Kimberlites

From Deep Earth to Diamond Mines

What is a Kimberlite?

Geochemical Probes of Earth’s Mantle

Origins of Kimberlite Magmas

Geochronology and Emplacement Patterns

Kimberlite Volcanology

Diamond Exploration and Deposits
Liddicoat Postdoctoral Research Fellowships in Mineralogy, Materials Science and Gemology at GIA

GIA (Gemological Institute of America®) invites qualified candidates to apply for the Richard T. Liddicoat Postdoctoral Research Fellowships at its Carlsbad, California and New York City locations. The one- to two-year fellowships encourage early career scientists to pursue full-time academic research in mineralogy, geology, physics, materials science and other fields related to gemology – the study of diamonds, colored gemstones, pearls and their treatment. Fellows are expected to conduct creative, independent, publishable research and collaborate with GIA scientists, outside research institutions and universities.

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In a recent study published in Science magazine (Dec. 16, 2016), GIA Postdoctoral Research Fellow Evan Smith and coauthors uncovered clues about Earth’s deep mantle by examining the distinct characteristics of large, exceptional gem diamonds known as “CLIPPIR” diamonds. Not normally available for research, inclusions found in these cut diamond pieces led to two breakthrough discoveries.

Established in 1931, GIA is the world’s foremost authority on diamonds, colored gemstones and pearls. A public benefit, nonprofit institute with locations in 13 countries, GIA is the leading source of research knowledge, standards and education in gems and jewelry. Visit GIA.edu
Kimberlites: From Deep Earth to Diamond Mines
Andrea Giuliani and D. Graham Pearson

What is a Kimberlite? Petrology and Mineralogy of Hypabyssal Kimberlites
Roger H. Mitchell, Andrea Giuliani, and Hugh O’Brien

Kimberlites as Geochemical Probes of Earth’s Mantle
D. Graham Pearson, Jon Woodhead, and Philip E. Janney

Kimberlites from Source to Surface: Insights from Experiments
Stephen F. Foley, Gregory M. Yaxley, and Bruce A. Kjarsgaard

Dating Kimberlites: Methods and Emplacement Patterns Through Time
Larry M. Heaman, David Phillips, and D. Graham Pearson

Kimberlite Volcanology: Transport, Ascent, and Eruption
J. Kelly Russell, R. Stephen J. Sparks, and Janine L. Kavanagh

Diamond Exploration and Resource Evaluation of Kimberlites
Bruce A. Kjarsgaard, Nicole Januszczak, and Johann Stiefenhofer

Volume 15, Number 6 • December 2019

PARTICIPATING SOCIETIES

The Mineralogical Society of America is for individuals interested in mineralogy, crystallography, petrology, and geochemistry. Founded in 1919, the society promotes knowledge, through research, education, and publications, the understanding and application of mineralogy by industry, universities, government, and the public. Membership benefits include Elements magazine, access to the electronic version of the American Mineralogist, as well as discounts on journals, Reviews in Mineralogy & Geochemistry, textbooks, monographs, reduced registration fees for meetings and short courses, and participation in workshops that support the many facets of mineralogy.

Website: www.minsocam.org
Contact: business@minsocam.org

Society News Editor: Andrea Koizol
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The Mineralogical Society of Great Britain and Ireland is an international organization for those working in the mineral sciences. The society aims to advance the knowledge of the science of mineralogy and related subjects. It promotes crystallography, geochemistry, petrology, environmental science and economic geology. The society furthers its aims through scientific meetings and the publication of a journal, The Mineralogical Record, and a monograph series. The society publishes Mineralogical Magazine and Clay Minerals. Students receive membership as a first year subscription for free. All members receive Elements.

Website: www.minersoc.org
Contact: info@minersoc.org

Society News Editor: Kevin Murphy
(kevin@minersoc.org)

The Clay Minerals Society (CMS) began as the Clay Mineralogy Committee of the US National Academy of Sciences – National Research Council in 1952. In 1962, the CMS was incorporated with the primary purpose of stimulating research and disseminating information relating to all aspects of clay science and technology. Its annual meetings, workshops, and field trips, and publications, such as Clays and Clay Minerals and the CMS Workshop Lectures, and Elements are dedicated to promoting geochemistry internationally. The society is a dynamic association that organizes the Goldschmidt Conference® in Europe, publishes Geochemical Perspectives and Geochemical Research, recognizes scientific excellence through awards, supports Early Career Scientists, sponsors workshops and conferences in Europe, organizes Distinguished Lecture and Outreach Programs, publishes job opportunities, networking, social media, and partners with other learned societies to strengthen geochemistry. CMS workshops are incorporated with the primary purpose of fostering cooperation in the advancement of geochemistry through its metals, lectures, and awards. Members receive a subscription to Elements, special member issues of GCA and G-cubed, and publication and conference discounts.

Website: www.geochemsoc.org
Contact: office@geochemsoc.org
Society News Editor: Kevin Johnson
(kjohnson@geochemsoc.org)

Founded in 1965, the European Association of Geoscientists and Engineers (EAEG) is a non-profit organization dedicated to promoting geochemistry internationally. The society is a dynamic association that organizes the Goldschmidt Conference® in Europe, publishes Geochemical Perspectives and Geochemical Research, recognizes scientific excellence through awards, supports Early Career Scientists, sponsors workshops and conferences in Europe, organizes Distinguished Lecture and Outreach Programs, publishes job opportunities, networking, social media, and partners with other learned societies to strengthen geochemistry.

Website: www.eag.eu.com
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Society News Editor: Alice Williams
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The International Association of GeoChemists (IAGC) has been a preeminent international geochemical organization for over 40 years. Its principal objectives are to foster cooperation in the advancement of applied geochemistry by sponsoring specialist geochemical symposia and the activities organized by its working groups and by supporting its publication, the IAGC Journal. The administration and activities of IAGC are guided by its council, comprising an executive and ten regional members. Day-to-day administration is performed through the IAGC business office.

Website: www.iagc-society.org
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Society News Editor: Chris Gardner
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The Société française de Cristallographie, the French Mineralogical and Crystallographic Society, was founded on 21 March 1878. The purpose of the society is to promote mineralogy and crystallography. Membership benefits include the Journal of Mineralogy, a digital events calendar, and reduced registration fees for SMFC meetings.

Website: www.smfc-fr.org
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Society News Editor: Mary-Alix Kaczmarek
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The Association of Applied Geochemists is an international organization that specializes in the field of applied geochemistry. The society promotes knowledge of the science of geochemistry and aims to advance the science of geochemistry as it relates to exploration and the environment. The society promotes the interests of exploration geochemists, facilitates the exchange and discussion of scientific knowledge, promote the exchange of information, and encourage research and development. The society publishes the AAG journal, Geochemistry: Exploration, Environment, Analysis, the AAG newsletter, EXPLOR, and Elements.

Website: www.appliedgeochemists.org
Contact: office@appliedgeochemists.org
Society News Editor: John Carranza
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The Deutsche Mineralogische Gesellschaft (DMG), German Mineralogical Society was founded in 1908 to “promote mineralogy, its application to other subjects, including mineralogical science and education and publications.” Membership benefits include receiving the European Journal of Mineralogy, Minerals, and other publications, and a subscription to Elements.

Website: www.dmg-home.org
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The Società Italiana di Mineralogia e Petrologia (SIMP) is an international organization for Italian Society of Mineralogy and Petrology. “The aim is the national body representing all researchers dealing with mineralogy and related disciplines. Membership benefits include receiving the European Journal of Mineralogy, Minerals, and Elements, and a reduced registration fee for the annual meeting.

Website: www.socminpet.it
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The International Association of GeoAnalysts is a worldwide organization supporting the professional interests of those involved in the analysis of natural and environmental materials. Activities include the management of professional programmes for formal and micro-analytical methods, the production and certification of reference materials and the publication of the association’s journal, Geostandards and Geoanalytical Research.

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

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The Sociedad Española de Mineralogía (Mineralogical Society of Spain) was founded in 1975 to promote the study of mineralogy, petrology, and geochemistry. The society organizes annual conferences and further training activities. The society promotes young researchers via seminars and special publications. The SEM Bulletin publishes scientific papers from 1978 to 2003, the year the society joined the European Journal of Mineralogy.

Website: www.appliedgeochemists.org
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affiliated Societies

The International Mineralogical Association, the International Association of Geoanalysts, the International Association for the History of Mineral Sciences, and the International Association for the History of Science, were founded in 1913 to promote international cooperation and increase knowledge in the field of the history of ore deposits and is affiliated with the International Union of Geological Sciences (IUGS). The society organizes symposiums, conferences and workshops on mineralogy and geochemistry.

Website: www.iagod.org
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The Swiss Society of Mineralogy and Petrology was founded in 1949 as an international society from academia and industry and has a dynamic program to promote knowledge in the fields of mineralogy, petrology, and geochemistry and to disseminate science to the public and other communities. The society organizes the annual Swiss Geoscience Meeting and publishes the Swiss Journal of Geosciences jointly with the national geological and palaeontological society.

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The Meteoritical Society is an international organization for meteoriticists, scientists, collectors, and other professionals interested in meteoritics, meteor showers, and other extraterrestrial material and their potential and actual, terrestrial and extraterrestrial applications. Members receive our journal, Meteoritics, The Meteoritical Bulletin, and Elements. We organize our annual meetings, workshops, field trips, and support young planetary scientists to provide a forum for the presentation of research, become involved in international cooperation and alliances, and educate the public. Membership benefits include receiving the journal Meteoritics, The Meteoritical Bulletin, and Elements. Members also receive reduced rates for our meetings, workshops, field trips, and support young planetary scientists to provide a forum for the presentation of research.

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The Japan Association of Mineralogical Sciences (JAMS) was established in 2007 by merging The Mineralogical Society of Japan, founded in 1955, and the Japanese Association of Mineralogists, Petrologists, and Economic Geologists, established in 1928. JAMS covers the wide field of mineral sciences, geochemistry and applied geology. Membership benefits include receiving the Journal of Mineralogical Sciences (JMS), the Japanese Journal of Mineralogy, Petrology, and Geochemistry (JMP), the Geochemistry and Geophysics of the Elements (GGE), and Elements. Members receive our journal, the Journal of Mineralogical Sciences (JMS), the Japanese Journal of Mineralogy, Petrology, and Geochemistry (JMP), the Geochemistry and Geophysics of the Elements (GGE), and Elements.

