standard pattern, these roles are much less demanding than they used to be, but no less critical.

Following the successes of past Goldschmids, we are now looking for venues for the Goldschmidt in 2017, 2018 and 2019. The ideal venue would be one that delegates will want to visit, where the conference centre has an appropriate size, configuration and cost, and where accommodation is plentiful, varied and affordable. The cost of the conference centre is important but is not the only important factor. The biggest cost delegates have in mind is the time they take away from their labs, jobs and families. Flights, accommodation and food can easily add up to more than €1000, especially for those who need an intercontinental flight. The chosen venue must therefore allow delegates to take full advantage of the investment they make in attending the meeting. Choosing an attractive venue is therefore vital in arranging a successful meeting.

The EAG and GS want Goldschmidt Conferences to be great meetings at a reasonable cost. It is important that a meeting be as effective scientifically and as enjoyable socially as possible, and we aim to ensure that sufficient monies are spent to ensure that a meeting is well resourced. However, we bargain hard to contain costs and we negotiate strongly with all suppliers. This approach seems to have the approval of our community. More than 85% of those who responded to the Goldschmidt2013 survey said that the conference was a good or excellent meeting, and fewer than 15% would support a policy of making the meeting cheaper if it would reduce its quality.

Putting on a high-quality conference is not cheap and forces a range of strategic choices. These include:

- For a conference centre to host a Goldschmidt successfully it needs to have approximately 15–20 rooms each with space for about 150 seats, a plenary venue of at least 1000 seats and 7500 m² of open space for the posters, exhibition and catering. There are very few such venues in Europe, and most are not cheap. In the US it is common for a city to offer a convention centre for a low price knowing that the city can recoup this through more expensive hotels and restaurants, and in many venues food and drink can be very expensive.
- The Goldschmidt Conferences are serious about educating younger members of our community. Goldschmidt does this by enabling a significant fraction of them to speak at the conference. While at most international conferences students and post-docs are allocated posters, at Goldschmidt the majority of delegates who wish to can speak, and approximately half the presentations are given orally. This is great for communication and education, but it is much more expensive to hire another lecture theatre for 15 minutes than it is to hire an additional 2 m² of floor space for one more poster.
- Goldschmidt also puts on a range of workshops which are administered centrally to make it as easy as possible for their organizers to gather together all the early-career workers in their field and educate them together. This is efficient and economical for the students, as they can follow the course during their first experience at a major international conference. Goldschmidt also provides field trips for those whose interests are based outside the lab.
- Significant effort and resources are put into a media program to reach out to future decision makers for funding, but also to the general media which influence politicians and their electorates. At Goldschmidt2013 this resulted in an enormous amount of coverage in the scientific and public media, culminating in a live broadcast on the UK’s most listened to radio station.
- Goldschmidt wants to make the conference as affordable as possible both for students and for delegates from low-income countries, and therefore allocates substantial funds to support students and delegates from these countries.

The major investment related to the conference is the time of some of our community’s top scientists, and the science program is key to the value of the conference. If the science program is poor then there is little point optimizing everything else. Over 500 scientists are involved in optimizing the science content and designing the science program and conference schedule. Once about 200 sessions have been designed, they are allocated time and space in a way that optimizes the flow of information, and the programming ensures that the inevitable clashes between sessions are kept to an absolute minimum.

The Goldschmidt Conferences invest seriously in poster sessions, as they are the prime events for informal scientific interchange, and also because presenting a poster is typically the first opportunity graduate students have to show their work. Scientific interaction is sustained by the relaxed and social atmosphere at the iconic Goldschmidt-style poster sessions. This encourages scientists at all stages of their careers to spend time with others interested in the same topic. We suspect that many important new ideas emerge here.

Goldschmidt also ensures that the conference centre is a welcoming place by providing tea, coffee and snacks throughout the day – because you’re worth it! Goldschmidt also incorporates a series of social events so that the conference experience is varied and enjoyable for all.

Professional conference administration is a critical element in the success of Goldschmidt. While a few companies have been involved over the years, no single company has organized more Goldschmidt Conferences, been more involved during the period in which attendance has quadrupled, and done more to embody and promote the Goldschmidt spirit and brand than Cambridge Publications. Cambridge Publications, founded in 1994, is an independent professional conference-organizing company spearheaded by geochemist and entrepreneur Paul Beattie. Cambridge Publications make all the information easily available on an efficient website and provide

Cont’d on page 135

SOCIETY NEWS
Houtermans Award to Liping Qin

Liping Qin (University of Science and Technology of China) got her PhD from the University of Chicago, where she showed, using $^{182}$Hf–$^{182}$W systematics, that most iron meteorite parent bodies accreted in the first two million years of the formation of the Solar System. Iron meteorites may thus be the only remnants of a first generation of planetesimals, all of which were molten due to the high abundance of radioactive $^{26}$Al at that time. During a Carnegie Postdoctoral Fellowship at the Geophysical Laboratory in Washington, DC, she identified the elusive carrier of $^{34}$Cr anomalies in planetary bodies as pre-solar nano-oxides and thus solved a problem that had been haunting cosmochemistry for two decades. During a second postdoc at Lawrence Berkeley National Laboratory, she applied her knowledge of chromium isotope geochemistry to the study of Cr(VI) reduction in terrestrial surface environments. Liping’s work is characterized by a willingness to tackle the most challenging problems and to use all instrumentation and modelling tools necessary to achieve her scientific goals.

EAG Distinguished Lecturer 2014

Rachael James (University of Southampton) has been selected as EAG Distinguished Lecturer for 2014. Rachael’s research focuses on the development and application of chemical and isotopic techniques to improve our understanding of Earth and planetary processes, both now and in the past. As in previous lecture tours, institutions in Central and Eastern Europe interested in Rachael’s research can invite her to present one or two lectures. Additional information is available at www.eag.eu.com/education/dlp/.

EAG PHOTO CONTEST

The EAG is excited to announce its first photo contest, open to everyone. Submission will be open until June 15, and there will be 3 geochemistry themes proposed. The winners will receive a 5-year EAG membership (including subscriptions to Elements and Geochemical Perspectives, as well as the member rate for Goldschmidt conferences), and will see their photos published on the EAG website and newsletters. Additional details will be provided on the EAG website and newsletters.

2014 EAG MEDALLISTS

Urey Award to Edward Boyle

Edward Boyle (Massachusetts Institute of Technology) combined chemistry, biology and physics to understand oceanographic processes. Ed developed two fields of low-temperature geochemistry: trace metal oceanography and chemical palaeo-oceanography. Ed’s meticulously clean methods proved that the ocean indeed had consistent patterns of trace metals. He and his colleagues determined the marine cycling of Cd, Fe, Ni, Al, Cu, Zn and Pb, using them as tracers of oceanographic processes. He pioneered new methods, including isotope dilution by ICP-MS. Ed determined and Pb, using them as tracers of oceanographic processes. He pioneered his colleagues determined the marine cycling of Cd, Fe, Ni, Al, Cu, Zn and Pb, using them as tracers of oceanographic processes. He pioneered new methods, including isotope dilution by ICP-MS. Ed determined that shells incorporate the chemistry of the ocean using Cd/Ca and carbon isotopes in forams to determine different circulation regimes in the deep ocean during the Last Glacial Maximum. In estuarine science he introduced the concept of salinity as a reference frame for chemical mass balance.

Samuel Epstein Science Innovation Award to James Farquhar

By exploring the mass dependence of sulfur isotope fractionation in sedimentary rocks through geologic time, James Farquhar (University of Maryland) has completely revolutionized our understanding of the early history of Earth’s oxygenation. Indeed, his discovery of the mass-independent sulfur isotope effect in Archaean rocks is one of the major breakthroughs in Earth science of the last 15 years. Not only did James discover that mass-independent sulfur isotope fractionations were preserved in the ancient sedimentary record, but he quickly appreciated what might be the cause of these fractionations. This work has become the cornerstone for discussions on the history of Earth-surface oxygenation and provides the most robust, and also quantitative, indicator of the ‘Great Oxidation’ of the Earth’s atmosphere some 2.3 to 2.4 billion years ago.

CALL FOR BLOGGERS

Scientists wishing to share their experiences and insights are invited to join our team of bloggers. If interested, contact us at office@eag.eu.com. EAG Blog: blog.eag.eu.com.
PRESIDENT’S LETTER

American (and All Other) Mineralogists

Like many of the other learned societies that make up the ‘Elements family’, the Mineralogical Society of America (MSA) was established to enable scientists working in the area broadly defined as ‘mineralogy’ to publicise and to publish their work. In the case of MSA, the launch of the American Mineralogist journal actually preceded the formation of the Society by several years. That was almost 100 years ago, and since then many of the classic papers on what we now call ‘Earth and planetary materials’ have appeared in its pages. We publish a journal that has a distinguished past, but what of its future? Last year my predecessor, John Hughes, outlined various positive changes in the journal in one of his President’s Letters. These have involved new editorial arrangements as well as innovations in the content and style of this flagship publication.

The American Mineralogist aims to attract the very best papers in its field, and last year our editor, Keith Putirka, addressed the scientific community in an article entitled “Why you should publish your best papers in American Mineralogist” (see Am. Min. 98: 1377-1378 for detailed arguments). Certain key points made in this article are worth repeating, not least because they debunk some of the myths surrounding scientific publishing. For example, all authors want their work to be widely read and highly cited. Contrary to popular belief, this does not necessarily mean publishing in Nature or Science despite their high impact factors. These impact factors come from the papers such magazines publish in medicine, biology and materials sciences, not in Earth sciences. This has nothing to do with the quality of publications in these various fields; it is because disciplines such as medicine have many more research scientists, publishing many more papers in more journals, so leading to much greater opportunities for citations. It is clear that the best papers in ‘mineralogy’ will garner more citations if published in American Mineralogist. This publication choice also means that a paper will reach its intended audience via familiar databases such as Google or Web of Science, in which our journal is incorporated and which is now the route used by nearly all scientists researching a topic. Furthermore, papers will be actively promoted by MSA, for example, through distribution of summaries of notable papers to the members of networks such as MSA-Talk.

The world of scientific publishing continues to develop at extraordinary speed. Whether it is dealing with the demands of ‘open access’ publication or the latest in IT systems for the efficient handling of manuscripts, we intend to be in the forefront of these developments. Fortunately we have a talented and extremely hardworking editorial and production team making this possible. The parallel advances in style and content of American Mineralogist: An International Journal of Earth and Planetary Materials (to give our publication its full title) are aimed at attracting new readers and authors. But let me reassure our ‘old’ readers and authors, whether American mineralogists or (like me) from the international community, that there will always be a place in our journal for the best papers in the more traditional fields of mineralogy and crystallography.

David J. Vaughan (david.vaughan@manchester.ac.uk) 2014 MSA President

NOTES FROM CHANTILLY

- MSA will use electronic balloting for the 2014 election of MSA officers and councilors. The slate of candidates follows. President: Steven B. Shirey (Carnegie Institution of Washington); vice president (one to be selected): Carol D. Frost (University of Wyoming) and Rebecca A. Lange (University of Michigan); treasurer: Howard W. Day (University of California–Davis); councilors (two to be selected): Barry R. Bickmore (Brigham Young University), Abby Kavner (University of California–Los Angeles), Matthew J. Kohn (Boise State University), and Donna L. Whitney (University of Minnesota). Andrea Kozioł continues in office as secretary. Continuing councilors are Isabelle Daniel, Kirsten P. Nikolaysen, Edward S. Grew, and Wendy Panero.

MSA members will have received a message at their current e-mail address with voting instructions in April. Make sure MSA has your most recent e-mail address! Those who do not wish to vote online can request a paper ballot from the MSA business office. As always, the voting deadline is August 1. Individuals elected to office decide on the direction of the Society. Voting is an important job for all MSA members.

- There is now a single portal page (www.msapubs.org) where you can access electronic versions of all MSA publications: American Mineralogist, Reviews in Mineralogy and Geochemistry, open access publications, and Elements. Select the appropriate link there based on the type of subscription (individual member or institutional). If your institution subscribes to GeoScienceWorld (GSW), we ask that you preferentially use those links. You will also benefit from all the extra features of MSA publications on GSW.

- MSA’s Special Papers from the 1960s have been scanned and posted online as open access publications on the MSA website. The topics are: (volume 1) Symposium on Layered Intrusions, Symposium on the Mineralogy of the Sulfides, as well as the General Session and the Third General Business Meeting of the IMA; (volume 2) Pyroxenes and Amphiboles: Crystal Chemistry and Phase Petrology; and (volume 3) Fiftieth Anniversary Symposia on (a) Mineralogy and Petrology of the Upper Mantle, (b) Sulfides, and (c) Mineralogy and Geochemistry of Non-Marine Evaporites.

- MSA members who previously subscribed to the online version of the Reviews only had access to volume 39 to the present on GeoScienceWorld. Now you have access to the entire Reviews series, volume 1 to 78, on the MSA website at www.msapubs.org. If you did not subscribe to the series when you renewed, you can subscribe to this, or any journal offered through MSA, any time at “MSA subscriptions.” For those with more limited requirements, single chapters of the Reviews can be purchased as electronic files or print-on-demand copies at www.minpubs.org. You can also buy electronic or print versions of entire volumes of the out-of-print Reviews at www.minpubs.org.

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

VOTE

2014 MSA ELECTIONS

VOTED 

2014 MSA President

David J. Vaughan (david.vaughan@manchester.ac.uk)
The Mineralogical Society of America is again offering a lecture program for the 2014–2015 academic year, with the arrangement that the MSA will pay travel expenses of the lecturers and the host institutions will be responsible for local expenses, including accommodation and meals. The program will include 3 lecturers, one of whom resides in Europe. Depending on the response, one or more lecture tours will be arranged outside North America.

The 2014–2015 Distinguished Lecturers are Bethany Ehlmann (Department of Geological and Planetary Science, California Institute for Technology, and the Jet Propulsion Laboratory, Pasadena, CA, USA), Colleen Hansel (Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, MA USA), and Lutz Nasdala (Institute of Mineralogy and Crystallography, University of Vienna, Vienna, Austria). Their lecture titles are posted on the MSA website. If your institution is interested in requesting the visit of an MSA Distinguished Lecturer, check the website for lecturers and titles and e-mail your request to the Lecture Program Administrator, Dr. Timothy W. Grover, Castleton State College, Dept. of Natural Sciences, Jeffords Center, 233 South St., Castleton, VT 05735-0001, USA; e-mail: tim.grover@castleton.edu; tel.: +1 (802) 468-1289; fax: +1 (802) 468-1170. The lecture program is designed to run from September 2014 through April 2015. Lecturer requests received by May 4, 2014, will be given priority. Late applications will be considered on a space-available basis. In making your request please include (1) the proximity of the airport and travel time to your institution, (2) the name of a contact person at your institution for the months of May and June (when lecturer schedules will be assembled), (3) contact e-mail addresses and phone numbers, (4) flexibility on lecturer preference, and (5), for schools outside the U.S., the starting and ending dates of the academic terms. Because of travel and schedule constraints, it is normally not possible to satisfy requests for tightly constrained dates such as seminar days.

NEW TITLE

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


Spectroscopy is the study of the interaction between matter and radiation, and spectroscopic methods measure this interaction by measuring the radiative energy of the interaction in terms of frequency or wavelength or their changes. In 1988 a Reviews in Mineralogy volume (volume 18) was published with the title Spectroscopic Methods in Mineralogy, edited by Frank Hawthorne. Since 1988 there have been many significant advances in both the technological aspects of these techniques and their applications to problems in Earth sciences in general, while the range and breadth of the techniques have greatly expanded since those formative years. The current volume complements the original volume and updates many of the techniques. In addition, new methods, such as X-ray Raman and Brillouin spectroscopy, and nonspectroscopic chapters, such as Transmission Electron Microscopy and Atomic Force Microscopy, have been added for completeness.

For a description and ordering online, go to www.minsocam.org, or contact the Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110, USA; phone: +1 (703) 9550; fax: +1 (703) 652-9951; e-mail: business@minsocam.org. Cost is $45 ($33.75 for members of MSA, GS, CMS).

NOMINATIONS MUST BE RECEIVED BY JUNE 1, 2014

The Roebling Medal (2015) is MSA's highest award and is given for eminence as represented by outstanding published original research in mineralogy.

The Dana Medal (2016) recognizes continued outstanding scientific contributions through original research in the mineralogical sciences by an individual in the midst of their career.

The Mineralogical Society of America Award (2015) is given for outstanding published contribution(s) prior to the 35th birthday or within 7 years of the PhD.

The Distinguished Public Service Medal (2015) is presented to an individual who has provided outstanding contributions to public policy and awareness about mineralogical topics through science.

Society Fellowship is the recognition of a member's significant scientific contributions. Nomination is undertaken by one member with two members acting as cosponsors. A form is required; contact the committee chair or visit the MSA home page.

Submission requirements and procedures are on MSA's home page: http://www.minsocam.org/.

Now available for iPad and Mac!

Our “Mineral Database” app is also available on the App Store.

For more information or to purchase the digital version of the textbook, “Mineralogy and Optical Mineralogy” go to www.minsocam.org

For more information or to purchase the digital version of the “Mineralogy and Optical Mineralogy series” go to www.tasagraphicarts.com/minbooks
FROM THE PRESIDENT

As I start my two-year term as president of the Association of Applied Geochemists (AAG), I would like to express my gratitude to the AAG executive and councillors who have made the last two years successful, especially our esteemed outgoing president, Bob Eppinger, as well as Gwendi Hall, Dave Smith, and Beth McClenaghan. Ryan Noble from CSIRO, Australia, is the Association’s new vice president. We are going to miss the services of Betty Arseneault, AAG’s long-time business manager, who has stepped down from this position. However, at least in the interim, Al Arseneault will be taking her place. Sarah Lincoln has stepped down as business manager for EXPLOR, and Pim van Geffen has agreed to continue Sarah’s excellent work.

I would like to thank outgoing AAG councillors Rob Bowell, Bruno Lemiere, Ryan Noble, and Todd Wakefield for all their efforts over the past years. Continuing AAG councillors are Patrice de Caritat, Romy Matthies, Tom Molyneux, Peter Rogers, Cliff Stanley, and Peter Winterburn. Newly elected councillors for 2014–2015 are Alejandro Arauz, Dennis Arne, Stephen Cook, Mel Lintern, Paul Morris, and Peter Simpson. The AAG’s regional councillors are Neil Brewed, Theo Davies, Benedetto De Vivo, João Larizzatti, Pertti Sarala, Brian Townley, and Xueqiu Wang. You can read a little more about them in the adjacent column.

The AAG recently held its 26th International Applied Geochemistry Symposium (IAGS) in Rotorua, New Zealand. The success of this symposium was in large part due to the dedicated work of the chair of the Local Organizing Committee, Tony Christie, his team, and the professional conference organizers Absolutely Organized. Success was also due to the joint meeting with the Geothermal Workshop, which allowed for cross-pollination of ideas between those working in the geothermal energy realm and those of us using geochemistry to understand, explore, and mitigate the effects of the mineralization styles formed from geothermal processes. The next IAGS will be held in Tucson, Arizona, USA, in April 2015, so start planning your travel now (www.27iags.com).

Look for two special issues of GEEA on field-portable XRF to be published this year; note that accepted manuscripts are now available online prior to the print edition coming out.

I would also like to take this opportunity to express the condolences of the entire AAG family to the family of Bill Coker, who passed away recently. We will all miss Bill’s presence and contributions to the exploration geochemistry community.

I wish everyone a successful 2014.

Matt Leybourne
(Matthew.Leybourne@alsglobal.com)
ALS Global, AAG President

A call for laboratory support...

The Association of Applied Geochemists (AAG) invites analytical laboratories to participate in pairing their analytical facilities with student projects to develop emerging geochemists and their science. The AAG Education Committee is seeking analytical laboratories to offer in-kind support to students in terms of analysis, while receiving acknowledgement on AAG’s website and in the Association’s EXPLORE newsletter.

"Today’s students are tomorrow’s clients"

Alejandro J. Arauz is a geologist/geochemist with over 28 years of experience in mineral exploration, environmental studies, and mining environmental management in Latin America. He has a BSc in geology from Universidad de Costa Rica, an MSc in geology from the Colorado School of Mines, and an MBA in natural resources from INCAE. He is a part-time professor at Universidad de Costa Rica.

Dennis Arne is Principal Consultant Geochemistry and the director of CSA Global Canada. He has been a principal geochemical consultant for the last five years, based primarily in Vancouver, Canada. Prior to that, he was a senior geochemist at Geoscience Victoria, Australia, a senior lecturer at the Western Australian School of Mines, and a lecturer at the University of Ballarat.

Stephen Cook received his BSc from Carleton University in 1984 and MSc from the University of British Columbia in 1991. He worked with the Geological Survey of Canada in 1985–1988, and in 1991 he joined the British Columbia Geological Survey. In 2000 he joined Anglo American and later ran his own consultancy until joining then Teck Cominco in 2006. For the past eight years he has directed geochemical exploration at Teck Resources.

Mel Lintern is a research geochemist for CSA Global’s Minerals Down Under Flagship and Earth Science and Resource Engineering Division. His expertise lies in the application of geochemistry, particularly using biological sampling media and calcite. His research is enabling mining companies to explore with more confidence when tackling greenfield areas where sedimentary cover dominates, particularly in the arid and semiarid regions of Australia.

Paul Morris is the chief geochemist at the Geological Survey of Western Australia, where he is responsible for carrying out regional geochemical programs and acquiring lithogeochemical data. He has been an AAG member since 1999 and has held various positions in the Association, including president.

Peter Simpson’s primary interests concern innovative research topics designed to train MSc and PhD students in exploration and environmental geochemistry. This also supports research into the exploration for and development of mines and mineral deposits, while reducing their environmental impact, by professional graduates in leading roles worldwide. He is based at Imperial College in London.

David Smith (dsmith@usgs.gov)
U.S. Geological Survey, AAG Secretary
DMG AWARDS FOR 2013

The Abraham Gottlob Werner Medal is the highest award given by the German Mineralogical Society (DMG). It recognizes outstanding original research in mineralogy (silver medal) or distinguished service in the advancement of the mineralogical sciences (gold medal).

In 2013 the silver medal was presented to François Holtz (Institute for Mineralogy, Leibniz University Hannover) for his outstanding achievements in the petrology of magmatic rocks. François is a recognized international authority in experimental petrology. His studies on the influence of volatiles on the formation of SiO$_2$-rich melts are fundamental to our knowledge of the evolution of magmas in the Earth’s crust.

Heidi Höfer (Institute for Geosciences, Goethe University Frankfurt) received the Abraham Gottlob Werner Medal in gold. She has been the DMG’s officer for public relations since 2001. Mineralogists all over the world remember her efforts in organizing the 10th International Symposium on Experimental Mineralogy, Petrology, and Geochemistry (EMPG) in 2004, the 9th International Kimberlite Conference, and the 1st European Mineralogical Conference (emc) in 2012, all in Frankfurt/Main, Germany. We thank Heidi for her distinguished service representing German mineralogy across the world.

The Victor Moritz Goldschmidt Prize is given to young researchers for outstanding contributions to the mineralogical sciences. The 2013 awardee is Hella Wittmann-Oelze (Helmholtz Centre Potsdam–GFZ German Research Centre for Geosciences) in recognition of her fundamental contributions to the geochemistry of cosmogenic nuclides. She earned a PhD in science from the University of Hannover in 2008 with her thesis entitled “New applications to in-situ-produced cosmogenic nuclides in river sediment: High mountain belt denudation in the Swiss Alps and Bolivian Andes and sediment transfer and storage in the Amazon basin.” Hella has contributed significantly to the understanding of landscape-forming processes at the orogenic scale.

The Beate Mocek Prize was awarded by the German Mineralogical Society for the first time in 2013. In memory of the late petrologist and geochemist Beate Mocek, this prize was created by her family to encourage young female scientists in the areas of petrology and geochemistry. The first awardee is Donjá Aßbichler (Ludwig Maximilians University, Munich, Department of Earth and Environmental Sciences). Donjá qualified for the prize with her excellent studies on the metasomatism of metapelites and talschists in the eclogite zone of the Tauern window (Austrian Alps). She is now investigating the transport phenomena of high-field-strength elements in sandstones (Eslamy peninsula, northwestern Iran). A grant of 600 euros will help fund the field trip to Iran.