Website: jams.la.coocan.jp
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The International Association on the Genesis of Ore Deposits (IAGOD) was established in 1963 to promote international cooperation and increase knowledge in the field of the origin of ore deposits and is affiliated with the International Union of Geological Sciences (IUGS). The society organizes symposiums, conferences and workshops on mineralogy and geochemistry.

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Contact: info@iagod.org/node/87
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CARBON – BEAUTIFUL, ESSENTIAL, DEADLY

DOI: 10.2138/gselements.15.6.367

The unique physical chemistry of carbon confers an extraordinary ability to form molecules that are variously beautiful (think diamond), essential (think living cells), and toxic (think greenhouse gas). Nowhere is this split personality more evident than in the enigmatic igneous clan of kimberlites, the topic for this issue of Elements. No one who has set eyes on a cut diamond, especially the delicate pink stones from soon-to-close Argyle Mine in Western Australia (see photo to the right), can fail to be awestruck at Nature’s capacity for beauty. Kimberlite magmas that bring diamonds to the surface are carbon-fuelled, whether by methane through a complex series of redox melting reactions (see Foley et al. 2019 this issue p. 405), or by carbon dioxide exsolving from kimberlite melt at sub-crustal depths and propelling it explosively to the surface (see Russell et al. 2019 this issue p. 405). We have yet to witness a kimberlite eruption – the last known eruption, in Tanzania, was ten thousand years ago – but we can be fairly sure that the greenhouse gas delivery of a single kimberlite pipe in full flow was pretty substantial. For kimberlites, carbon is both passenger and propellant.

Carbon is just as essential for life itself; it is almost impossible to conceive of living without carbon. Paradoxically, however, living with carbon, in the form of carbon dioxide and its sinister sibling, methane, is increasingly problematic. As I write this editorial, travelling (by train) to a school reunion in the north of England, my newspaper is awash with news of political manoeuvring ahead of a United Kingdom general election in which CO₂ and CH₄ co-star (alongside Brexit) in the battle for voters’ hearts and minds. At long last, it seems Planet Earth is on the political agenda. This, we are told, is the “climate election”, with politicians clamouring to tell us what they will do to reduce greenhouse gas emissions, if only we would vote for them.

And what, indeed, might they do? If the solution were simple, we would have set about it immediately after the first Framework Convention on Climate Change, in Rio de Janeiro (Brazil) back in 1992. But potential solutions are complex, and the many pronouncements of media and activists are quite confusing, even to a scientist. Give up air travel? Go vegan? Eschew the motor car? Cut pink diamond from Argyle (Australia)

©Unleashed Images

Cut out concrete? It is hard to choose how to reduce greenhouse gas emissions, if only we would vote for them.

Climate scientists have been telling us for some time, and in ever more gory detail, that the patient is unwell, very sick, at death’s door. We recognise the symptoms and understand the prognosis. We now need to urgently move from diagnosis to medication. And in this sense, Earth scientists are physician and pharmacist rolled into one. The transition to a low-carbon world of wind, water, and sun (± nuclear and geothermal), will require a bewildering diversity and quantity of natural resources. Some of these, like copper, are already well known to us – we will just need an awful lot more, perhaps as much as ten times current known reserves.

Others, like lithium, are set to acquire a global economy of their own as we strive to meet the battery needs of a billion electric cars. There are still other resources that we don’t yet know we’ll need – a glance at the periodic table gives a sense of the myriad possibilities. As engineers of the future develop the technologies needed to sustain the planet’s growing and developing population, so pressure on Earth scientists to find the requisite elements will grow. Innovative ways to locate and sustainably extract nature’s bounty will become essential. And no one innovates quite like an Earth scientist. At a recent meeting of the Society of Economic Geologists, I met a Canadian mining geologist whose company is developing a method of extracting battery-grade lithium from powdered, peraluminous obsidian in southern Peru. The nearby tuffs host supergene uranium minerals that were formed by reaction of volcanic glass with glacial melt water. Here is a single mineral deposit simultaneously providing the lightest and heaviest naturally occurring metals. And extraction is all powered by local hydroelectricity. Innovative indeed!

As global citizens, we have a collective responsibility to modify our lifestyles for the benefit of a sustainable planet. How we do this is chiefly up to us, at least until politicians really seize the initiative. As Earth scientists, we have a unique responsibility (and ability) to enable the transition to a sustainable global economy by finding the necessary natural resources. These are dark days for humankind, perhaps, but step-up-to-the-plate times for the Earth sciences.

Jon Blundy, Principal Editor
ABOUT THIS ISSUE

You have probably heard or used the statement, “Diamonds are a girl’s best friend.” It draws its popularity from a song performed by Marilyn Monroe (a US actress) in the 1953 film Gentlemen Prefer Blondes. Marilyn, or the song writers (Leo Robin and Jule Styne), likely had no idea that “These rocks [that] don’t lose their shape” were derived from the Earth’s mantle (200 km deep) and were rapidly transported to the surface via a kimberlite magma. The resulting kimberlite deposits have been exploited by modern diamond-mining companies for well over 100 years. The multibillion-dollar diamond industry has been dependent on finding the next diamond-bearing deposit, and this has helped drive research on kimberlites. The authors of the articles in this issue of Elements explore the origins, evolution, transport, emplacement, and economic potential of kimberlites. And, if you want to read more about diamonds, check out the articles in the March 2005 issue of Elements (“Diamonds”), which can be found at elementsmagazine.org.

A JOINT ENDEAVOUR

The copy of Elements you are holding in your hands (or reading online) is the result of the creativity and expertise of our 18 participating societies, authors, editors, reviewers, graphic designers, business and administrative staff, print and shipping vendors, and advertisers. Every issue represents hundreds of hours of effort by many individuals working together for a common goal … to deliver Elements to you, the reader. Elements is a joint endeavour. Each year, in our final issue, we take a moment to extend our appreciation to those that brought Elements to life. This year is no different.

We want to first thank the 18 participating societies and their members who support this magazine. Without them, Elements wouldn’t exist. The Elements Executive Committee, with representatives from each participating society, provides financial oversight and guidance. They have kept Elements financially viable over the years, which has enabled us to produce a high-quality publication for our readership. The Mineralogical Society of America provides everyday business operations of the magazine: database management, finances, legal matters, tax audits, warehouse maintenance, computer support and so much more. And, Johanne Caron, of the Mineralogical Association of Canada, annually balances our finances for audit and tax reporting. The editorial team thanks these societies and individuals for their commitment to Elements.

We also like to thank the 13 guest editors and 81 authors who contributed thematic content to the six issues of volume 15 and our feature editors (Cari Corrigan, Andrea Koziol, Ian Parsons, Michael Wiedenbeck, and David Vaughan) who coordinate the CosmoElements, Meetings Calendar, Parting Shots, Elements Toolkit, and Mineralogy Matters. We also acknowledge the reviewers, our copyeditor Patrick Roycroft, and our graphic artist Michel Guay.

2020 PREVIEW AND FUTURE ISSUES

The authors and editors are already hard at work preparing the articles that will be published in Elements in 2020. Some of the articles are almost complete, others are still in development. You can find a listing of those articles in our thematic preview on pages 370 and 371.

The principal editors will be meeting in early 2020 to review proposed topics for the 2021 lineup. If you have ideas for a thematic issue, contact one of our principal editors and submit a proposal for our consideration. More information about publishing in Elements can be found at elementsmagazine.org/publish-in-elements/.

In addition, we appreciate our advertisers for their continued support. Please take the time to visit their websites or speak with their representatives to learn about their products and services. Those that advertised in 2019 were Analab, Cambridge University Press, CAMECA, Crystal Maker, Dr. Eduard Gübelin Association, Excalibur Minerals Corporation, Gemological Institute of America (GIA), Geochemist’s Workbench, Geological Society of London, International Association of Geoanalysts, International Centre for Diffraction Data, Iomplus+, Materials Research Society, ODLAB, ProtoXRD, Savillex, Scott-Smith Petrology Inc., Smart Elements, the University of Cambridge, and the University of Wisconsin.


Finally, we want to extend our appreciation to Allen Press (https://www. allenpress.com/) and APC Postal Logistics, LLC (https://www.apc-pli.com/). These companies print and/or ship Elements to you.

Nancy Ross, Jon Blundey, John Eiler, and Jodi Rosso

FROM THE EDITORS
Scientific Instruments for Radiocarbon Dating and Accelerator Mass Spectrometry

MICADAS Mini Carbon Dating System

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Dedicated to excellence.
The application of Raman (microprobe) spectroscopy in the geosciences has rapidly broadened and deepened over the past 40 years. This has been sparked by both improvements in technology and recognition of the quantitative, as well as qualitative, capabilities of the technique. Raman spectroscopy claims relative ease of use; is typically nondestructive at the (sub-)micrometer scale; has the ability to analyze solids, liquids, and gases; can differentiate polymorphs; and can enlarge the available spectral databases for minerals. Geoscientists can create Raman maps/images based on selected spectral features, which simultaneously capture chemical-structural and microtextural information. In a single sample, one may investigate quantitatively the P-T path history during metamorphism, determine the composition and internal pressure of mixed volatiles in micrometer-size fluid inclusions, study the strain pattern or radiation damage in minerals, and/or target possible biosignatures.