The Paul Ramdohr Award, given for the best oral presentation by a student at the annual meeting of the DMG, was presented to Shreya Karmakar, a PhD student at the Institute for Geosciences of Christian Albrechts University, Kiel. The award recognizes the excellence of her talk “Archean UHT metamorphism and Paleoproterozoic reworking at Uweinat in the East Sahara Ghost Craton,” which she delivered at the 1st European Mineralogical Conference in Frankfurt in 2012.

Dear colleagues,

This year’s annual meeting of the German Mineralogical Society (DMG) will be held for the first time at the University of Jena, Germany. We cordially invite you to join in this event on 21-24 September 2014.

Organized under the motto “Minerals at Focal Point,” the conference aims to bring together researchers from all fields of mineralogy, our multifaceted discipline. The meeting program advertises, therefore, a wide range of topics in or at the crossroads of crystallography, applied mineralogy, petrology, and geo-/cosmochemistry.

The organization of the 2014 DMG meeting coincides with the 100th anniversary of the journal Chemie der Erde/Geochemistry, which was founded in Jena. To mark this occasion, a special volume is in preparation and will be handed out to the attendees of the conference. The meeting also offers a half-day excursion to the nearby former uranium mining district at Ronneburg. The deadline for abstract submission is 30 May 2014. For further information (e.g. list of sessions) please see our web page (www.dmg2014.de).

We are looking forward to your attendance and contributions and welcome you to the city of light.

On behalf of the Organizing Committee,

Falko Langenhorst
UCLA METEORITE GALLERY OPENS
The grand opening of the UCLA (University of California, Los Angeles) Meteorite Gallery was marked by a ceremony and reception on 10 January 2014. UCLA Chancellor Gene Block praised the Department of Earth, Planetary, and Space Sciences for creating the gallery and also thanked Arlene and Ted Schlazer for a gift of 65 meteorites and a generous bequest. The gallery has track lighting, carpeted floors, and seven exhibit cases containing about 100 meteorites. Numerous posters show images of meteorite sections and explain cosmochemical processes, such as chondrite metamorphism, mass-independent isotopic fractionation, and asteroidal sources of meteorites. The centerpiece of the gallery is the Clark iron, a beautifully sculpted, 162 kg chunk of the Canyon Diablo meteorite given to UCLA in 1934.

The seven display cases illustrate (1) meteorite classification; (2) ordinary and carbonaceous chondrites; (3) iron meteorites, mesosiderites, and back-lit pallasites; (4) chondritic breccias and impact melts; (5) tektites and Libyan Desert Glass; (6) California meteorites (including the type specimen of the 2012 L6 Novato fall) and meteor-wrongs; and (7) extraterrestrial and terrestrial basalts. The latter case features the type specimen of the Los Angeles Martian meteorite. The gallery is open weekdays from 9:00 am to 4:00 pm and (with docents present) on Saturday or Sunday, as detailed on the website, http://meteorites.ucla.edu. We are grateful for financial help from the Endowment Fund of the Meteoritical Society, the UCLA Dean of Science, and the UCLA Institute for Planets and Extrasolar Planets.

ANNUAL MEETING SCHEDULE
- 2014, September 8–12, Casablanca, Morocco
- 2015, July 27–31, Berkeley, California, USA
- 2016, August 7–12, Berlin, Germany
- 2017, dates to be announced, Albuquerque or Santa Fe, New Mexico, USA

WORKSHOP ON RADAR IMAGERY FOR METEORITE RECOVERY
A 1-day workshop on using radar imagery for meteorite fall detection and recovery

Convener: Marc Fries and Mike Zolensky (NASA Johnson Space Center)

Date and Venue: 7 September 2014, in Casablanca, Morocco (just prior to the 77th Annual Meeting of the Meteoritical Society in Casablanca)

Weather radar imagery is a proven new means of locating fresh meteorite falls. In the United States, weather radars have assisted in the recovery of the Sutter’s Mill and Battle Mountain meteorite falls, as well as two more falls in Alabama and California, within the past two years. This presents an important new opportunity, because weather radars are operated by national weather bureaus worldwide, which usually make their radar imagery available to the public. It should be possible for researchers around the world to use their local weather radar networks to locate meteorite falls. This workshop has the goal of teaching researchers how to analyze weather radar imagery in their own country for real-time meteorite fall information, thereby greatly increasing the recovery rate for new large meteorite falls.

For additional, continually updated information on this workshop, please visit www.metsoc2014casablanca.org/workshops.php, or e-mail Marc Fries (marc.d.fries@nasa.gov) or Mike Zolensky (michael.e.zolensky@nasa.gov).

COMMITTEE MEMBERS THANKED
Many thanks to all those members who are serving on the Society’s committees this year. We have listed their names below, with names of the committee chairs in bold. Without the generous help of all these members, the Society could not function. We greatly appreciate their help.

Leonard Medal and Nier Prize Committee (5 members, 3-year term)
- Phil Bland (Curtin University) 2018
- Sara Russell (Natural History Museum London) 2018
- Christine Floss (Washington University) 2017
- Noriko Kita (University of Wisconsin–Madison) 2016
- Herbert Palme (Senckenberg Museum Frankfurt) 2014

Barringer Award Committee (4 members, 4-year term)
- Alex Deutsch (University of Munster) 2017
- Mark Burchell (University of Kent) 2016
- Alvaro Crosta (University of Campinas–UNICAMP) 2015
- Barbara Cohen (NASA Marshall Space Flight Center) 2014

Pellas-Ryder Award
- Debra Buzzowski (GS) Johns Hopkins University 2016
- Susan Schwenzer (Open University) 2016
- Phil Bland (Curtin University) 2015
- Bob Anderson (GS) Columbia University 2014
- Hilary Downes (Birkbeck College) 2014
- Danielle Wyrick (GS) University of Tennessee, Knoxville 2014
Deer, Howie and Zussman

ROCK-FORMING MINERALS

New and Recent Publications in the Rock-Forming Minerals series from the Geological Society Publishing House

RFM3C Rock-Forming Minerals, Volume 3C: Clay Minerals By M.J. Wilson
What are clays and why do they have such special properties? This book reviews much of the latest research over a variety of scientific disciplines and is an essential reference for those requiring a better understanding of clay material, whether in research or technical applications.

Rock-Forming Minerals (Second Edition): Complete set of 11 volumes
Rock-Forming Minerals is an essential reference work for professionals, researchers and postgraduate students in Earth sciences and related fields in chemistry, physics, engineering, environmental and soil sciences.

For full details visit: www.geolsoc.org.uk/bookshop

Other titles in the series include...

RFM1A Rock-Forming Minerals, Volume 1A: Orthosilicates By W.A. Deer, R.A. Howie and J. Zussman
RFM1B Rock-Forming Minerals, Volume 1B: Disilicates & Ring Silicates By W.A. Deer, R.A. Howie and J. Zussman
RFM3A Rock-Forming Minerals, Volume 3A: Micas By M.E. Fleet
RFM3C Rock-Forming Minerals, Volume 3C: Clay Minerals By M.J. Wilson
RFM5B Rock-Forming Minerals, Volume 5B: Non-Silicates: Sulphates, Carbonates, Phosphates and Halides By L.Y. Chang, R.A. Howie and J. Zussman
FROM THE NEW PRESIDENT

Many thanks to my predecessor, Prof. Jon Davidson, for his hard work during his two years at the helm. I look forward to picking up the threads of some of the initiatives he started, in particular working with the special interest groups (SIGs). It is nearly ten years since I completed an enjoyable term of office in the role of general secretary, and now, with the honour of serving for two years as president, it is instructive to review what has changed – and not changed – over the ten years. First, Elements was just starting as I finished. Joining the Elements inaugural group was one of the easier Council decisions during my time as secretary, and the venture has been tremendously successful – congratulations to all concerned! Among the things that have not changed, I would choose the continuing worry about decline in library journal subscriptions and whether we are responding in the best ways to the changing publications environment. The business model of the Mineralogical Society of Great Britain and Ireland relies on earning a surplus from our two journals, Mineralogical Magazine and Clay Minerals, and using this to fund our other activities, particularly our SIGs, which convene meetings and are the heart of our society community. The treasurer, general secretary, executive director and custodian trustees are currently conducting a review of activities and finances to see if we have the most efficient set-up possible for society business. Do we need to ‘clip our wings’ in some areas to live within the means provided by the journals? An important question for SIG members is – do you publish in the society journals as your first choice? For many, I suspect, despite all the hard work of editors and production staff, the honest answer is usually ‘no’, me included actually, I don’t mind admitting. But what should we do to encourage submission of our best papers to our learned society’s journals? The recent open access special issues are an example of a well-received initiative. Are there other ideas we should pursue? I am keen to receive good ideas.

Frances Wall (F.Wall@exeter.ac.uk)
MSGBI President

NOTES FROM LONDON

Impact of Open Access on Citations

In the past 18 months or so, the Mineralogical Society has engaged in a new method of publishing content, a version of open access, where a special issue is published (which is in addition to the regular set of four or six in any given volume) and paid for by a sponsor or set of sponsors. This means that the content, or papers, are available to all Internet users, free of charge from the day of publication. Early indications are very positive. Usage of the material is up to ten times that of comparable restricted-access content. That in itself demonstrates the impact of this method. Citations vary from average to twice as high as normal. Overall, it is working out to be a worthwhile venture. And it has the added benefit of bringing our journals to the attention of readers who might not otherwise read them.

The effort in this regard continues in 2014: in Mineralogical Magazine we will have special issues of papers arising out of an IGD-TP meeting on geodisposal of radioactive waste in Manchester; they will comprise a set of papers on mineral scales in pipes and mineral reactivity with application to carbon storage. In addition, we have two thematic sets (not open access): one arising out of a March 2014 meeting on North Atlantic cratons, and another from presentations given during the Goldschmidt 2013 meeting in Firenze.

By the time this issue of Elements appears, we will have published the latest ‘Cambridge Clay’ issue, the seventh in this incredible series of special issues in Clay Minerals. The most recent meeting, from which these papers are taken, had the title ‘Clay and Carbonate Facies and Their Diagenetic Pathways in Reservoir Rocks’. Check the contents now at www.ingentaconnect.com/content/missoc/cmr or http://gsclaymin.highwire.org/ – it’s the open access April 2014 issue.

Welcoming New Officers and Members of Council

Frances Wall of Camborne School of Mines is the Society’s first female president since its foundation in 1876! She will serve until the end of 2015.

As mentioned by Frances, the Society has begun a campaign to review the Society’s activity and finances. Robust discussions have already taken place, and steps will be taken to ensure that we are as lean as we can be in terms of costs while affecting core and other activity as little as possible. Key to these discussions is our new treasurer, Prof. John Adams.

Welcome to these new Society officers and also to incoming Council members: Brian O’Driscoll (University of Keele), Claire Corkhill (University of Sheffield) and Chris Greenwell (Durham University). Thank you all for serving the Society and the mineralogical community in this way.

Prof. John Adams

North Atlantic Cratons Meeting

The Society was involved in the organization of the North Atlantic Cratons meeting held in St. Andrews in late March 2014. More than 80 delegates attended the excellent scientific programme followed by a well-attended field trip to the Scottish Highlands. A full report will appear on the Society’s website in due course. The organizing team consisted of Hannah Hughes, Josh Hughes, Kathryn Goodenough, Dennis Schlatter, Adrian Finch and Kevin Murphy.
Books

- In the past year, sales of our books have been going very well. The 3rd edition of the Introduction to Rock-Forming Minerals, by Deer, Howie and Zussman, has been jumping off the shelf. Don’t worry, we still have copies for sale! At a book launch in November 2013, Prof. Jack Zussman spoke movingly and amusingly about the history of DHZ and the roles of the authors and others in various aspects of production. Visit www.minersoc.org/dhz.html to see a video recording of the event – it’s well worth 20 minutes of your time.

- Volumes in the EMU series have been well received by reviewers in Elements and have been selling well on both sides of the Atlantic. These are priced very affordably for individuals and institutions. Buy yours today at www.minersoc.org.