- Welcome to Raman Spectroscopy: Successes, Challenges, and Pitfalls Jill D. Pasteris (Washington University in Saint Louis, USA) and Olivier Beyssac (CNRS-Sorbonne University Paris, France)
- Micro-scale Chemistry: Raman Analysis of Fluid and Melt Inclusions Robert J. Bodnar (Virginia Tech, USA) and Maria Luce Frezzotti (University of Milan-Bicocca, Italy)
- Applications of Raman Spectroscopy in Mineralogy and Geochemistry Lutz Nasdala (University of Vienna, Austria) and Christian Schmidt (GFZ German Research Centre for Geosciences, Potsdam, Germany)
- Applications of Raman Spectroscopy in Metamorphic Petrology and Tectonics Andrew V. Korsakov (Sobolev Institute of Geology and Mineralogy, Russia), Matthew J. Kohn (Boise State University, USA) and Maria Perraki (Technical University of Athens, Greece)
- Geoscience Meets Biology: Raman Spectroscopy in Geobiology and Biominaleralization Andrew Steele (Carnegie Institution of Washington, USA), Marc D. Fries (NASA Johnson Space Center, USA) and Jill D. Pasteris (Washington University in Saint Louis, USA)
- New Trends in Raman Spectroscopy: From High-Resolution Geochemistry to Planetary Exploration Olivier Beyssac (CNRS-Sorbonne University Paris, France)
THEMATIC TOPICS IN 2020

LITHIUM: LESS IS MORE

Guest Editors: Robert J. Bowell (SRK Consulting Ltd., UK), Philip A.E. Pogge von Strandmann (University College London and Birkbeck, University of London, UK) and Edward S. Grew (University of Maine, USA)

Lithium is concentrated in Earth’s upper continental crust and is an essential constituent of 122 mineral species with the greatest mineralogical diversity found in pegmatites. Lithium occurs naturally in two isotopes, $^6$Li and $^7$Li, which are readily fractionated, thus becoming sensitive to geological and environmental processes. Closed-basin brines (58%) and pegmatites plus related granites (26%) constitute the main sources of exploitable lithium worldwide. Rechargeable batteries that take advantage of lithium’s light weight and high electrochemical potential offer the greatest potential benefit to the most people. Lithium compounds are also used to control bipolar disorder. In a word, life as we know it at the start of the 21st century would not be possible without lithium.

• The Minerals of Lithium, a Quintessential Crustal Element Edward S. Grew (University of Maine, USA)
• The Cosmic Lithium Story Katharina Lodders (Washington University in Saint Louis, USA)
• Is it Time for Lithium Isotopes? Horst R. Marschall (Goethe Universität Frankfurt am Main, Germany) and Ming Tang (Rice University, USA)
• Lithium and Lithium Isotopes in Earth Surface Cycles Philip A.E. Pogge von Strandmann (University College London and Birkbeck, University of London, UK), Simone A. Kasemann (University of Bremen, Germany) and Josh Wimpenny (Lawrence Livermore National Laboratory)
• Natural Resources: Where Do We Find Lithium at Economic Potential? Robert J. Bowell (SRK Consulting Ltd., UK), Julien Declercq (SRK Consulting Ltd., UK), and Camilo de los Hoyos (SRK Consulting S.A., Argentina)
• Lithium in Society Thomas Bibienne (Nemaska Lithium Inc., Canada), Jean-François Magnan (Nemaska Lithium Inc., Canada), and Alexander Benedikt Angar Rupp (German Heart Centre Munich, Institute of Laboratory Medicine, Germany)

Volume 16, Number 4 (August)

HYDROTHERMAL FLUIDS

Guest Editors: Matthew Steele-MacInnis (University of Alberta, Canada) and Craig E. Manning (University of California, Los Angeles, USA)

Fluids are one of the principal agents of heat and mass transfer in the Earth. This thematic issue will explore the physical and chemical properties of hydrothermal fluids and how they affect geologic processes. The issue will discuss our current understanding of the nature of hydrothermal fluids across a range of geologic settings; interactions between fluids and rocks; and the interrelationships between fluid-driven processes in different settings. Each chapter will highlight both broad and specific overlaps between “normal” and ore-forming hydrothermal fluids, and describe how the features of hydrothermal systems reflect the specific properties of the fluids in each setting.

• Hydrothermal Properties of Geologic Fluids Matthew Steele-MacInnis (University of Alberta, Canada) and Craig E. Manning (University of California, Los Angeles, USA)
• Crustal Metamorphic Fluids Katy A. Evans (Curtin University, Australia) and Andrew G. Tomkins (Monash University, Australia)
• Fluids in Submarine Hydrothermal Settings Esther M. Schwarzenbach (Freie Universität Berlin, Germany) and Matthew Steele-MacInnis (University of Alberta, Canada)
• Fluids in Subduction Zones and the Upper Mantle Craig E. Manning (University of California, Los Angeles, USA) and Maria-Luce Frezzotti (Università degli Studi di Milano, Italy)
• Magmatic-Hydrothermal Fluids Andrea Audetat (Universität Bayreuth, Germany) and Marie Edmonds (University of Cambridge, UK)
• Geothermal Fluids Isabelle Chambefort (GNS Science, New Zealand) and Andri Stefansson (University of Iceland, Iceland)

Volume 16, Number 6 (December)

NOBLE GAS THERMOCRONOLOGY

Guest Editors: Marissa M. Tremblay (Purdue University, USA), Emily H. G. Cooperdock (University of Southern California, USA), and Peter K. Zeitler (Lehigh University, USA)

Noble-gas thermochronology takes advantage of the time-dependent production of noble gases and the thermally activated diffusion of these gases to constrain the temperature histories of minerals found in crustal rocks. Thermochronology has become widely used to address research questions across Earth and planetary science. These questions include when and how valleys are cut by glaciers; from where sediment is sourced; what thermal conditions occur on fault planes during slip; and how the surfaces of planetary bodies evolve on billion-year timescales. This issue will highlight how noble-gas thermochronology can be used to address questions like these, as well as what new avenues of research noble-gas thermochronology could be used for in the future.

• The Thermal History of Rocks as Recorded by Noble Gases Peter K. Zeitler (Lehigh University, USA) and Cecile Gautheron (Université Paris Sud, France)
• Detrital Thermochronology: Recorder of the Earth’s Dynamic Past Daniel F. Stockli (University of Texas at Austin, USA) and Yani M. R. Najman (Lancaster University, UK; University of Colorado, Boulder, USA)
• Faults, Fluids, and Heat: New Insights from Fe-Oxide (U-Th/He) Thermochronology Emily H. G. Cooperdock (University of Southern California, USA) and Alexis K. Ault (Utah State University, USA)
• Vestiges of Deep Time: Noble-Gas Thermochronology of Ancient Rocks Kalin T. McDannell (Geological Survey of Canada, Canada) and Rebecca M. Flowers (University of Colorado, Boulder, USA)
• Noble-Gas Thermochronology of Extraterrestrial Materials Marissa M. Tremblay (Purdue University, USA) and William S. Cassata (Lawrence Livermore National Laboratory, USA)
• Lazed and Diffused: Untangling Noble-Gas Thermochronology Data Matthew Fox (University College London, UK) and David L. Shuster (University of California, Berkeley, USA)

Volume 16, Number 5 (October)
Meet the Authors

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Andrea Giuliani is currently a Swiss National Science Foundation Ambizione Fellow at the ETH (Switzerland). After completing his BSc and MSc studies in Italy, he obtained a PhD at the University of Melbourne (Australia) where he was later appointed lecturer in igneous petrology. In Melbourne, Andrea established the Kimberlites and Diamonds (KiDs) Research Group, which investigates the origin of kimberlites and related rocks, and the formation of diamond deposits. Andrea is currently exploring the evolution of Earth’s deep mantle using kimberlites and related magmas. His awards include a Discovery Early Career Research Award (DECRA) by the Australian Research Council hosted by Macquarie University (Sydney), and a Marie Curie-Skłodowska Fellowship at the Free University of Amsterdam (Netherlands).

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With all due respect to basalt, and I appreciate a granite as much as the next person, Kimberlite is hard to beat. But what is a Kimberlite? Kimberlites may be classified as igneous rocks but it is difficult to know how exactly to describe them in terms of magma, at least in any conventional sense of the word. Kimberlites tap the deepest recesses of our planet that we can sample. Propelled by a formidable volatile load, Kimberlite melts transit hundreds of kilometers of mantle and crust, perhaps in just a few days, to form unique ballistic deposits at Earth's surface. Kimberlites accumulate and transport ripped-up bits from throughout most, if not all, of their ascent path, including diamond, that classic gem of desire with its remarkable qualities that have fueled a global market. Indeed, much of our understanding of Kimberlite is owed to the intrepid explorers who searched for and studied elusively diamond deposits. Adding to the veil of petrological complexity Kimberlites are often pervasively altered by fluids, some of which were magmatic but some of which were not. The study of Kimberlites over many decades has revealed glimpses of their origins and the paths by which they have travelled.

To begin to understand Kimberlites we start by considering where and when they occur. Kimberlites typically form giant carrot-shaped deposits symptomatic of their volatile-driven high-velocity emplacement, being fed at depth from a complex network of cracks and veins that draw melt out of the mantle. They are found only in continental settings (none are known from ocean basins) and seem to be intimately related to the thick lithospheric keels that anchor our landmasses into the deep mantle. Kimberlites first appear in the rock record about three billion years ago but are conspicuously concentrated in the last several hundred million years. These space-time relations tell us that Kimberlites do not form in shallow upwelling mantle and that they are somehow related to a deep-seated geodynamic process that began during the late Archean, eerily coincident with the onset of plate tectonics as we understand it.

Before addressing more speculative matters, what are Kimberlites made of? In general, Kimberlites are something of a grotesque mixture of phenocrysts, xenocrysts, xenoliths, lithoclasts, lapilli and all manner of groundmass. Many are full of foreign materials, making the original magmas all but impossible to reconstruct. Kimberlite melts exorcize the rocks they pass through, tearing up chunks of the mantle from depths of several hundred kilometers. They may (but not always) bear diamonds, which form at depths greater than about 150 km. These crystals themselves harbor mineral and fluid inclusions that reveal a rich story of how they formed and the processes affecting their host rocks. Although most diamonds are from the cooler lithosphere, some originate at much greater depths and bear direct witness to processes in the deep, convecting upper mantle, in the transition zone, or even in the lower mantle.

Defocusing somewhat from the inherently complex detail, while eyeing those rare occasions when Kimberlite magma crystallizes underground rather than exploding to the surface, we can see that Kimberlite is an ultramafic rock. Kimberlite has low silica and aluminum, is high in magnesium, is low in total alcalis yet typically high in potassium relative to sodium, geochemical features that link Kimberlite melts to a deep mantle source. A defining feature is that Kimberlites are rich in carbon dioxide and water, which are stored in minerals such as calcite, phlogopite, and serpentine. Just how much of this vaporous hoard is primary is difficult to assess yet is fundamental to deciphering a Kimberlite's origin. Kimberlites are also inordinately well-endowed in magmaophile trace elements, enrichments that indicate an origin in low-degree partial melts of the mantle. Kimberlites carry an isotopic essence most consistent with a convecting mantle source, rather than other types of somewhat similar magmas such as their "orangeite" cousins that equilibrate with the old, cold lithosphere through which they pass.

Evidently, Kimberlite melts tap the deep mantle, but where do they originate, and why? And how is one to identify, much less separate, the original melt components from the constituents that have been added during the crystallization and transport of a several hundred-kilometer vertical ride? One certainty is that carbon dioxide and water are essential ingredients in Kimberlites. This is not surprising because both substances radically reduce the melting points of the rocks in which they reside; they also enter almost wholesale into the melt. A quandary is whether both volatile species were present in mutually significant amounts during original Kimberlite formation. Another unknown is to what degree either were incorporated later in the melt's evolution or post emplacement. Experiments indicate that low-degree melts of volatile-rich mantle at deep upper-mantle conditions have characteristics broadly similar to what might ostensibly be a primitive Kimberlite. It seems that proto-Kimberlites melts originate as some kind of a hydro-silico-carbonatitic melt generated beneath continental lithosphere (e.g., >250 km) that becomes modified as it ingests and digests mantle rock on its way to the surface. Understanding the physical, chemical, and dynamic details of this process is where the action lies in terms of Kimberlite generation.

 Kimberlites magmas and their precious cargo provide a truly unique window into mantle processes and dynamics. The bits of mantle rock they sample have allowed geologists to reconstruct the lithospheric thermal structure, composition, and age. But these deep mantle melts may ultimately owe their existence to volatile elements once located at Earth's surface and subsequently transported to depth. The diamonds that Kimberlites sample from beneath the lithosphere provide a wealth of evidence for recycling of oceanic crustal materials and a key role for both carbonated and hydrated fluids in their origin. Some diamonds have mineral inclusions that are thought to have originated from the transition zone or even the lower mantle, suggesting an almost unimaginably deep Kimberlite source region. An intriguing question is whether diamonds and Kimberlites form as a result of the same fundamental process.

The modern style of plate tectonics, characterized by opening and closing of ocean basins, is driven by subduction of oceanic lithosphere into the mantle, a process that possibly began during the Archean or early Proterozoic. Subduction provides a convenient mechanism for transporting carbon- and water-rich fluids into the deep mantle where they are released at upper mantle to transition zone depths in a series of dehydration and decarbonation reactions. Liberation of these fluids beneath stable continental lithosphere effectively creates a continuous mechanism for "juicing up" the sublithospheric mantle over time. These volatile-charged, inviscid and buoyant fluids could be truly proto-Kimberlitic, the original agents of chemical mass transfer that stain the mantle with slab components. Perhaps such volatile-charged mantle is always poised to melt to a low-degree given the right tectonic impetus, with melts accumulating beneath the lithosphere only to "pop up" every now and again to provide yet another exquisite probe into the deep mantle. Kimberlites and their putative origins are indeed bewildering. But they reveal more about Earth's deep interior than any other rock or magma type.

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2 Kimberlite, as used here, refers to Group I or 'archetypal' Kimberlite but not rocks formerly called Group II Kimberlite or orangeites that are now best referred to as types of lamproite, derived from partial melting of enriched lithospheric mantle sources (see Pearson et al. this issue, page 387)
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Kimberlites are rare, enigmatic, low-volume igneous rocks. They are highly enriched in magnesium, volatiles (CO₂ and H₂O) and incompatible trace elements and are thought to be the most deeply derived (>150 km) magmatic rocks on Earth. Kimberlites occur in ancient and thick continental lithosphere, forming intrusive sheets and composite pipes, commonly in clusters. Despite their rarity, kimberlites have attracted considerable attention because they entrain not only abundant mantle fragments but also diamonds, which can provide a uniquely rich picture of the deep Earth.

This issue summarises current thinking on kimberlite petrology, geochemistry, and volcanology and outlines the outstanding questions on the genesis of kimberlites and associated diamond mines.

**KEYWORDS:** kimberlite, diamond, craton, mantle

**KIMBERLITES: WHAT, WHERE, WHEN, AND WHY**

Kimberlites are low-volume, mantle-derived igneous rocks emplaced in Earth’s upper crust (Fig. 1). They have an ultrabasic (i.e., silica-poor, magnesium-rich) composition and are highly enriched in volatiles – primarily CO₂ and H₂O – and in incompatible trace elements compared to common silicate melts. Kimberlites are demonstrably hybrid rocks comprising three main components: 1) magmatic phases crystallised directly from the parental melt; 2) mantle and crustal xenocrysts derived from the disaggregation of entrained wall rocks during magma ascent and emplacement; 3) hydrothermal and alteration products formed through interactions with fluids of diverse origins (i.e., magmatic and external) that followed magma emplacement. A major challenge, touched on in several articles in this *Elements* issue, is to constrain the composition of a “primary” kimberlite melt as it leaves its mantle source region.

Kimberlites have a unique place in the Earth sciences for three reasons. First, kimberlites are the principal host of diamonds (>70% by value), including the majority of commercial diamond production. These diamonds are not phenocrysts but xenocrysts that have been entrained by a kimberlitic magma on its way to the surface. Second, kimberlites transport a wealth of mantle and crustal xenoliths (Fig. 1F), which provide a rich record of the composition of the sub-continental lithosphere. Third, kimberlites are the most deeply derived melts (>150 km) that reach the surface of the Earth (Fig. 2) and, therefore, provide unique insights into the deepest realms of our planet. The occurrence of diamonds and of mantle xenoliths that have been sourced from the mantle transition zone and uppermost lower mantle (e.g., Sautter et al. 1991; Pearson et al. 2014) suggest that kimberlites might derive from at least these depths. However, the significance of these ultradeep diamonds for kimberlite genesis remains contentious (Harte and Cayzer 2007).

The history of kimberlite-related research is inextricably linked with diamond exploration and mining. Until 1865, diamonds originated solely from alluvial deposits in India and Brazil. The finding of alluvial diamonds in South Africa in 1866 sparked a diamond rush, which led to the discovery of primary diamond deposits in 1869 at farms located in the present-day townships of Kimberley, Koffiefontein and Jagersfontein (Field et al. 2008). The organised mining of the De Beers, Kimberley, Bultfontein and Dutoitspan deposits provided the first evidence that the host rocks to diamonds were of igneous origin. These rocks were later named “kimberlites” after the town of Kimberley (Lewis 1887) where these four deposits occur. However, it was not until the 1950s and 1960s, when kimberlites were discovered outside southern Africa – Yakutia (Russia), Colorado and Wyoming (USA), and Tanzania (see Mitchell 1986) – that the global significance of kimberlite...
migmatism was fully appreciated. Modern research on kimberlites was catalysed by two key events: the publication of the influential book *Lesotho Kimberlites* (Nixon 1973) by Peter H. Nixon (Professor Emeritus, University of Leeds, UK), and the organisation of the First International Kimberlite Conference in Cape Town (South Africa) in 1973 by the late John J. Gurney (see inset).

To date, about 3,500 kimberlites have been identified. They occur on every continent on Earth (Fig. 3), and there are ~3,000 more kimberlites inferred by diamond exploration companies. The majority of kimberlites occur within the stable nuclei of continents, i.e., the Archean cratons, and surrounding mobile belts. The association between diamondiferous kimberlites and cratons (or peri-cratonic regions) was established in the 1960s (Kennedy 1964) and later became known as “Clifford’s rule”. Kimberlites are commonly associated with major lithospheric structures, such as sutures between continental blocks and shear zones, and commonly occur at the intersection of crosscutting lineaments (e.g., Jelsma et al. 2009). Evidently, kimberlite magma ascent exploits pre-existing, upper lithospheric zones of mechanical weakness.

Although kimberlite eruptions have never been observed, deep mining (up to ~1 km beneath present-day surface) of diamond deposits (e.g., Fig. 1A) has resulted in a detailed characterisation of kimberlite rocks within volcanic vents. Kimberlites exhibit variable styles of emplacement (Sparks 2013) that can be broadly divided between intrusive (i.e., hypabyssal kimberlites) (Fig. 1G) and extrusive (i.e., volcanioclastic kimberlites) (Fig. 1B). Hypabyssal kimberlites occur as dikes (Fig. 1E) and, less commonly, as sills, often in swarms, commonly associated with the root zones of many kimberlite pipes (Fig. 4) (Mitchell et al. 2019 this issue). Pipes, the most common volcanic feature produced by kimberlites, consist of downward-tapering structures (Fig. 4) that range in diameter from ~1 km to <100 m (Figs. 1C) and have variable vertical extents of 100s metres to 2–3 km (e.g., Kjarsgaard 2007; Field et al. 2008). Depending on the level of erosion and preservation in the geological record, kimberlite pipes may culminate upwards in a crater zone above the diatreme and root zones (see Fig. 4). Pipes are infilled with units of volcanioclastic and hypabyssal kimberlite, which represent discrete phases of magmatic activity. Surface expression of the pipes includes the location of lakes, as in many areas of northern Canada, or, in rare cases, modest positive topography, such as at Kimberley (South Africa) or Somerset Island (Canada) (Fig. 1C). Volcanic edifices (e.g., tephra cones, maars) are rarely preserved but do occur at the buried Fort à la Corne kimberlites (Canada) (Kjarsgaard et al. 2009). This is because, with the potential exception of the ~12 ka Igwisi Hills Volcano (Tanzania) (Brown et al. 2012), kimberlites are all older than 30 Ma (Heaman et al. 2019 this issue) and have been eroded to or below ground level. Kimberlites typically occur in clusters of up to ~20 or more pipes in close proximity (100 m to a few km, such as the Kimberley cluster in South Africa), often with broadly similar emplacement ages that are usually within <10 My. Multiple clusters in the same area constitute a field. For example, the Lac de Gras field in north-western Canada contains more than 300 kimberlites (Fig. 3), which may represent up to 50 My of punctuated activity fuelled by genetically related kimberlite magmas.