“Raman Spectroscopy Applied to Earth Sciences and Cultural Heritage (#12) is an outstanding contribution that should be included in the personal library of anyone interested in Raman...” Elements 9: 233

“This volume (#13) helps define the modern field of environmental mineralogy, which is still in its infancy.” Elements 9: 396

“The overall series has been exceptionally well done since the first volume in 1997 and this latest volume (#14, published in 2013) is no exception...” Elements 9: 477

Whither Twitter?

As we move closer and closer to online-only journals, we publishers think about finding ways to let readers know about exciting new content in our journals. I still enjoy pushing back my chair and browsing the contents of my paper journals as they land on my desk, but those days are numbered. The editor of American Mineralogist has been doing a good job of highlighting new content in that journal via MSA-Talk. And every page of every website I visit these days seems to have the ubiquitous social media links.

Some time ago, I signed up for Scholarly Kitchen (scholarlykitchen.sspnet.org/). Every day, or every second day, a link to an interesting article (on subjects related to scholarly publishing) appears in my inbox. I’m interested to know whether journal readers out there would like to receive messages like this about content in Mineralogical Magazine and Clay Minerals? Not too many, but something to replace that content list on the back cover of the paper journal. I know we all have too much e-mail to read. I object to lots of spam, but have no problem with mail that carries value. Let us know what you think.

Membership Survey

Many thanks to those of you who took the time to complete the membership survey. It’s been some time since we foisted such a survey on you, at least 20 years, so we appreciate the detailed responses received. We will publish our findings in forthcoming issues of Elements and welcome continued contributions to the discussion. Our aim is to provide a service tailored to your needs as much as we can.

History

A plaque to honour the Mineralogical Society founder, Joseph Collins (after whom the Society’s Collins Medal is named), has recently been refurbished.

The plaque was erected some years ago in St Paul’s, Charlestown, Cornwall. Charlestown (including the church) is part of the Cornwall and West Devon Mining Landscape World Heritage Site. Joseph Collins lived nearby at Crinnis House (now demolished) and was actively involved with the church, which was built in 1846–1851. Charlestown is a well-preserved, late 18th–early 19th century harbour built by Charles Rashleigh to export china clay and copper ore, which were extensively mined within the parish.

RUSSELL COMMEMORATION

The 50th anniversary of the death of Sir Arthur Russell has been commemorated by the publication of an article by Roy Starkey of the Russell Society (a sister mineralogical society). The open access paper contains much previously unpublished information about Russell, and extensive use is made of the Mineralogical Magazine’s online journal archive. Enjoy reading about one of Britain’s most important mineral collectors in this wonderful collection of memories, photographs and other research (www.russellsoc.org/russell.html/russella).

Kevin Murphy, Executive Director

Please note that not all subscription payments have been received yet. Please contact the Society to arrange payment as soon as possible. Alternatively, go to www.minersoc.org and click on ‘member login’.
**FROM THE PRESIDENT**

**On Rivalries, Cooperation, and Friendships**

During the recent Winter Olympics, the television coverage here in Colorado was heavily slanted towards athletes from the USA, but one couldn’t help but see the large number of countries represented at the Games. Even though the athletes are highly competitive, one also couldn’t miss seeing the camaraderie they share. I am struck by the similarities to our Society—international in scope and composition, but I hope with much more emphasis on the camaraderie than the competition! A little healthy rivalry helps us all, to be sure, but my experience tells me that our rivalries take a back seat to the numerous international collaborations, linkages, and friendships we share in our geochemical community. These linkages are on full display in our working group meetings. In 2013 two of our working groups had tremendously successful meetings, one of which is described on this page. Two more are planned for 2014, including the inaugural meeting of our revitalized Urban Geochemistry Working Group. Our working groups and our Society thrive because of the efforts of all of us, so I encourage you to get to as many of the WG meetings as possible.

On a related note, one person who has been a tremendously valuable contributor to our Society is getting ready to retire. Tom Bullen has been the secretary of IAGC since 2008, but he has been active in IAGC for as long as I can remember. He has been a pivotal member of our Water–Rock Interaction and Applied Isotope Geochemistry working groups, and he will be missed by all of us. On the other hand, as a personal friend, I congratulate Tom on a truly illustrious career in geochemistry and for the numerous contributions he has made over the years, particularly in the field of isotope geochemistry. Well done, my friend! Tom’s retirement leaves a big gap in our Society, not only for his scientific contributions but also his role as secretary. Thus we are currently seeking someone willing to serve as secretary in Tom’s place. If you are interested, please contact Tom directly at tdbullen@usgs.gov. He will be able to tell you what the major jobs are and how much time commitment is involved.

Richard Wanty, USGS
IAGC President

**MEETING REPORT**

**10th Applied Isotope Geochemistry Conference (AIG-10)**

The Applied Isotope Geochemistry (AIG) Working Group of the International Association of GeoChemistry (IAGC) organizes a series of highly successful biennial conferences focused broadly on the emerging field of applied isotope geochemistry and biogeochemistry. The 10th Applied Isotope Geochemistry Conference was held on September 22–27, 2013, in Budapest, Hungary. The venue was the marvellous main building of the Hungarian Academy of Sciences. A total of 180 abstracts was received, and the presentations were distributed among ten sessions: Biogeochemistry and ecological applications, Recent applications and developments in dendroisotopes, Isotope techniques in environmental geochemistry, Isotope geochemistry of natural gases, Isotope geochemistry of sedimentary to high-temperature geological processes and ore deposits, Isotope hydrology as a tool for water-supply policy, Isotope studies in hydrocarbon exploration, Nongeoscience applications (archeometry, forensic studies, food authenticity, medical studies, doping investigations, etc.), Isotopic tools to study the fate of organic contaminants, and Paleoclimatology and paleoenvironmental changes.

More than 150 participants arrived from 38 countries, and participants delivered 73 talks and presented 80 posters. The conference started with an icebreaker party on Sunday held at the venue, where the participants could enjoy the local atmosphere, food and drinks, the view of the Buda castle, and lively chats. The scientific program started on Monday with conventional geological research subjects, followed by sessions on paleoclimate, dendrochemistry, and nongeoscience applications. The paleoclimate session continued on Tuesday, along with presentations on environmental research and studies on hydrocarbon gases. Wednesday was a “social day,” when many of the participants visited the historic town of Eger, tasted local wines, and visited the travertine terraces formed by carbonate precipitation from hot water flowing from a drill hole.

Thursday was dominated by environmental research and isotope hydrology, whereas on Friday biogeochemistry and isotope studies on organic compounds were the main focus. At the end of the conference a session on hydrocarbon exploration was held, with special emphasis on unconventional hydrocarbon reserves and the potential impact of hydraulic fracturing on the environment. The meeting closed with a wine tasting at the venue, with more than 50 participants persisting up to the very end (“and indeed the wine was very good,” said Tom Bullen).

Based on the feedback received by the organizers during and after the conference, the participants had a happy and successful week in Budapest. The number of presentations was sufficient to organize specialized sessions that reached the critical mass needed to have colleagues interact effectively, thus making the meeting a success for the individual participants.

The meeting was supported by the Hungarian Academy of Sciences who provided the venue, by the International Association of GeoChemistry as main sponsor, and by financial contributions from several analytical companies (Thermo Fisher Scientific, Elementar Analysensysteme GmbH, IVA Analysentechnik e. K., OEA Laboratories Limited), all of them contributing to the success. Thanks to the sponsors, the registration fees of 27 young colleagues were provided, making the conference a lively one with a good number of researchers in the starting phase of their career.

Attila Demény and István Fórizs
Hungarian Academy of Sciences, Budapest
Thanks to the vagaries of CMS’s Annual Meeting calendar, this is (already) my last President’s Corner. The end of my (short) term brings retrospective remarks to mind, but the contents of this page draw me to the future instead. The research that our recent Student Travel Grant recipients presented at our recent Annual Meeting sampled the clay science that CMS members have advanced for the past 50 years and will for the next 50. Their research embraces geology, environmental chemistry, and crystallography. It spans basic and applied science. It is international. It is a microcosm of CMS. It bodes well for the future of clay science, and for CMS as a major meeting place for clay scientists. CMS’s second half-century is off to a most promising start!

With that, I bid you farewell. I look forward to seeing you in College Station at our S14 Annual Meeting. Best wishes,

Michael Velbel (velbel@msu.edu)
President, The Clay Minerals Society

STUDENT RESEARCH SPOTLIGHT

Congratulations to John Ross Harper (Colorado School of Mines), Sabrina Sharmeen Alam (Texas A&M University), Xiaoli Wang (Freiberg University of Mining and Technology), and Andras Fehervari (Monash University) for winning a CMS Student Travel Grant award!

John Harper’s research aims to elucidate the provenance and depositional history of organic matter within unconventional shale deposits. In particular, he is examining the Smoky Hill Member of the Niobrara Formation, which was deposited in the Western Interior Seaway during the Late Cretaceous and is hypothesized as an oceanic anoxic event, a rapid, global deposition and concentration of organic-rich marine facies. John’s mineralogical and isotopic results reveal the distribution of carbon and nitrogen among inorganic phases, organic particulates, and expandable interlayers of layered clay minerals (smectites). His results support the hypothesis of an oxic to anoxic transition over time. Improved understanding of the accumulation of organic material and the progression of anoxia in marine sediment can assist scientists in pursuing similar formations in the exploration of unconventional hydrocarbon deposits.

Sabrina Alam’s research aims to evaluate the performance of smectite clays in removing aflatoxin during biofuel production. Contamination of corn ethanol by the mycotoxin aflatoxin is a significant concern in biofuel production. Aflatoxin can be removed by adsorption on smectite. Sabrina’s experimental results show that smectite maintains most of its capacity to adsorb aflatoxin in ethanol and glucose solutions. As compared with adsorption in pure water, at least 90% of the clay’s aflatoxin adsorption capacity is preserved in the presence of up to 20% ethanol. No remarkable changes in the Fourier transform infrared spectroscopy bands of smectite-aflatoxin complexes are observed even with higher amounts of ethanol and glucose. Variable-temperature X-ray diffraction (XRD) results show that high temperatures have little influence on the d-spacing of smectite-aflatoxin complexes treated with ethanol and glucose solutions.

Xiaoli Wang’s research aims to develop advanced techniques for the XRD analysis of the structural parameters of dioctahedral smectites by the Rietveld method. X-ray powder diffraction is one of the most common methods used for analysis of the structural properties of smectites. The Rietveld structure refinement technique provides the possibility of obtaining structural parameters from XRD powder patterns of natural or impure samples, such as bentonites and clays. Unfortunately, almost all smectites show a turbostratic disorder that leads to strongly asymmetric peak broadening and makes the use of conventional structural models impossible. Xiaoli’s project aims to determine how much structural information (such as cation content, layer charge density, and the proportion of trans- and cis-vacant structures) can be obtained from powder diffraction patterns of dioctahedral smectites, particularly in mixtures such as bentonite.

Andras Fehervari’s research aims to develop improved robust hydraulic barriers capable of retaining hypersaline leachates, which are produced mainly by the mining industry in Australia and worldwide. Andras has combined bentonites with various cyclic organic carbonate modifying agents to develop organo-mineral nanocomposites that are resistant to osmotic contraction under high ionic strength conditions. Glycerol carbonate (GC) and its derivatives are identified as promising inexpensive additives that yield robust bentonite-based hydraulic barriers. Glycerol carbonate can be produced using a “green chemical” method from glycerol and urea (both abundant waste resources) with a polymeric zinc monoglycerolate catalyst. Characterization of GC-bentonite using geotechnical techniques (swell index, fluid loss tests) and XRD measurements indicates effective hydraulic barrier performance to saline leachates as strong as 5 M of NaCl or 7.5 M of CaCl₂.

Submission of abstracts is due February 14, and the meeting will be held May 16-19, 2016 at Texas A&M University, College Station, Texas, USA. Visit www.clays.org for more information.
MAC TRAVEL AND RESEARCH GRANT AWARDS IN 2013

MAC awarded 11 student travel and research grants in 2013 for a total of $10,000 (2 to undergraduate students, 3 to MSc students, and 6 to PhD students). Congratulations to these deserving individuals! Excerpts of their reports follow.