The distribution of kimberlites through time indicates that kimberlite magmatism is episodic, with major peaks in the late Mesoproterozoic, late Neoproterozoic, early Cambrian, Devonian, Jurassic and Cretaceous (Haggerty 1994; Tappe et al. 2018; Heaman et al. 2019 this issue). The temporal distribution of kimberlites is skewed towards recent geological times, the majority being emplaced in the last 250 My. To date, the oldest rock proposed to be a kimberlite is the heavily altered and metamorphosed 2.85 Ga Mitzi kimberlite in Gabon (Henning et al. 2003). However, the finding of alluvial diamonds with typical kimberlitic features, as well as kimberlite indicator minerals, in 2.89–2.82 Ga sedimentary rocks from Witwatersrand (South Africa) suggests that kimberlite magmatism could be even older (Gurney et al. 2005).

Of the kimberlites discovered to date, only 3% are significantly diamondiferous (i.e., containing macrodiamonds at a grade >1 carat per hundred tons) (de Wit 2010). Less than 100 kimberlites have been commercially mined for diamonds on a large scale, in addition to the few olivine lamproites (including rocks previously defined as “orangites” or “Group II kimberlites”) that host diamond mines, such as Argyle in Western Australia and Finsch in South Africa. Many different factors influence the economic potential of a kimberlite, including: 1) diamond grade (i.e., the quantity of diamonds in a mass of kimberlite...
What is the composition of primitive kimberlite melts? Our poor knowledge of the major element composition of primitive kimberlite melts complicates any inference on the mineralogy of their source (Pearson et al. 2019 this issue). The carbonate-rich nature of kimberlites is commonly invoked as support of either metasomatic CO₂ enrichment of the source or derivation from low-degree partial melting of fertile peridotites. An alternative hypothesis whereby kimberlites derive from a reduced, methane-bearing source is explored by Foley et al. (2019 this issue).

Where is the kimberlite source? Radiogenic isotope and trace element compositions of kimberlites, which largely overlap the range shown by some ocean island basalts, argue strongly for a source located in the convecting mantle (Pearson et al. 2019 this issue and references therein), i.e., the asthenosphere, the transition zone, or the lower mantle (Fig. 2). This conclusion is supported by the occurrence of sub-lithospheric mantle xenoliths and diamonds, the latter being recognised in an increasing number of kimberlites worldwide. Alternatively, both the superdeep diamonds and the convecting-mantle “isotopic flavour” could be introduced to the base of the lithosphere by mantle convection, where most authors agree that kimberlite melts start to take the form of the hybrid rocks seen at the surface.

What are the triggers for kimberlite magmatism? Proposals range from plumes and related mantle hot-spot tracks, to deep subduction of recycled slab material into the convecting mantle beneath continents, to changes in far-field stresses associated with plate tectonics (Jelsma et al. 2009; Heaman et al. 2019 this issue). All these mechanisms are supported by different lines of evidence, so perhaps kimberlite magmatism is related to a range of different tectono-thermal processes.

What parameters govern the fast ascent mechanism of kimberlite magmas? Although volatile exsolution, potentially triggered by assimilation of silicate material, has been proposed as an important ingredient driving fast ascent (e.g., Brey et al. 1991; Russell et al. 2012; Russell et al. 2019 this issue), it is also possible that buoyancy intrinsic to carbonate-rich melt compositions (i.e., without volatile exsolution) might be the major driver (Sparks 2013).

**Outstanding Questions and Objectives of this Issue**

Despite decades of dedicated studies, considerable debate surrounds many aspects of kimberlite genesis. These include the following:

- **What is the composition of primitive kimberlite melts?** Proposals span between H₂O + CO₂–rich ultramafic, silicate–carbonate and chlorine-rich carbonate compositions (see Mitchell et al. 2019 this issue; Pearson et al. 2019 this issue). The difficulty in addressing this seemingly simple question arises from the hybrid nature and extensive alteration common to all kimberlites, such that no primitive kimberlite found at the surface resembles its parental melt composition. Attempts to unravel the composition of kimberlites using melt inclusions have provided important constraints on the chemical evolution of kimberlites towards decreasing Si and increasing CO₂ and alkalis through crystal fractionation (Mitchell et al. 2019 this issue and references therein). However, melt inclusion studies have not provided conclusive constraints on primitive melt compositions partly because of the extensive interaction between kimberlites and wall rocks during ascent (Foley et al. 2019 this issue; Russell et al. 2019 this issue).

- **Where is the kimberlite source?** Radiogenic isotope and trace element compositions of kimberlites, which largely overlap the range shown by some ocean island basalts, argue strongly for a source located in the convecting mantle (Pearson et al. 2019 this issue and references therein), i.e., the asthenosphere, the transition zone, or the lower mantle (Fig. 2). This conclusion is supported by the occurrence of sub-lithospheric mantle xenoliths and diamonds, the latter being recognised in an increasing number of kimberlites worldwide. Alternatively, both the superdeep diamonds and the convecting-mantle “isotopic flavour” could be introduced to the base of the lithosphere by mantle convection, where most authors agree that kimberlite melts start to take the form of the hybrid rocks seen at the surface.

- **What are the triggers for kimberlite magmatism?** Proposals range from plumes and related mantle hot-spot tracks, to deep subduction of recycled slab material into the convecting mantle beneath continents, to changes in far-field stresses associated with plate tectonics (Jelsma et al. 2009; Heaman et al. 2019 this issue). All these mechanisms are supported by different lines of evidence, so perhaps kimberlite magmatism is related to a range of different tectono-thermal processes.

- **What parameters govern the fast ascent mechanism of kimberlite magmas?** Although volatile exsolution, potentially triggered by assimilation of silicate material, has been proposed as an important ingredient driving fast ascent (e.g., Brey et al. 1991; Russell et al. 2012; Russell et al. 2019 this issue), it is also possible that buoyancy intrinsic to carbonate-rich melt compositions (i.e., without volatile exsolution) might be the major driver (Sparks 2013).
What is the optimal strategy to assess if a kimberlite body is diamondiferous and so quantify its resource value? As summarised by Kjarsgaard et al. (2019 this issue), a combination of indicator mineral sampling (i.e., minerals commonly associated with diamond deposits such as inclusions in diamond or as constituents of diamondiferous mantle rocks) and geophysical surveys are employed to locate diamondiferous kimberlite bodies. Bulk micro-diamond analyses and petrographic examinations of drilled material, coupled with higher-resolution geophysical surveys, are then utilised to constrain the size and internal structure of the body and to assess the potential macro-diamond grade, grade distribution and ore value.

Over 45 years since the seminal Lesotho Kimberlites volume (Nixon 1973), and three decades after the publication of the comprehensive Kimberlites review by Roger Mitchell (Mitchell 1986), the significant advancements in the field of kimberlite research warrant the status report presented in this Elements issue. Our objective is to present an overview of current knowledge of key aspects of kimberlite-related science, including petrology (Mitchell et al. 2019 this issue), geochemistry (Pearson et al. 2019 this issue), experimental petrology (Foley et al. 2019 this issue), geochronology (Heaman et al. 2019 this issue), and volcanology (Russell et al. 2019 this issue). The final paper (Kjarsgaard et al. 2019 this issue) is dedicated to the formation of diamond deposits, including a synopsis of current methods of diamond exploration and resource evaluation applied to kimberlites.

With this issue of Elements, we hope to encourage new kimberlite and diamond enthusiasts who may bring fresh ideas and approaches to the study of these rare, important, and fascinating rocks.

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ACKNOWLEDGMENTS

We thank Chiara Mattioli and Hayden Dalton for assistance with figure drafting and Peter Nixon, Angus Fitzpayne and Ashton Soltys for informal reviews. Journal reviews by Tom Geron and Matthew Field, plus editorial input by Jon Blundy, improved the clarity of this work. AG acknowledges funding from the Swiss National Science Foundation (grant n. PZ00P2_180126/1). m#
hypabyssal kimberlites are subvolcanic intrusive rocks crystallised from mantle-derived magmas poor in SiO₂ and rich in CO₂ and H₂O. They are complex, hybrid rocks containing significant amounts of mantle-derived fragments, primarily olivine with rare diamonds, set in a matrix of essentially magmatic origin. Unambiguous identification of kimberlites derived fragments, primarily olivine with rare diamonds, set in a matrix of essentially magmatic origin. Unambiguous identification of kimberlites requires careful petrographic examination combined with mineral compositional analyses. Melt inclusion studies have shown that kimberlite melts contain higher alkali concentrations than previously thought but have not clarified the ultimate origin of these melts. Because of the hybrid nature of kimberlites and their common hydrothermal alteration by fluids of controversial origin (magmatic and/or crustal), the composition of primary kimberlite melts remains unknown.

**Keywords:** kimberlite, olivine, spinel, phlogopite, carbonate, serpentine, melt inclusions

**INTRODUCTION: HYPABYSSAL VERSUS VOLCANICLASTIC KIMBERLITES**

Kimberlites are a group of silica-undersaturated, olivine-rich (~50 modal %) igneous rocks formed from mantle-derived magmas. Kimberlites are enriched in CO₂ (~10 wt%) and H₂O (≥5 wt%), they are potassic (<0.5 wt% Na₂O; ≤3.0 wt% K₂O) and are deficient in Al₂O₃ (<3.0 wt%). All kimberlites are hybrid rocks containing xenocrystal, primary magmatic, and hydrothermal minerals: this in itself precludes identification of the primary melt based on bulk rock composition. Determination of the primary composition remains one of the outstanding questions of kimberlite petrology. Older literature distinguished Group I kimberlites and Group II kimberlites (“orangerites”), but these latter are the petrogenetically unrelated olivine lamproites, originally linked to kimberlites because both contain diamonds. Lamproites are not discussed further here.

Kimberlites show two distinct modes of emplacement, each resulting in characteristic textural and mineralogical differences. **Hypabyssal** (i.e., subvolcanic) dikes, sills, and small intrusive bodies of holocrystalline coherent rock (Fig. 1A) occur at different depths in kimberlite pipes (see Fig. 4 in Giuliani and Pearson 2019 this issue) or as regional dike swarms (Mitchell 1986). **Volcaniclastic** kimberlites (Scott Smith et al. 2013) are represented by in-vent, or diatreme, “Kimberley-type pyroclastic kimberlites” (KPK; formerly “tuftitic kimberlite”; named after a classic locality in South Africa) (Fig. 1B), and by subaerial “Fort-à-la-Corne-type pyroclastic kimberlites” (FPK; named after a classic locality in Canada) (Fig. 1C). In contrast to hypabyssal kimberlites, both KPK and FPK volcaniclastic varieties exhibit clastic textures. Examples of the KPK variety contain abundant country-rock xenoliths, macrocrystal olivine and rounded magmaclasts set in a serpentine-chlorite matrix (Fig. 1B). Magmaclasts consist of olivine and, less commonly, other mantle- or crustal-derived cores rimmed by phlogopite, serpentine, calcite, diopside clinopyroxene, apatite, spinel and perovskite. Magmaclasts are the “hallmark” of the KPK variety and do not occur in hypabyssal kimberlites. Examples of the FPK variety are characterised by vesicular, lobate, juvenile lapilli and pyrocrysts (i.e., single crystals of olivine liberated from mildly explosive eruption columns) (Scott Smith et al. 2013) and a relative paucity of country rock xenoliths (Fig. 1C).

Volcaniclastic varieties have lost some of their primary components, become extensively modified by deuteric (i.e., late-stage magmatic) and/or meteoric fluids, and are contaminated by crustal material during emplacement. Thus, the only varieties useful for kimberlite magma characterisation and geochemical studies are coherent kimberlites, namely hypabyssal varieties and rare extrusive rocks that lack clastic features (Scott Smith et al. 2013).

**PETROGRAPHY OF HYPABYSSAL KIMBERLITES**

Hypabyssal kimberlites typically exhibit a distinctive inequigranular texture resulting from the presence of macrocrysts, principally olivine, set in a finer-grained matrix (Fig. 1A). The matrix consists of microphenocrysts of olivine, Mg–Cr–Ti-rich spinel, monticellite, mica (phlogopite–kinoshitalite solid solutions), perovskite, apatite and occasionally calcite, all set in a late-stage groundmass of carbonate (calcite and/or dolomite) and serpentine (Fig. 2) (Mitchell 1986, 1995). Kimberlites are commonly named on the basis of groundmass mineralogy whereby the two or
three most abundant phases, excluding olivine, are listed in order of increasing abundance (e.g., calcite, serpentine, kimberlite). Feldspar, feldspathoids, clinopyroxene, and amphibole only occur in contaminated kimberlites. The common presence of diverse xenoliths (and xenocrysts derived therefrom) is a characteristic feature of kimberlites (see Fig. 1 in Giuliani and Pearson 2019 this issue). Xenoliths include mantle-derived rocks (e.g., Iherzolite, harzburgite, eclogite), lower- and mid-crustal rocks entrained during ascent through the lithosphere (see Fig. 2 in Giuliani and Pearson 2019 this issue), and near-surface country rocks incorporated during emplacement.

Macrocrysts are predominantly mantle-derived xenocrysts, commonly displaying deformation features. Olivine macrocrysts are a dominant and characteristic constituent of hypabyssal kimberlites (Fig. 1A), typically comprising ~20–30 modal %. They commonly have anhedral-to-rounded morphology and a wide range of sizes (1–10 mm; less commonly >20 mm). Less common (<1 modal % and occasionally up to 5 modal %) macrocrysts include purple-burgundy Cr-rich Ca-poor pyrope garnet (from harzburgites), red Cr-pyrope garnet (from Iherzolites), red Ti-pyrope and orange almandine garnet (from eclogites), Mg-ilmenite, Cr-Al-spinel, chrome diopside, rare enstatite, phlogopite, zircon and diamond (Mitchell 1986, 1995). Being derived from regions of Earth’s mantle where diamond is stable, the majority of kimberlites probably contain some diamond, albeit mostly as a very rare constituent. Olivine and phlogopite macrocrysts, when not partially altered, commonly have overgrowths that crystallised from the kimberlite melt (Kamenetsky et al. 2008; Brett et al. 2009; Giuliani et al. 2017; Lim et al. 2018).

The megacryst suite comprises large crystals of mantle-derived minerals, ranging in size from ~1 to 10 cm and including olivine, garnet, Mg-ilmenite, chrome diopside, orthopyroxene, zircon, phlogopite, and rare baddeleyite. These megacrysts probably derive from mantle pegmatites, although specific compositional features indicate they are genetically and compositionally distinct from the peridotite- and eclogite-derived macrocrysts. Megacrysts of clinopyroxene, garnet, ilmenite and zircon have radiogenic isotope compositions similar to their kimberlite host (Newell et al. 2004). The majority of zircon megacrysts give U/Pb ages indistinguishable from the emplacement age of the kimberlite host (Woodhead et al. 2017). These data imply a close genetic relationship between megacrysts and kimberlites (Mitchell 1986). Regardless, widespread disequilibrium textures between megacrysts and the kimberlite host (e.g., Mitchell 1986; Kamenetsky et al. 2014; Bussweiler et al. 2016) provide strong evidence of chemical reaction with the transporting magma. Thus, megacrysts are best described as “antecrysts”, derived from magmas that are genetically related to, but distinct from, the final host.

Olivine is the initial liquidus phase of kimberlite magma. Euhedral-to-subhedral olivine microphenocrysts (<0.5 mm) form ~25 modal % of a typical hypabyssal kimberlite (Fig. 1A). Microphenocrysts can have compositionally distinctive cores that are commonly considered to be mantle-derived xenocrysts. Early formed Mg-chromite is the second phase to crystallize from a kimberlite magma and is commonly found as inclusions in olivine. Magnesian chromite occurs as subhedral-to-euhedral crystals zoned to Ti–Mg-rich qandilite [(Mg,Fe²⁺)₂(Ti,Fe³⁺,Al)O₄] margins (Fig. 2E), commonly with atoll textures (Fig. 2F) and mantles of Ti-poor magnetite or perovskite reaction rims. Subsequent crystallization proceeds as follows. Translucent brown perovskite is a common groundmass phase (Fig. 2E) typically showing concentric or oscillatory zoning. Monticellite occurs as zoned, colourless to pale-yellow, anhedral–subhedral crystals (<0.2 mm) (Figs. 2D, 2F). Phlogopite forms pale orange-brown to colourless laths (Figs. 2C, 2E), with micas of the colourless Ba-phlogopite–kinoshitalite [(Ba,K)₂(Mg,Fe²⁺)₃Si₄Al₆O₂₀(OH)₄] series forming plate-like, late-stage crystals enclosing earlier-formed spinel, perovskite, apatite and monticellite (Fig. 2E). Apatite typically occurs as laths and/or sprays of prismatic crystals. Carbonates occur in four main styles: (1) prismatic laths co-crystallising with the main groundmass minerals (Fig. 2B); (2) late-stage anhedral grains in the groundmass (Fig. 2A); (3) irregular segregations with serpentine (Fig. 2A); (4) veins cross-cutting the groundmass and replacing olivine. Serpentine associated with late-stage carbonates is typically polygonal serpentine (Mitchell 2013). Partial-
OLIVINE AND ITS COMPOSITIONAL ZONING

A distinctive feature of olivine in kimberlites is zoning between core and rim, rarely with one or more intermediate zones (Fig. 3A) (Giuliani 2018). Some olivine grains in the kimberlite groundmass represent bona fide phenocrysts, i.e., without a xenocrystic core. There are three distinct phases of olivine crystallization (Giuliani 2018): (1) in the mantle from earlier kimberlite melts; (2) in the ascending kimberlite (internal zones first, then rims and microphenocrysts); (3) after emplacement (rinds).

Olivine cores range from angular to rounded in habit with occasional evidence of resorption. They exhibit large compositional variations (mg# = 80–95) (mg# = Mg/[Mg + Fe] x 100) (Fig. 3B) (Giuliani 2018), with more restricted ranges in some localities (e.g., mg# = 90–94 at Grizzly, Canada) (Lim et al. 2018). Compositions of the majority of olivine cores overlap those of olivine in mantle peridotites and olivine megacrysts. This evidence, combined with the inclusion of mantle-derived phases (orthopyroxene, clinopyroxene, garnet) that are not stable in kimberlite melts at low pressure, supports a xenocrystic origin of olivine cores by disaggregation of mantle-derived lithologies (Mitchell 1986; Kamenetsky et al. 2008; Brett et al. 2009; Arndt et al. 2010). Yet, there remains considerable debate regarding the nature of the mantle source of the olivine cores. Proposed origins range from kimberlite-related dunites, megacrysts and sheared peridotites, and also an early magmatic origin (Giuliani 2018 and references therein). Understanding the origin of olivine cores is a fundamental question of Kimberlite petrology because of the relative abundance of these different varieties in Kimberlites (e.g., 20 vol% in a sample from the Bultfontein Kimberlite) (Soltys et al. 2018).

In contrast to cores, olivine rims contain inclusions of groundmass phases such as spinel, ilmenite and rutile, and, thus, the rims must be of magmatic origin. Rims develop a euhedral habit only if the cores are sufficiently small (i.e., <0.5–1.0 mm) (Brett et al. 2009). Olivine rims feature a narrow range in mg# values (typically <1 mg# unit) with decreasing concentrations of NiO (<0.4 wt%) and Cr$_2$O$_3$ (<0.1 wt%), and increasing MnO and CaO (up to ~0.3 wt%) towards rim boundaries (Fig. 3B) (Giuliani 2018 and references therein). The average mg# of kimberlite olivine rims ranges between ~84 and 92 (Mitchell 1986; Giuliani 2018; Lim et al. 2018), which clearly implies variations in the compositions of kimberlite magmas emplaced near the surface. Whereas the compositional trends

![Figure 2](image-url)  
**Figure 2** Six hypabyssal kimberlite textures. (A) Segregations of serpentine (srp) and calcite (cc) in the Batty Bay kimberlite (Somerset Island, Canada). (B) Groundmass with abundant calcite laths (small white rectangles) in the Nikos kimberlite (Somerset Island, Canada). (C) Abundant phenocrysts and macrocrysts of mica and olivine (oliv) in the Buffelboudonfontein kimberlite (South Africa). (D) Groundmass rich in monticellite (mtc), from Pipe 1 at Koskenniemi (Finland). (E) Mica microphenocrysts with black spinel (spl) and brown perovskite (pvk) in the Monastery kimberlite (South Africa). (F) Atoll spinels (spl) with a chromite core (orange) overgrown by a Ti–Mg-rich qandilite (green) and having an outer rim of Ti-magnetite (red) from Lac de Gras (Northwest Territories, Canada). Photos (A) to (E) are optical microscope images; (F) is a false-coloured backscattered electron image. Photo credits: (A, B, E, F) by Roger Mitchell; (C) by Andrea Giuliani; (D) by Hugh O’Brien.
shown by minor elements (Ni, Mn, Ca, Cr) are typical of magmatic differentiation by fractionation of olivine and chromite, the relatively invariant mg# is a unique feature of kimberlitic olivine (and some carbonate-rich lamproites). This has been attributed to four factors: 1) the carbonate-rich composition of kimberlites, which results in high Mg/Fe distribution coefficient between olivine and melt (Kamenetsky et al. 2008); 2) assimilation of mantle silicate phases, especially orthopyroxene (Pilbeam et al. 2013); 3) removal of exsolved CO₂ during ascent; and 4) melt oxidation during olivine crystallisation (Giuliani 2018).