Michael A. Antonelli, a master’s student at the University of Maryland–College Park, travelled to the 44th Lunar and Planetary Science Conference to present his research on the anomalous sulfur isotope compositions of magmatic iron meteorite groups IC, IIAB, IIIAB, IVA, and IIIF. These anomalous compositions are indicative of inheritance from early nebular photolysis reactions between UV rays and H2S gas. Michael received a BSc from the University of Alberta in 2011 and has started a PhD at the University of California, Berkeley.

Thomas C. Chudy (University of British Columbia) attended the GAC-MAC meeting in Winnipeg where he presented a comprehensive study of regional marbles and carbonates that share the same tectonometamorphic history. He showed that a careful examination of carbonate microtextures by a range of petrologic methods can provide important information about the magmatic and metamorphic evolution of carbonatites in mobile belts. This is part of his PhD project on the tantalum-bearing Fir carbonatite system, east-central British Columbia.

Mallory Dalsin, an MSc student at the University of British Columbia, attended the GAC-MAC conference where she presented her research on the mineralogy of the Wicheeda Carbonatite Complex. Subsequent to this presentation she was asked to submit a paper for a special issue on critical metals in Ore Geology Reviews. Attending the conference allowed her to learn about similar research elsewhere, and network with like-minded researchers.

Zach A. DiLoreto travelled to New Zealand to perform field sampling for his upcoming MSc project at the University of Windsor. He will investigate the mineralogical and biological dynamics of a bioreactor used to treat acid mine drainage at the Stockton mine, as well as determine the fate of sequestered contaminants after decommissioning. This trip allowed him to meet with professionals, scientists, and other students at the mine, as well as consulting firms and universities.

Andrew Fagan, a PhD student at the University of British Columbia, travelled to the Scottish Carbonatite Complex. Subsequent to this presentation she was asked to submit a paper for a special issue on critical metals in Ore Geology Reviews. Attending the conference allowed her to gain insight into the processes that form impact craters on Earth and other terrestrial planetary bodies, particularly the Moon. The MAC travel award allowed her to participate in the GAC-MAC annual meeting and in a field trip to the Lake St. Martin impact structure, where she collected shock-metamorphosed feldspars.

Maryam Far Shahabi (University of Windsor) attended the GAC-MAC conference and the preconference short course Petrography of Layered Mafic Intrusions. Since her PhD project is about Cu-PGE deposits, she mostly attended the session “Magmatic Ni-Cu-PGE Deposits: Ore-Forming Processes with Implications for Exploration.” Furthermore, she presented her research and the results obtained thus far.

Laura MacNeil, an undergraduate student at Queen’s University, attended the GAC-MAC 2013 conference to present results on her mineralogical studies of a low-temperature, hydrothermal, barium-rich skarn deposit, Gunn Claim, Yukon Territory. She strongly recommends this conference to all undergraduate and graduate students, as the variety of topic sessions is extensive and the experience one of a kind.

Krisztina Pandur, a PhD student at the University of Saskatchewan, attended the 22nd European Current Research on Fluid Inclusions (ECROFI) meeting in Antalya, Turkey, on June 4–9, 2013. She presented results from her study of the Hoidas Lake magmatic–hydrothermal REE deposit, which focused on fluid inclusion petrography, microthermometry, and evaporate mound SEM EDS analysis. She also attended the preconference short course on fluid and melt inclusions, and a postconference, 2-day field trip to western Anatolia.

Annemarie Pickersgill is currently finishing up her MSc at the University of Western Ontario. Her project is focused on examining the effects of shock metamorphism on feldspars in order to gain insight into the processes that form impact craters on Earth and other terrestrial planetary bodies, particularly the Moon. The MAC travel award allowed her to participate in the GAC-MAC annual meeting and in a field trip to the Lake St. Martin impact structure, where she collected shock-metamorphosed feldspars.

Ann C. Timmermans, a PhD candidate at Carleton University, is investigating a complex surge of Tertiary magmatism that swept southwest across southwestern North America. Her research tests the hypothesis that volcanic activity resulted from the shallowing and eventual rollback of the subducted Farallon plate. MAC funding made it possible to complete whole-rock stable oxygen isotope analyses, which can provide constraints on enrichment of the magma at the source versus contamination from the crust during ascent.

Rui Wang (University of Alberta) attended the first joint scientific meeting of the Geological Society of China and the Geological Society of America. He presented his work on the subject “Magmatic and structural controls on the development of post-collisional porphyry copper deposits in Gangdese belt.” After the meeting, he travelled to the Tibet plateau for fieldwork. He visited more than 10 deposits in the 1000 km long Gangdese belt and collected numerous rock samples for his PhD project.
FROM THE PRESIDENT

Starting in 2014, the European Union framework programme for research and innovation (Horizon 2020) will address raw materials as a main societal challenge, on the same level as climate and the environment. Minerals and materials of natural or artificial origin are thus in the core of the scientific and technical issues raised by the global management of raw-materials resources. The issues include extracting, recycling and substitution processes, the whole chain of environmental impacts, and the necessity to reinforce the relevant research, education, training centres and networks. Mineralogical societies, and the Société française de Minéralogie et de Cristallographie in particular, need to participate in this “renaissance” of the world’s interest in minerals by maintaining bridges between academic research and stakeholders of government and industry.

It is a true pleasure and great honour for me to serve the SFMC as president for the second time, during the term 2014–2015. With our two vice presidents and Council, I wish to lead the SFMC in its involvement in this renaissance challenge by reinforcing our representation in stakeholder forums and committees. In addition, we will maintain our traditional activities as an organizer and sponsor of workshops. We will pursue our support of the involvement of students in mineralogy by funding congress participation for some of them and by recognizing the best PhD theses through the Haüy-Lacroix award.

Bruno Goffé, SFMC President

SFMC ELECTION RESULTS FOR 2014–2015


BOARD: Bruno Goffé (president), Bertrand Devouard (vice president), Christian Chopin (2nd vice president), Marc Blanchard (secretary), Guy Libourel (assistant secretary), Stéphanie Rossano (treasurer), Amélie Bordage (vice treasurer), Anne-Marie Boullier (bulletin editor)


AUDITORS: Jannick Ingrin, Michel Madon

The Society thanks outgoing councilors Muriel Andréani, Delphine Charpentier, Valérie Chavagnac, Alain Cheilletz, Stéphanie Duchêne and Denis Testemale for four years of dedicated service.

TRAINING DAYS: “MÉTHODES D’ANALYSE DES MINÉRAUX ET DES MATÉRIAUX”

The Society is organizing two training days, which will be held in Paris, France (Université Pierre et Marie Curie), on November 20 and 21, 2014. These days will be devoted to a review of a wide range of technical tools, and will be held in the spirit of the previous sessions in 2000, 2002, 2004 and 2010. This meeting is intended for a wide audience, including PhD students, engineers and researchers. Each invited speaker will present one or two analytical methods suitable for the study of minerals and/or fluids. The applications will be related to open questions in the Earth and planetary sciences, and will show how parameters determined at the molecular or nanometre scale can provide important constraints on our understanding of global processes.

Organizing committee: Anne-Line Auzende, Étienne Balan and Marc Blanchard (contact: methodesdanalyse@sfmc-fr.org). Early registration will open on September 8.

Further information is available at http://sfmc-fr.org.

24e RÉUNION DES SCIENCES DE LA TERRE

SFMC members will be conveners of five sessions during the 24e Réunion des Sciences de la Terre, organized by the Université de Pau et des Pays de l’Adour, France, and the Société Géologique de France and held on October 27 to 31, 2014. Registration started on March 15, 2014. The meeting website is http://rst2014-pau.sciencesconf.org.
SWISS GEOSCIENCE MEETING 2013 IN LAUSANNE

The 11th Swiss Geoscience Meeting (SGM) was organized jointly by the University of Lausanne, the Cantonal Museum of Geology and the Swiss Academy of Natural Sciences. On 15 November 2013, the plenary session was held in the Palais de Rumine, and on 16 November, the special sessions were held in the new building of the Faculty of Geosciences and the Environment – Géopolis – of the University of Lausanne.

The Lausanne meeting broke all records with regards to the number of participants (750 in total), the number of scientific symposia (24), and the number of presentations (over 430); please go to www.geoscience-meeting.scnatweb.ch/sgm2013/ for details of the program and presentations, and the abstracts. The theme of the SGM was “Cycles and Events in the Earth System.” Five invited keynote speakers illustrated the importance of stochastic events and recurrent mechanisms in shaping and changing the Earth and its biosphere. Kurt Konhauser of the University of Alberta spoke about the importance of biogeochemical cycles during the Precambrian and their impact on the evolution of the atmosphere and biosphere; Angela Coe of the Open University discussed the importance of global oceanic anoxia events during Earth’s history and their impact on life and the environment; Oliver Korup of the University of Potsdam talked about events and cycles in the Earth’s sediment-routing systems; Bruce Yardley from the University of Leeds gave a presentation on the changing nature of crustal processes and the role of fluids through orogenic cycles; and Peter Kelemen from Columbia University addressed issues pertaining to CO₂ capture and storage in the Earth’s lower crust and mantle. The 24 scientific symposia covered a fairly complete spectrum of current research in the geosciences in Switzerland, encompassing the lithosphere, the hydrosphere, the cryosphere, the biosphere, the atmosphere and the anthroposphere, and ranging from human geography to applied geophysics.

Karl Föllmi
University of Lausanne

BAPTISTE DAFFLON RECEIVES THE 2013 PAUL NIGGLI MEDAL

At the 11th Swiss Geoscience Meeting in Lausanne, Baptiste Dafflon, a Swiss research scientist currently working at the Lawrence Berkeley National Laboratory in the US, was awarded the Paul Niggli Medal for 2013 for his original research contributions to the geophysical exploration of aquifers and permafrost environments. Baptiste studied geophysics at ETH Zürich and did his MSc thesis in the field of hydrogeophysics, specifically on the geostatistical characterization of aquifers based on geophysical measurements. Before starting his PhD at the University of Lausanne in 2005, he completed his fifteen months of civil service constructing and restoring dry stone walls in the Alps. During his PhD he developed quantitative integration methods designed to assimilate a large variety of geophysical and hydrogeological data to improve the estimation of hydrological properties. Baptiste finished his PhD in just over three years, with six papers accepted or already published at the time of his defense. He was awarded the Prix de la Faculté des Géosciences et de l’Environnement de l’Université de Lausanne, and he received a best student paper award from the AGU.

Baptiste was then awarded an SNF postdoctoral fellowship and moved to Boise State University in Idaho, USA, which operates the world’s premier hydrogeophysical test site. He spent a year and a half working productively on the development of novel hydrogeophysical methods for enhanced 3-D simulation and inversion of hydraulic properties, before winning a prestigious postdoctoral fellowship at the Lawrence Berkeley National Laboratory (LBNL) in Berkeley, California. There, he initially worked on advanced complex electrical monitoring methods for detecting and imaging CO₂ intrusions into shallow aquifers. Recently, Baptiste has become interested in the use of geophysical techniques for studying the terrestrial carbon cycle. In particular, he is seeking to develop multi-method monitoring strategies across a wide range of spatial scales. Baptiste has now been promoted to a stable position at LBNL and has thus achieved what is widely considered the most critical step in a scientific career. Still, Baptiste’s objective is to eventually find a similarly rewarding opportunity back in his native and beloved Switzerland. With this in mind, please join us in congratulating Baptiste and wishing him continuing joy and success in his research and the very best for his future career.

Christoph Heinrich (ETH Zürich) and Klaus Holliger (University of Lausanne), for the Board of the Paul Niggli Foundation.

Klaus Holliger
University of Lausanne
DISCOVERY OF A NEW TOURMALINE: ADACHIITE

Dr. Daisuke Nishio-Hamane, a mineralogist at the Institute for Solid State Physics of the University of Tokyo, has found and described a new tourmaline, called adachiite, in collaboration with Dr. Tetsuo Minakawa, a professor of mineralogy at Ehime University, and other members of JAMS. The new mineral was found at the Kiura mine, Oita Prefecture, Japan. It is named in honor of Tomio Adachi (b. 1923) (Fig. 1), a well-known amateur mineralogist who has contributed to the field of mineralogy as a local guide. Adachiite has been approved by the IMA Commission on New Minerals, Nomenclature and Classification (#2012-101).

Adachiite occurs in “emery,” which is an ultrahard rock consisting mainly of corundum, hercynite, and magnetite. Emery deposits were discovered in the Kiura mine in 1959. Emery is mined as a raw material from hard aggregates, and the unmarketable low-grade material is generally discarded. Adachiite was found in a hydrothermal vein in the low-grade material. Adachiite occurs as hexagonal, prismatic crystals (Fig. 2) and forms a zoned structure closely associated with schorl. The massive tourmaline aggregate is black (Fig. 3), while small crystals are transparent with a brownish to bluish purple color (Fig. 2).

A notable feature of adachiite is its chemical composition. Adachiite, CaFe$_3$Al$_6$(Si$_5$AlO$_{18}$)(BO$_3$)$_3$(OH)$_3$(OH), is characterized by Al in the T site, and can be compositionally formed by Tschermak-like substitution (M$^{2+}$ + $\text{Si}^{4+}$ ↔ Al$^{3+}$ + $\text{Al}^{3+}$) from calcic tourmaline, CaFe$_3$(MAl$_5$)(Si$_6$O$_{18}$)(BO$_3$)$_3$(OH)$_3$(OH). Adachiite is the first tourmaline formed via Tschermak-like substitution, and conclusively has the lowest Si content. The formation of adachiite is facilitated by the extremely high-Al and low-Si environment in emery.

JOURNAL OF MINERALOGICAL AND PETROLOGICAL SCIENCES

Vol. 109, no. 1, February 2014

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- Compositional zoning and inclusions of garnet in Sanbagawa metapelites from the Asemi-gawa route, central Shikoku, Japan – Tomoki TAGUCHI and Masaki ENAMI
- Calciborite from the Fuka mine, Okayama Prefecture, Japan – Shoichi KOBAYASHI, Tamami ANDO, Akiko KANAYAMA, Mitsuo TANABE, Shigetomo KISHI, and Isao KUSACHI
- Electron irradiation effects on cathodoluminescence in zircon – Yuta TSUCHIYA, Masahiro KAYAMA, Hirotsugu NISHIDO, and Yousuke NOUMI
- Distribution and mineralogy of radioactive Cs in reservoir sediment contaminated by the Fukushima nuclear accident – Yusuke AOI, Keisuke FUKUSHI, Taeko ITONO, Norio KITADAI, Kenji KASHIWAYA, Hirohisa YAMADA, Tamao HATTAN, and Yugo MANPUKU
- Behavior of rare elements in Late Cretaceous pegmatites from the Setouchi Province, Inner Zone of Southwest Japan – Kei SATO, Tetsuo MINAKAWA, Takenori KATO, Kenshi MAKI, Hideki IWANO, Takafumi HIRATA, Seiji HAYASHI, and Kazuhiro SUZUKI
- Iwateite, Na$_2$BaMn(PO$_4$)$_2$, a new mineral from the Tanohata mine, Iwate Prefecture, Japan – Daisuke NISHIO-HAMANE, Tetsuo MINAKAWA, and Hanako OKADA
- Formation of discordant chromitite at the initiation of sub-arc mantle processes: Observations from the northern Oman ophiolite – Makoto MIURA, Shoji ARAI, and Akihiro TAMURA
- Appearance of as-grown c face in the internal texture of high-quartz crystals collected from Nagatani, Nose-town, Osaka Prefecture – Norimasa SHIMOBAYASHI, Yu KODAMA, and Masaki TAKAYA

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Appearance of as-grown c face in the internal texture of high-quartz crystals collected from Nagatani, Nose-town, Osaka Prefecture – Norimasa SHIMOBAYASHI, Yu KODAMA, and Masaki TAKAYA
CERTIFICATION AND PROFICIENCY TESTING WORKSHOP
17–19 MARCH 2014

The venue for our workshop was the Kavli Royal Society International Centre at Chicheley Hall (near Milton Keynes, UK), a stunning early 18th-century mansion set in 80 acres of beautifully kept grounds. The secluded location meant there were few distractions to lure participants away from their main purpose, which was to consider the effectiveness of the IAG Proficiency Testing and Certification Protocols and to recommend revisions as necessary. The IAG was very pleased to welcome Steve Ellison (LGC Group) and Christophe Quétel (IRMM) as external mentors on the certification of geological reference materials under ISO Guide 35 and some of the challenges this represents, particularly those involving the assessment of uncertainties and traceability.

The workshop also reviewed the operational aspects of GeoPT, IAG’s proficiency testing scheme for powdered silicate rocks. Since its inauguration in 1996, GeoPT has amassed a large amount of data, with some 90 laboratories contributing 3000–3500 values in recent rounds. Trends in reported data and overall performance of the scheme were used as a basis for proposing possible modifications. Outcomes from these sessions will be presented at a GeoPT user’s forum during the Geoanalysis 2015 conference (8–14 August 2015, hosted by Montanuniversität Leoben, Austria).

Discussions on the role of G-Probe, IAG’s microanalytical proficiency testing programme, highlighted the difficulties in developing test materials for in situ analytical techniques as diverse as EPMA and LA-ICP-MS. In this case, one technique requires major element homogeneity at the 2 µm spot size, whereas the other requires trace element (mg kg⁻¹) homogeneity at 20–50 µm. The production of materials for the G-Probe programme has already resulted in several advances pertinent to the development of microanalytical reference materials. Future G-Probe efforts offer a multitude of opportunities with respect to the development of new materials, including synthetic minerals, with an expanded range of major element, trace element and isotopic compositions, unusual element matrices, and mixtures of glasses and powders that will expand the usefulness to techniques such as LIBS and LA-ICP-MS.

The format of the workshop enabled participants to propose ideas that might have been regarded as heretical in other situations and led to a common understanding of many of the fundamental issues raised. Thanks to some splendid organisation behind the scenes by Phil Potts and Jenny Cook, the workshop successfully laid the groundwork for implementing the agreed priorities for the IAG’s proficiency testing and certification programmes.
IMA2014 IS WELL ON TRACK

Arrangements for the quadrennial International Mineralogical Association meeting in Johannesburg, South Africa, on 1–5 September 2014 are well on track, reports Dr Sabine Verryn, chair of the Organising Committee: “The scientific committee is thrilled at the response to calls for session topics and workshops, and is excited by the number of registrants at this early stage.”

IMA2014 is held under the auspices of the Geological Society of South Africa and the Mineralogical Association of South Africa. The overall theme of the meeting is “Delving Deeper – Minerals as Mines of Information.” Although with an emphasis on the theme of economic mineralogy, session topics are incredibly varied. Many of the field trips, compiled by Prof. Judith Kinnaird of the University of the Witwatersrand, reflect the mining heritage of the country. There are 32 excursions on offer, each to be led by specialists. Many trips offer unique opportunities to visit mines and world-class mineral deposits that would not be available to casual visitors. Pre-conference field trips vary in length from 2 to 12 days and include Madagascar pegmatites, Orange River and the Northern Cape geology, the northern Bushveld, the Vredefort impact structure, and the alkaline complexes of Pilanesberg and Bulhoek. The ‘Big Five’ trip will include visits to gold, platinum, diamond and iron mines, and the Palaborwa mine, followed by a few days in the Kruger Park to appreciate the other ‘Big Five’. One-day pre-conference trips will visit vanadium, chromite, diamond, platinum, gold, and silver mines; a coal pilot plant and combustion test facility; and the Cradle of Humankind; there will also be a historical tour of the Witwatersrand goldfield and a scenic trip to the Magaliesberg. Various short tours during the conference will take participants to local mineralogical laboratories and cement and ceramic factories. Post-conference trips vary in length from one to 12 days. One-day visits include the sites of the “Golden City”; a Bronze-age lead-zinc mine; the Tswaing meteorite crater; and the geology, fauna and flora of the Pilanesberg alkaline complex, with a further opportunity to see some of the Big Five. Longer trips are scheduled for ore deposits in southern Namibia, iron ore and manganese deposits of the northern Cape, Namibian pegmatites and industrial minerals, the geology of the early Earth in Barberton, and a Cape Peninsula tour. There is also an exciting programme for accompanying persons. With the rand having lost value against the dollar, euro and pound, these field trips are very affordable for overseas delegates, so there is no better time to visit South Africa and perhaps add a personal holiday to the conference and field trip schedule.

A comprehensive programme is grouped into more than 70 oral and poster sessions, with additional workshops and short courses, reports Dr Desh Chetty of Mintek and chair of the Scientific Programme Committee. There is also a series of pre- and post-conference workshops, which can be booked separately from the conference.

The conference will be held at the Sandton Convention Centre, a 5-minute walk from Sandton City. This cosmopolitan centre is a vibrant hub with more than 300 shops, bars and restaurants offering world cuisine or simply the chance to enjoy a coffee around the central plaza, watched over by a giant statue of Nelson Mandela. Special rates have been negotiated with hotels and guest houses in the Sandton area, with a wide variety of accommodation options to suit the needs and budgets of conference delegates. As well as display booths from major companies, smaller stands have been made available to mineral dealers to enable them to display examples of southern African minerals and to sell small samples to delegates. Dr Craig Smith, chair of the Finance Committee, says there are still a few stand spaces available. Conference registration and field trip bookings can be made online at www.ima2014.co.za.

Prof. Judith Kinnaird
IMA2014 Field Trips Chair
International Conference coming to South Africa!

Experience mineralogy at its best in South Africa at IMA 2014

21st General Meeting of the International Mineralogical Association

1 - 5 September 2014
Sandton Convention Centre, Gauteng, South Africa

We are very pleased to invite you to attend the 21st General Meeting of the International Mineralogical Association, which will take place at the Sandton Convention Centre, Johannesburg, from 1 to 5 September 2014.

The Scientific Programme Committee has received fantastic feedback to their call for session proposals, with over 70 sessions and 10 workshops being accepted for inclusion in the programme, and over 850 abstracts have been received. The various sessions are covered under the following themes:

- Open Theme
- Clay Science
- Deep Earth
- Environmental Mineralogy / Geochemistry
- Economic Geology / Mineralogy, Applied Mineralogy
- Geochemistry and Petrology
- Mineralogical Crystallography
- Methods and Applications
- Minerals, Museums, Culture and History
- Planetary and Cosmic Mineralogy

WORKSHOPS

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<td>Absorptophysical Characteristics of Precious Metals</td>
<td>Sunday, 31 August (half day)</td>
<td>R2,000</td>
<td>Dr. Olga Kotova - Commission IMA-CAM</td>
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<td>Applied Mineralogy of Cement and Concrete (Sponsored by PPC Cement)</td>
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<td>Coding of Mineral Rock &amp; compositions and their ordering using the RHA method</td>
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<td>Gem diamonds: Treatment, synthetics and its identification (Hosted by GIA)</td>
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<td>Infrared core imaging: An emerging technology for geological &amp; mining applications</td>
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<td>Raman and IR Spectroscopy in Mineralogy</td>
<td>Saturday, 6 &amp; Sunday, 7 September</td>
<td>R5,500</td>
<td>Dr Sherif Kharbish</td>
<td>Sandton Convention Centre</td>
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FIELD TRIPS

The Organising Committee is planning the following field trips for IMA delegates:

- Vredefort Dome
- Pilanesberg Alkaline Complex
- Skorpion, Rosh Pinah and Orange River Alluvial Deposits
- Northern Bushveld
- Namibia Pegmatites and Industrial Minerals
- Eastern Bushveld and Nkomati
- Pilanesberg Geology, Fauna and Flora
- Witwatersrand Golden Geology
- Iron Ore and Manganese Deposits of the Northern Cape
- Geology of the Early Earth
- Cape Peninsula and West Coast
- Day trips to various localities

For more information, visit our website and select the “Field Trips” button on the menu.

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When metal sulfide minerals are exposed to air and water, they break down and give rise to acidic, sulfate-rich waters contaminated with dissolved metals, particularly iron. Most commonly, this exposure is due to mining, and the waters are called acid mine drainage (AMD). Sulfides may also be exposed by natural processes or construction projects, and then the resulting contaminated waters are called acid rock drainage. In the USA alone, over 15,000 kilometers of rivers are polluted by AMD, a legacy of the mining of metals and coal. AMD reduces water quality, kills aquatic organisms, and makes receiving waters unsuitable for domestic and industrial use. By far the most important sulfide mineral contributing to AMD is pyrite (FeS₂). In this article we discuss the processes involved in AMD generation and in the management of AMD, focusing on pyrite as the source of contamination, and we demonstrate the role of “mineralogy” in our understanding of this problem.