Outermost olivine rinds, which are rarely preserved in some kimberlites, have compositions that deviate from the trend of constant mg# shown by rims towards higher mg#, Mn, and Ca at lower Ni contents (Fig. 3B). The formation of these olivine rinds has been attributed to crystallisation from, or equilibration with, carbonate-rich residual melts (Pilbeam et al. 2013) in which high oxygen fugacity has increased the Fe³⁺/Fe²⁺ ratio of the melt, inhibiting incorporation of Fe into the olivine structure (e.g., Howarth and Taylor 2016; Lim et al. 2018).

The discrete internal zones that are observed in back-scattered electron images of olivine from kimberlites worldwide (Kamenetsky et al. 2008; Giuliani 2018; Lim et al. 2018) exhibit variable shape and composition (Fig. 3). Some internal zones feature a euhedral habit, inclusions of (magnetic) chromite, and higher mg# and Ni than in olivine rims (Fig. 3B). These internal zones are considered to represent the primary magmatic olivine crystallising from the kimberlite melt at mantle depths. Other internal zones are diffusional between cores and rims and possibly form by partial equilibration of the cores in the entraining kimberlite prior to rim formation.

In summary, olivine represents a rich repository of information on the composition, metasomatism, and thermal conditions of the mantle sampled by kimberlites. Olivine provides important constraints on the composition and evolution of kimberlite melts, because its formation can persist from the earliest stages (i.e., internal zones, rims, some microphenocrysts) to the latest stages (i.e., rinds) of crystallisation.

THE UNIQUE COMPOSITIONS OF SPINEL AND PHLOGOPITE: KEYS TO KIMBERLITE IDENTIFICATION

Kimberlites contain spinels and micas with characteristic compositional evolutions that permit discrimination between kimberlites and petrographically similar, but genetically unrelated, alkaline rocks, such as olivine lamproites and ultramafic lamprophyres.

**Spinel**

Groundmass spinels in kimberlites are typically complexly zoned (Fig. 2F). Some contain cores of xenocrystal low-TiO₂ (<1 wt%) aluminous chromite e, whereas others are continuously zoned from Ti-magnesian chromite to Ti-Mg-Fe-spinels (i.e., qandilit). A specific textural variety termed “atoll spinel” (Fig. 2F) consists of a core of zoned spinel and a mantle of magnetite (“atoll”) of similar habit separated by a continuous zone (or “lagoon”) of groundmass carbonate and serpentine. Whereas in some cases, remnants of pleonaste [(Mg,Fe⁺I)Al₂O₄] indicate that this phase originally filled the lagoon (O’Brien and Tyni 1999), the origin of this relatively common feature in kimberlites remains enigmatic (see summary in Roeder and Schulze 2008).

The compositional trend of spinel in kimberlites [termed Trend 1, or the “magnesian ulvöspinel trend” by Mitchell (1986)] shows evolution from titaniferous magnesian aluminous chromite or titan-magnesian chromite to members of the magnesian ulvöspinel (qandilit)–ulvöspinel-magnetite series. The trend is best illustrated in the six component “reduced spinel prism” (Fig. 4) in which all Fe is calculated as Fe²⁺ (i.e., FeO total). Trend 1 runs across the prism at approximately constant Fe²⁺/Fe²⁺ + Mg) ratios (0.3–0.5) to the Mg₂TiO₄–Fe₂TiO₄ apex. The trend has been substantiated in many hypabyssal kimberlites worldwide (Mitchell 1986; Roeder and Schulze 2008). Mitchell (1986, 1995) determined that another spinel compositional trend (Trend 2, or the “titanomagnetite trend”) is characteristic of lamproites and ultramafic lamprophyres (e.g., alnöite, aillikite). In the reduced spinel prism (Fig. 4), this trend exhibits decreasing Fe²⁺/Fe²⁺ + Mg) ratios (0.3–0.7) at relatively constant, but low, Ti, followed by a rapid increase in Ti at Fe²⁺/(Fe²⁺ + Mg) >0.8.

**Phlogopite**

Groundmass mica can exhibit continuous, discontinuous, or patchy compositional zoning. Although macrocrystal mica is typically phlogopite, groundmass mica exhibits a characteristic compositional variation within the phlogopite–kinoshitalite solid solution series. This compositional trend represents increasing Al and Ba and decreasing Si, Ti, and Fe and is very different from the compositional trends shown by micas in lamproites (i.e., decreasing Al, increasing Fe) and ultramafic lamprophyres (e.g., minettes; increasing Al and Fe) with no enrichment in Ba (see Mitchell 1995).

**LATE-STAGE MINERALS: MAGMATIC VERSUS HYDROTHERMAL CARBONATE AND SERPENTINE**

Carbonates in kimberlites also have diverse origins, as indicated by their different textural parageneses. The demonstrably primary origin of prismatic calcite microphenocrysts (Fig. 2B) is confirmed by its minor element composition, low ⁸⁷Sr/⁸⁶Sr ratios, and mantle-like carbon and oxygen stable isotope ratios (Castillo-Oliver et al. 2018). These compositions are matched by some, but not all, groundmass calcite in fresh kimberlites, with oxygen
isotope compositions commonly displaced towards higher $^{18}$O values due to interaction with late-stage fluids (Wilson et al. 2007). Evidently, oxygen isotope analyses of bulk carbonate fractions are not representative of kimberlite melt compositions because different carbonate generations of variable origin and composition contribute to the bulk value (see also Wilson et al. 2007; Giuliani et al. 2014). Whereas cross-cutting carbonate veins clearly represent a secondary feature related to external crustal fluids, as corroborated by elevated $^{87}$Sr/$^{86}$Sr ratios in some cases (Castillo-Oliver et al. 2018), the origin of carbonate and carbonate–serpentine segregations is less straightforward. The Sr isotope compositions of calcite in these segregations range from magmatic values, similar to perovskite and groundmass calcite, to higher values indicative of a crustal contribution (Exley and Jones 1983; Castillo-Oliver et al. 2018).

The origin of serpentine in kimberlites is widely debated but crucial in defining the composition of kimberlite magmas. This is because serpentine is the principal host of H$_2$O and contributes substantially to the Si and Mg budget of kimberlite rocks. There are currently two opposing hypotheses. Based on textural observations and the ubiquitous occurrence of serpentine in kimberlites worldwide, Mitchell (1986, 2013) considers that groundmass calcite and serpentine in hypabyssal kimberlites form from deuteric carbono-hydrothermal gel-like solutions (i.e., CO$_2$–H$_2$O-rich fluids), which percolate pervasively throughout the kimberlite matrix. In contrast, Sparks (2013) used experimental evidence of lower solubility of water in silicate–carbonate melts at shallow crustal conditions compared to H$_2$O contents in kimberlite melts to conclude that the majority of serpentine is “secondary” and derived from influxes of exogenic water. This latter hypothesis might be plausible for serpentine and chlorite occurring in pyroclastic kimberlites but is less well-founded for low-porosity, hypabyssal rocks. Similarly, the oxygen isotope compositions of serpentine are ambiguous (Mitchell 2013; Giuliani et al. 2014) and will remain so until more complete isotopic studies of serpentine in hypabyssal kimberlites are undertaken.

**MELT INCLUSIONS AND THE EVOLUTION OF KIMBERLITE MELTS**

The composition of primitive kimberlite melts is a long-standing enigma. The study of melt inclusions in magmatic minerals has led to contrasting interpretations. Early investigations by Kamenetsky et al. (2004, 2008) focused on crystallised secondary melt inclusions in olivine and identified compositions dominated by Ca–Mg carbonates with abundant alkali-carbonates and chlorides plus lesser amounts of silicates (mainly phlogopite), phosphates, sulfates, sulfides and Fe–Ti oxides. These data were used to argue that kimberlite melts formed as alkali-rich chloride–carbonate melts in the deep Earth. This conclusion is, however, at odds with the secondary nature of the examined melt inclusions, which were probably trapped during the waning stages of kimberlite crystallisation (e.g., Kopylova et al. 2016).

Subsequent studies compared the compositions of crystallised primary melt inclusions in different magmatic minerals (i.e., olivine rims, spinel, perovskite, monticellite, apatite) (e.g., Abersteiner et al. 2017; Giuliani et al. 2017) (Fig. 5). Primary inclusions in early crystallised minerals (olivine rims, spinel, perovskite) contain abundant Ca–Mg carbonates and lesser amounts of silicate phases (phlogopite, olivine) and alkali carbonates. Later-formed monticellite and apatite host inclusions with scarcer silicate components but with more abundant alkali carbonates and exotic phases (e.g., chlorides, phosphates). In effect, these later inclusions are transitional to the secondary inclusions in olivine that are dominated by Na–K carbonates and chlorides with few or no silicates (Kamenetsky et al. 2004; Giuliani et al. 2017). In combination, these results show a progressive evolution of kimberlite melts from Si–alkali-bearing Ca–Mg carbonate compositions towards melts with decreasing SiO$_2$ and increasing alkalis, chlorine and other incompatible and volatile elements. The final products are residual C–O–H fluids enriched in alkalis and chlorine. A key conclusion is that higher concentrations of alkalis (especially Na) probably occur in kimberlite melts but are lost to exsolved fluid phases at various stages of kimberlite ascent and/or crystallisation.