PYRITE AND AMD GENERATION

Three steps characterize the AMD process (Fig. 1). The first step is the oxidation of the disulfide anion in pyrite to sulfate. This is an electrochemical reaction in which electrons are transferred from the pyrite surface to either O₂ or Fe³⁺. These electrons come from sulfur atoms elsewhere on the pyrite surface. As the sulfur atoms become more electronegative, they react with adsorbed water molecules to form S–O bonds.

When sulfur species such as sulfuric acid, bisulfate, or sulfate are released, relatively fast reactions occur that feed back into the oxidation reaction. For example, O₂ oxidizes pyrite to Fe³⁺ and releases sulfite or sulfate, which are oxidized by Fe³⁺ to sulfate and Fe²⁺. A slower but continuous process is the oxidation of pyrite to Fe³⁺ by other iron oxidation products such as ferric hydroxide minerals (e.g., ferrihydrite, ferrihydrite, and schwertmannite). Fe³⁺ precipitates as goethite or other iron hydroxides, which can then be oxidized by Fe²⁺ to precipitate more Fe³⁺. Thus this cycle is self-perpetuating and becomes more rapid as the pH drops below 4, when the oxidation rate of pyrite by Fe³⁺ is faster than the neutralization rate of H⁺.

The second step is the conversion of Fe³⁺ to Fe²⁺ by Abiotic processes such as evaporation, dissolution of effluent sulfate minerals, and bacterial oxidation by Acidithiobacillus spp. and related microbes (Baker and Banfield 2003). Fe²⁺ is a more effective oxidant than O₂ and it quickly reacts with more pyrite to increase the rate of acid production and Fe³⁺ release. This creates a runaway condition where the iron released by pyrite oxidation causes even more pyrite oxidation; this lowers the pH to between 3 and 4, where iron-oxidizing microbes are especially active. The pH seldom drops below 2.5 because of the sulfate/bisulfate buffer. During dry periods some of the Fe³⁺ is stored in efflorescent sulfate minerals, such as copiapite [Fe₃(SO₄)₂(OH)₂·20H₂O] and fibroferrite [FeSO₄(OH)·S(OH)₃], until rain events put it back into play. In the third step, consumption of hydroxonium ions by reactions with bicarbonate ions (alkalinity) in receiving waters or by reaction with carbonate and silicate minerals causes the Fe³⁺ to hydrolyze and precipitate as ferric hydroxysulfate [schwertmannite, Fe₈O₁₅(SO₄)₃] and oxyhydroxide minerals [e.g., ferrihydrite, Fe₆(OH)₄(SO₄)₂], which eventually transform into goethite (FeOOH) or sometimes hematite (Fe₂O₃). Fe²⁺ hydrolysis releases more hydrogen ions and tends to offset the neutralization reactions.

It is important to note that the pyrite involved in AMD may contain a variety of minor contaminants, including As, Sb, and Cd (Abraitis et al. 2004); these are toxic to humans and other organisms at even low concentration levels and are released on pyrite breakdown. In AMD arising from the mining of metals, there are likely to be much higher concentrations of toxic elements coming from the oxidation of other sulfide minerals present. Minor and trace element contents, and stoichiometry, appear to have a significant although still poorly defined effect on the rate of pyrite breakdown.

REACTION RATES

AMD develops when the acid production by pyrite oxidation and ferric iron precipitation exceeds the acid neutralization rate due to solution alkalinity and reaction with nearby minerals. Figure 2 compares the rates of some important AMD reactions as a function of pH. When pyrite is first exhumed and exposed to air, the surrounding solutions are at near neutral pH and the O₂ oxidation reaction is faster than the Fe³⁺ reaction. Fe²⁺ is converted to Fe³⁺ by abiotic oxidation about as fast as it is released from the pyrite. Pyrite oxidation and the subsequent Fe³⁺ hydrolysis both release hydrogen ions. If this rate is faster than the neutralization rate, the pH declines. Near pH 4 the solubility of Fe³⁺ increases to the point where it reacts with pyrite as fast as O₂, and as the pH drops below 4 the rate of oxidation of pyrite by Fe³⁺ increases very rapidly. At low pH the abiotic Fe³⁺ oxidation rate is slow and contributes very little Fe³⁺ toward pyrite oxidation. However, at low pH the rate of microbial Fe³⁺ oxidation is very fast and replenishes the Fe³⁺ as fast as it is consumed by reaction with pyrite. This creates a fast feedback loop that is responsible for runaway AMD production.

This diagram illustrates the three steps of AMD: (1) pyrite oxidation, (2) deposition of Fe²⁺ as iron oxide minerals, and (3) microbial oxidation of Fe²⁺. The diagram shows the chemical reactions and the flow of Fe²⁺ and Fe³⁺ between the three steps. The pH is indicated on the y-axis, and the log of the reaction rate is plotted on the x-axis. The graph shows that the microbial Fe³⁺ oxidation rate is much faster than the abiotic Fe³⁺ oxidation rate, and that the pH drops below 4 as the Fe³⁺ oxidation rate exceeds the neutralization rate.
SULFATE MINERALS

Most of the pyrite oxidation occurs in the unsaturated zone where the rate of delivery of O₂ by diffusion and advection is fast. Pyrite oxidation adds ferrous sulfate to the pore water, and during dry times some of this solution wicks to the surface, evaporates, and leaves behind efflorescent sulfate salts. Evaporation of a ferrous sulfate solution produces melanterite, but the mineralogy of these efflorescent salts evolves during dissolution–recrystallization cycles caused by diurnal humidity variation and by alternating rain events and dry periods. The salts undergo three kinds of chemical changes (Jerz and Rimstidt 2003). The first is simple dehydration; for example, melanterite with seven waters of hydration per formula unit converts to rozenite with four waters of hydration. The second change involves oxidation of Fe²⁺ to Fe³⁺, yielding mixed-valence iron sulfate minerals such as copiapite. Eventually all the iron becomes Fe³⁺, as in ferriberite. The third change is neutralization, which causes some of the sulfate in the mineral formula to be replaced by hydroxide. Both copiapite and ferriberite contain OH⁻ as well as SO₄²⁻ in their structures. In addition to these major chemical changes, efflorescent sulfate minerals incorporate a host of trace elements, sometimes in relatively high concentrations. For example, Cu²⁺ and Zn²⁺ often substitute for Fe²⁺ in their structures. Efflorescent salts, which form during dry times, are flushed into nearby receiving waters during rain events, causing dramatic pH declines along with very high trace element and sulfate concentrations (Nordstrom 2011). These washout events can cause fish kills.

HYDROXYSULFATE AND OXYHYDROXIDE MINERALS

Oxidation of Fe²⁺ to Fe³⁺ not only raises the activity of ferric iron but it consumes hydrogen ions and raises the pH. This reaction, along with any other process that raises the solution’s OH⁻/SO₄²⁻ ratio, encourages schwertmannite and ferrihydrite precipitation. These minerals form by a process involving ferric hydroxide polymers that grow to nanometer sizes and then aggregate (Banfield et al. 2000; Michel et al. 2007; Gilbert et al. 2013). These minerals are metastable and eventually convert to goethite (Schwertmann et al. 2004; Schwertmann and Carlson 2005) or occasionally hematite. Goethite can also precipitate directly from solution. Goethite often cements stream sediments, forming ferricrete. In upland settings the porous goethite plus hematite remnants of pyrite oxidation are called gossan.

AMD MANAGEMENT

AMD management schemes fall into two broad classes: those that treat the symptoms and those that treat the cause. All are costly and their effectiveness is usually site specific. A wide variety of treatments have been tried but there are few comparative studies of their relative effectiveness and economics, so choosing one for a site is an art guided by limited scientific understanding.

Once pyritic rocks have been exhausted and runaway AMD has commenced, limiting AMD production is expensive and complicated. It is cheaper and easier to raise the pH by mixing with neutralizing agents [NaOH, Na₂CO₃, Ca(OH)₂, CaCO₃] in stirred, aerated tanks. This pH increase causes rapid oxidation of Fe²⁺ and iron oxyhydroxide precipitation. The precipitating iron oxyhydroxides incorporate and remove most of the trace elements from the solution. Equipment costs and the pumping and stirring required for this treatment make it expensive. Smaller, less contaminated discharges are usually treated using less costly, passive treatment systems. These range from limestone-lined ditches and anoxic limestone drains to engineered wetlands. Fresh limestone neutralizes the acidity quite effectively, but precipitation of iron and aluminum oxyhydroxides, and occasionally gypsum, on the limestone grains reduces their reactivity over time (Huminicki and Rimstidt 2008). Fe²⁺ oxidation does not occur in anoxic limestone drains, so iron oxyhydroxide precipitation is avoided and treatment lifetimes are extended. Engineered wetlands contain limestone and biochemically reactive organic matter that cause neutralization and convert sulfate to sulfide. Incorporation of trace elements into the precipitating sulfide minerals is an added benefit. Water retention ponds associated with these installations have the additional benefit of reducing storm washout effects on the receiving waters.

Ideally AMD management plans should treat the source to avoid or at least limit AMD production. Source treatment is usually too complicated and expensive for materials that have already been excavated and begun to generate AMD, so source treatment is usually applied during the excavation process. We know that AMD is caused by pyrite exposure to air and water, so limiting one or the other should decrease the problem. Restricting water access using soil covers or other hydrologic barriers to lower the pyrite oxidation rate will certainly curtail sulfate washout events. Covering AMD-generating material (Hammarstrom et al. 2005) at the 199 roadcuts near State College, Pennsylvania, with impermeable geofabric is an extreme example of this treatment. However, O₂ solubility and diffusion rate are very low in liquid water, so storing AMD-generating materials under water is a particularly effective way to limit pyrite contact with air. Various coatings on the pyrite surface offer another way to restrict O₂ access (Huminicki and Rimstidt 2009), but finding ways to specifically target pyrite has been difficult. Finally, because runaway AMD is due to the very fast microbial Fe²⁺ oxidation rates, a few schemes have been proposed to kill or incapacitate microbes using antibiotics or surfactants. Concerns about contamination of receiving waters by these treatments have limited their application.

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Huminicki DMc, Rimstidt JD (2008) Neutralization of sulfuric acid solutions by calcite dissolution and the application to anoxic limestone drain design. Applied Geochemistry 23: 148-165
Nordstrom DK (2011) Hydrogeochemical processes governing the origin, transport and fate of major and trace elements from mine wastes and mineralized rock to surface waters. Applied Geochemistry 26: 1777-1791
Williamson MA, Kirby CS, Rimstidt JD (2006) Iron dynamics in acid mine drainage. 7th International Conference on Acid Rock Drainage (ICARD), American Society of Mining and Reclamation (AMS), Lexington, KY, pp. 2411-2423.
METASOMATISM AND THE CHEMICAL TRANSFORMATION OF ROCK*  

The concept of metasomatism, or the chemical alteration of solid rocks, stems from the classical observations and interpretations of pioneering geochronists and petrologists, starting with W. M. Goldschmidt and including Hans Ramberg, Peter Misch, and D. S. Korzhinsky. Much of the early discussion centered around the origin of granite. In the middle decades of the last century, experimental studies on the melting of quartzofeldspathic rocks at elevated H$_2$O pressures began to subvert earlier interpretations of metasomatism. The experiments showed that rock melting temperatures dropped drastically from above 1000 ºC into the 600–800 ºC range thought to prevail during high-grade crustal metamorphism, fostering the implication that many of the intuitive interpretations based on the textures of granites could be better explained in the larger context of magmatism. Andrew Putnis and Haakon Austrheim state the situation succinctly in chapter 5 of Metasomatism and the Chemical Transformation of Rock* (p. 143). Referring to “the ultimate demise of metasomatism as a large-scale process,” they go on to say: “The magmatists won the argument with the experimental work of Tuttle and Bowen (1958) and for many years metasomatism was neglected…”

Recent developments in chemical, isotopic, and petrographic analysis have brought metasomatism roaring back into the vocabulary of petrology, as the 15 articles in this book edited by Daniel E. Harlov and H. Austrheim make abundantly clear. One problem has been that the chemical effects of metasomatic processes are often much more subtle than those of igneous processes. An example is the “cryptic” alteration of mantle peridotites, which alteration can now be apprehended by sophisticated modern trace element and isotopic analysis. Most importantly, the complex physical chemistry of multicomponent fluids and their interactions with rocks in reactive flow is orders of magnitude more difficult conceptually than a ternary melting diagram; hence the former lack of interest in an arduous, low-reward effort to understand it in detail.

The metasomatic nature of every petrologic regime, from the oceanic crust (chapter 8, by W. Bach, N. Jons, and F. Klein) to skarns and ore deposits (we already know those are metasomatic, but F. Pirajno’s descriptions in chapter 7 give a nice overview), to metasomatic processes in the mantle lherzolite (chapter 12, O’Reilly and Griffin) and in the deeper parts of the crust (chapter 11 by J. L. Touret and T. G. Nijland) mandate a concerted effort toward a quantitative understanding of fluid–rock inter-

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...of asteroidal parent bodies. This well-illustrated summary should be of considerable value to meteorite geochronists.

Chapter 3 on thermodynamic modeling and thermobarometry, by P. Goncalves, D. Marquer, E. Oliot, and C. Durand, is a good summary of the use of pseudosections as applied to metasomatic rocks. M. Rubenach’s chapter 4, on structural controls on metasomatism, gives a fascinating account of deformation-related mineralization in one of the world’s most spectacular metasomatic terrains, the Mt. Isa Inlier of Queensland, Australia. Chapter 6 on the geochronology of metasomatic events, by I. M. Villa and M. L. Williams, makes the point that all isotopically datable metamorphic events are by definition metasomatic. This chapter is a useful discussion of the procedures and problems of dating metasomatic rocks. Chapter 1, by the book’s editors, gives thumbnail sketches of all the articles. A well-cited article in this book might prove to be chapter 15, by M. Unsworth and S. Rondenay, on the mapping of fluids in the crust and lithosphere by geophysical methods, including seismic profiling and electrical resistivity studies. These authors make a good case for the large-scale existence of interconnected, saline pore fluids in areas of the lower crust undergoing thermal activation, as in the Great Basin of the western United States. Where there are low-resistance channels there must be some kind of conducting fluids, and hence, probable metasomatic action. This and other papers of this book (e.g. Klem and O’Reilly and Griffin) seem to lean to the view that deep-seated fluids (C–O–H fluids and brines) result from subduction of surficial volatiles.

The original metasomatism controversy was centered around the origin of granite, whether or not there is an important process that could be called “granitization.” There is no discussion of this kind of metasomatism in Harlov and Austrheim’s book. The commonly noted metasomatic phenomena of “ghost” gneissic foliation that passes seemingly unimpeded through granites and K-feldspar megacrysts that grow across boundaries of mafic inclusions in granite seem still to be off-limits for respectable scientists. Some day the tainted subject of granitization will also return to the realm of legitimate discussion. A shortcoming of my copy of this book is the low quality of many illustrations in black-and-white reproduction. A full-color version is now available with much improved illustrations. All in all though, this heavyweight book goes a long way toward making up for a half century of neglect of one of the principal petrogenetic processes of the rocky universe.

Robert C. Newton, Dept. of Earth and Space Sciences, University of California at Los Angeles

May 16–18 ACROFI_V, Xi’an, China. Web page: http://es.nju.edu.cn/ACROFI_V/Home.htm

May 17–21 51st Annual Meeting of The Clay Minerals Society (CMS), College Station, TX, USA. Web page: https://cms.2014.tamu.edu


May 24–28 American Crystallographic Association Meeting, Albuquerque, NM, USA. Web page: www.americrostalassin.org/content/pages/main-annual-meetings


May 26–31 Accretion and Early Differentiation of the Earth and Terrestrial Planets (ACCRETE), Nice, France. Web page: www.accrete.uni-bregenzerwald.de/?page=workshop


June 15–16 Short Course Environmental Geochemistry, Mineralogy, and Microbiology of Arsenic, Nevada City, CA, USA. Web page: www.minsocam.org/msa/SC/#open_sc

June 15–19 11th International Georaman Conference, Saint Louis, MO, USA. E-mail: alanw@levee.wustl.edu; web page: http://georaman2014.wustl.edu


June 25–27 ppw@10: A Meeting for the 10th Anniversary of the Discovery of Post-Perovskite, Bristol, UK. Web page: www.wlv.gly.bris.ac.uk/ppw

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

June 30–July 4 30th SEGH (Society of Environmental Geochemistry and Health) Conference, University of Northumbria, Newcastle, UK. Web page: www.segh.net/events/segh-conference


August 2–7 IUMAS-6 held in conjunction with Microscopy & Microanalysis 2014, Hartford, CT, USA. Web page: www.iumas6.org


August 5–7 First Meeting of the IAGC Urban Geochemistry Working Group, Columbus, OH, USA. Web page: www.iagc-society.org/IG.html

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

August 18–23 Geochemistry of the Earth’s Surface (GES-10), Paris, France. Web page: www.ipgp.fr/GES10

August 19–22 14th Quadrennial IAGD Symposium, Kunming, China. Website: www.14iagd.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 1–6 31st International Conference on Ore Potential of Alkaline, Kimberlite and Carbonatite Magmatism, Antalya, Turkey. Website: http://alkaline2014.com

September 4–7 ERES – European Rare Earth Resources Meeting, Milos Island, Greece. Web page: http://eres2014.conferences.gr


September 9–13 Cities on Volcanoes 8, Yogyakarta, Indonesia. E-mail: info@citiesonvolcanoes8.com; website: www.citiesonvolcanoes8.com

September 10–12 Joint SGI-SIMP Meeting, Milano, Italy. E-mail: secreta@socminpet.it; web page: www.geoscience2014.it

September 10–12 Planet Formation & Evolution 2014, Kiel, Germany. Web page: www.w1.astrophys.uni-kiel.de/~kielek2014/main

September 16–19 7th Mid-European Clay Conference (MECC2014), Dresden, Germany. Website: www.mecc2014.de

September 21–24 The 92nd Annual Meeting of the German Mineralogical Society (DGM), Jena, Germany. Website: www.dmg2014.de


October 12–16 MS&T’14: Materials Science & Technology Conference and Exhibition, Pittsburgh, PA, USA. Web page: www.matsitech.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

October 20–24 Short Course “Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences”, Potsdam, Germany. Web page: www.giz-potsdam.de/SIMS


November 21–22 12th Swiss Geoscience Meeting, Fribourg, Switzerland. Details forthcoming


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

December 15–19 AGU Fall Meeting, San Francisco, CA, USA. Web page: http://sites.agu.org/meetings

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January 25–30 39th International Conference and Expo on Advanced Ceramics and Composites, Daytona Beach, FL, USA. Details forthcoming

March 22–26 249th ACS National Meeting & Exposition, Denver, CO, USA. Web page: www.acs.org

April 20–24 27th International Applied Geochemistry Symposium (IACS), Tucson, AZ, USA. Website: www.27iags.com

May 31–June 3 AAPG 2015 Annual Convention & Exhibition, Denver, CO, USA. Web page: www.aapg.org/meetings


August 6–21 2015 Goldschmidt Conference, Prague, Czech Republic. Web page: www.geochromsoc.org/programs/goldschmidtconference

August 23–28 29th Meeting of European Crystallographic Association (ECM29), Rovinj, Croatia. Web page: http://ecm29.ceanews.org

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

September 10–23 Goldschmidt Conference, Cape Town, South Africa. Website: www.35igc.org

The meetings convened by the societies participating in Elements are highlighted in yellow. This meetings calendar was compiled by Andrea Kozioł (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.
3D printing is much in the news at present, and this Parting Shot was stimulated by an item on the radio programme that I enjoy at breakfast. Surgeons somewhere in England, I learned, are planning to print a replacement head for a young man terribly injured in a motorcycle accident. The reality was slightly less dramatic than the headline, but there is no doubt that computers have transformed our ability to visualize and manipulate complex 3D shapes. Learning to envision complex objects, very large (like mountain ranges) and very small (like crystal atomic structures), and sometimes abstract (like quaternary phase diagrams), in 3D has always been a big part of geological training, and I think we can collectively claim to be rather good at it.

Quite rightly, learning how to make, read and interpret geological maps is a central part of most geology degree programmes. Geological maps are really wonderful things, depicting how complex underground 3D features are really wonderful things, depicting how complex underground 3D features are expressed on a surface that is, in hilly country, itself a complex 3D shape. Their special characteristic, which sets them above mere topographic maps, is that they come with time as a fourth dimension. With training we can rapidly discern time’s arrow in bedded sequences and infer the ever-changing conditions of their formation. We can pick out the unconformities, sometimes representing vast breaks in recorded history, through which James Hutton realised he could glimpse ‘ancient worlds’. We can see the evidence for multiple phases of igneous activity, faulting, folding, and metamorphism. British maps sometimes bring us close to the present...
with notes on Quaternary deposits. I have a 1904 Geological Survey map of the county of Kent, south-east of London, beside me, with fascinating neat annotations hinting of a fast-changing, post-glacial world: ‘ELEPHANT RHINOCEROS, &c. IN MEDWAY GRAVEL AT AYLESFORD’. Palaeolithic hunters roamed where now the stockbrokers roam.

Few, if any, forms of human communication are as densely packed with information as a geological map, but for the general public they remain largely impenetrable. It is often hard to see topographic contours, and the key to the colours uses unfamiliar specialised names. Reading the map so that you can relate it to your surroundings and unravel their history needs training, a lot of training. I work for a voluntary organisation called Lochaber Geopark, which aims to explain the geology in this part of the West Highlands of Scotland to visitors and local people (www.lochabergeopark.org.uk). Lochaber’s main source of income is tourism. In 2013, 119,000 people, six times the population of Lochaber, climbed Britain’s rather modest highest peak, Ben Nevis, all on foot, from sea level.

I recently helped design 20 interpretative panels for the Geopark, which covers about 4500 km² and has a long fjord coastline. The panels form a ‘Rock Route’, and visitors can pick up a pamphlet that leads them, by car or bike, sometimes by ferry, to panels at points that combine stunning scenery with exciting geology (www.wildlochaber.com/things-to-do-geopark-rock-route). Writing text for the general public is challenging. You don’t get many words with which to introduce all the many rock types and tell their story. Many of the panels have, as their centrepiece, an oblique geological map like my example from Ben Nevis. They are based on originals very kindly provided by the British Geological Survey, who have some very smart software that allows the user to drape the geology over a 3D rendering of the landscape from any chosen direction.

When you have the geology in 3D before you, somehow the real scenery comes to life. With the help of some simple block diagrams, non-expert visitors can imagine the andesite flows in the Ben Nevis caldera descending 600 m while great ash clouds were erupting along the ring-fault, 420 million years ago. They can see, in the middle distance, the trace of the mighty Great Glen transcurrent fault and imagine the two terranes, built of metamorphic rocks of the Moine and Dalradian super-groups, grinding past each other. They can read how these rocks formed as sedimentary sequences at different times, the oldest stretching back a billion years, in different places, and how they have different metamorphic histories. And our visitors can imagine Ben Nevis a mere 12,000 years ago, when only its upper reaches were visible as a nunatak above an ice sheet a kilometre thick and modern humans had not yet arrived.

Ian Parsons (iparsons@staffmail.ed.ac.uk)
University of Edinburgh
Assistant Professor in Inorganic Chemistry/Biogeochemistry

This position is open to an outstanding scientist with a demonstrated track record of scientific achievements within Inorganic Chemistry and/or highly related research areas, such as Biogeochemistry. More specifically, we are searching for an experimentalist or a theoretician with research activities focused on inorganic solution chemistry, solids and/or interfaces that can complement scientific themes covered within the biogeochemistry research group of the department. Use of national infrastructures (e.g. MAX-lab, Swedish National Infrastructure for Computing) is encouraged, although not a prerequisite that will impact the outcome of the selection process.

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More details on the position (reference number AN 2.2.1.2-473-14) and on the application procedures can be found at:
www.umu.se/english/about-umu/open-positions

Further information can be obtained from Professor Jean-François Boly (jean-francois.boly@chem.umu.se). Application deadline is May 22, 2014.

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