Are primary carbonate melt inclusions in olivine rims and chromite representative of primitive kimberlite melts? Giuliani et al. (2017) rejected this hypothesis based on the abundance of silicates (olivine rims, monticellite, mica, perhaps serpentine) in kimberlites, which rather suggests a...
silicate–carbonate melt composition (see also Soltys et al. 2018 and references therein). They attributed carbonate and alkali enrichment in primary melt inclusions to fractionation of olivine and oxide phases (e.g., chromite, ilmenite) prior to inclusion entrapment. Furthermore, mass balance calculations indicate that assimilation of lithospheric mantle material cannot generate silicate–carbonate melt compositions from primary carbonate melts based on low concentrations of Cr and Ni in kimberlite melts (Soltys et al. 2018). There is abundant evidence of carbonate mantle metasomatism coeval with kimberlite magmatism (e.g., Soltys et al. 2016), including the occurrence of silicate–carbonate melt inclusions in megacrysts (e.g., Bussweiler et al. 2016; Howarth and Büttner 2019). These inclusions trap kimberlite or related melts at different stages of their evolution and, therefore, confirm that kimberlites magmas are carbonated melts. But to what extent they are carbonated is still unknown.

In summary, while significant advances have been achieved in understanding the compositional evolution of kimberlite melts during crystallisation, the composition of primary kimberlite melts as they begin their ascent from source, and the role of mantle (and especially orthopyroxene) assimilation in modifying these melts, remain inadequately constrained. Incomplete knowledge of primary kimberlite melt compositions hampers a clear understanding of the nature of the source that partially melted, its location (deep from the lithosphere, transition zone, or lower mantle) and the conditions of melting (pressure, temperature, degree of melting).

ACKNOWLEDGMENTS

AG would like to thank his wife, Chiara, for drafting Figures 3 and 5. Informal appraisals by Angus Fitzpayne and Ashton Soltys, together with reviews by Yannick Bussweiler, an anonymous referee, and Elements’ Editors Graham Pearson and Jon Blundy improved the clarity of this paper. AG acknowledges funding from the Swiss National Science Foundation (grant n. PZ00P2_180126/1).

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**Kimberlites as Geochemical Probes of Earth’s Mantle**

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Identifying the effects of crustal contamination on kimberlite compositions is critical to understanding their geochemistry. The often-used Clement’s “contamination index”, or CI [where CI = (SiO₂ + Al₂O₃ + Na₂O)/(MgO + 2K₂O)], lacks sensitivity because of the mutually opposing effects of xenocrystal olivine addition versus assimilation of granitic crust. Although using additional elements such as Yb, which is low in “uncontaminated” kimberlites (<0.5 ppm) and higher in granitic rocks (~1 ppm), provides additional sensitivity (le Roex et al. 2003), the dilution of Yb by the addition of mantle peridotite means that identifying even 5% addition of crust in the face of 20% peridotite addition is a challenge. It is, thus, impossible to guarantee that any given kimberlite is free from the effects of crustal or mantle contamination.

**KEY ASPECTS OF THE CHEMICAL COMPOSITION OF KIMBERLITES**

Most reviews of kimberlite geochemistry classify these rocks as silica-undersaturated, alkaline, potassic, CO₂- and H₂O-rich rocks. However, Kjarsgaard et al. (2009) noted that, for kimberlites with minimal crustal contamination, their relatively low K + Na contents lead to (Na + K)/Al < 1, and K₂O < 3 wt%; hence, these bulk compositions should not be referred to as potassic or even alkaline in nature. In fact, typical kimberlite K₂O contents are surprisingly similar to mid-ocean ridge basalt (MORB). The high bulk water and CO₂ contents have long been viewed as intrinsic features of kimberlite magmas due to their broad correlation with high carbonate and phlogopite content. However, a specific group of minimally serpentinitised samples from the Udachnaya East kimberlite (Russia) (e.g., Kamenskii et al. 2014 and references therein) possesses higher Na (up to ~6 wt% Na₂O) at very low water contents (<1 wt% H₂O) together with extremely elevated chlorine (up to 6 wt%) and sulfur (up to ~0.3 wt%), despite having similar SiO₂.

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In 1914, Percy Albert Wagner (1885–1929) published some of the first geochemical analyses of kimberlites, astutely using their bulk compositions (among other criteria) to distinguish them from rocks such as melilitites. Wagner highlighted the lower Al, Ca, and alkalies and the higher Mg of what he termed “basaltic” kimberlites compared to melilitites and related rocks. For the next seven decades, further geochemical work on kimberlites was sporadic (e.g., Ilupin and Lutts 1971; Smith et al. 1985). Major reviews by Mitchell (1986, 1995), le Roex et al. (2003) and Kjarsgaard et al. (2009) highlight key compositional characteristics.
It would be more accurate to classify kimberlite bulk rock compositions as ultrabasic, silica
undersaturated, Al-poor (Al2O3 < 5 wt%), CO2-rich (average 6.6 ± 3.3 wt%) rocks with variable-to-low
alkali contents and low K2O/Ka ratios (e.g., Mitchell 1986). Amongst archetypal kimberlites globally
there are clear geographic distinctions (Fig. 1). For example, kimberlites from Kimberley (South
Africa) have significantly higher TiO2, K2O and P2O5 (medians of 1.94 wt%, 1.29 wt% and 1.35
wt%, respectively) than most other locations, such as Lac de Gras (Canada) (0.48 wt%, 0.58
wt% and 0.51 wt%, respectively). Kimberlites from Maniitsoq (Greenland) have still higher TiO2
wt% at lower K2O, giving a very low K2O/TiO2 ratio (Fig. 1). Average kimberlite CO2 contents
are remarkably similar globally, between 6 and 7 wt%, although estimates of un-degassed primary
melt are much higher (23–25 wt%) (Soltys et al. 2018).

**KIMBERLITES, ORANGEITES AND LAMPROITES: A REVISION**

Kimberlites are compositionally distinct from other related rock types. Some rocks previously
called “micaceous” or “lamprophyric” kimberlites (Wagner 1914), such as those at Finsch, Bellbank
and Roberts Victor in South Africa, were originally considered kimberlites. These rocks, which
can represent major diamond sources, were termed “Group II kimberlites” by Smith (1983) or
“orangeites” after their occurrence in the former Orange Free State (Wagner 1914; Mitchell 1995). A
sub-group of orangeites – the “evolved” variety of Mitchell (1995) – are clearly distinguishable from
kimberlites, with these orangeites having much higher SiO2 and Al2O3 and lower MgO, CaO,
and CO2 contents. The “unevolved orangeites” of Mitchell (1995) have higher olivine macro-
cryst contents, imparting the higher MgO and lower SiO2 contents that make them less distinct
from kimberlites (Fig. 1). Nonetheless, these rocks have higher K2O/TiO2 ratios (typically >2)
compared with archetypal kimberlites (mostly <1). Unevolved orangeite compositions are more
similar to the range of K2O contents and K2O/TiO2 TiO2 displayed by olivine lamproites (0.8 to >2).

The average CO2 contents of kimberlites (6.6 ± 3.3 wt%; n = 307) and orangeites (5.8 ± 4.0 wt%; n = 38)
are similar and considerably higher than olivine lamproites (0.37 ± 0.24 wt%; n = 91). Overall, the closer mineralogical
similarities between orangeites and lamproites, together with their broadly similar bulk compositions (Dawson 1987)
(Fig. 1) and isotopic systematics (see below), lend support to the idea that orangeites are simply a CO2-rich sub-variet-y
of lamproites, derived from broadly similar source regions. As the more CO2-rich nature of orangeites correlates with
higher CaO contents (7.4 ± 3.8 wt%) compared to olivine lamproites (4.9 ± 0.8 wt%), we recommend the use of the
term “carbonate-rich olivine lamproite” for these rocks, or simply “lamproite” for the more “evolved” compositions.
In the remainder of our text, “kimberlite” is taken to mean archetypal Kimberlites, i.e., not including the former Group
II or orangeite categories.

A final, related, rock type is ultramafic lamprophyre: ultramafic rocks with olivine and phlogopite macrocrysts,
primary carbonate, and groundmass clinopyroxene. These rocks have some compositional similarities to kimberlites
(see Fig. 1) but are distinct in their higher TiO2, FeO and Al2O3 contents and lower SiO2/Al2O3 and MgO/CaO ratios.

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**Figure 1**

Box and whisker plots of eight key whole-rock weight
percent oxides of archetypal kimberlites and related rocks: (A) SiO2, (B) TiO2, (C) Al2O3, (D) MgO (E) Na2O (F) K2O (G) P2O5 (H) K2O/TiO2. The rock types shown are Group 1 kimberlites (from Lac de Gras (Canada), light blue; Maniitsoq (Greenland), grey; Kimberley (South Africa), green; Udachnaya (Sakha Republic, Russia), dark blue), orangeites (i.e., Group 2 kimberlites) in purple, olivine lamproites in red, and ultramafic lamprophyres (“lampro-
phryes”) in dark yellow. Central bar in each box is the median value, which is bounded by a box containing the 1st and 3rd
quarters; ends of the whiskers represent minimum and maximum values; yellow shaded zone represents the range in composition of various estimates of Kimberlite primary melts, with the orange line within the shaded zone being the average. For data sources see http://elementsmagazine.org/supplements/.
KIMBERLITE COMPOSITIONS REFLECT LOCAL LITHOSPHERIC MANTLE

There is wide agreement that kimberlites have incorporated varying proportions of the cratonic lithospheric mantle through which they have traversed, and that this appropriation of mantle rock is responsible for most of their diamond grade (Kjaersgaard et al. 2019 this issue). A measure of the influence of the local lithospheric mantle composition, and the degree of its incorporation on the bulk composition of kimberlites, is evident in the strong correlation between the kimberlite Mg/Si ratio and that of any entrained lithospheric mantle xenoliths from the same kimberlite or kimberlite field (Fig. 2).

Assimilation of orthopyroxene (Mg/Si ~0.83) and olivine (Mg/Si ~1.64) influences the bulk kimberlite Mg/Si ratio. Kimberlite erupted through olivine-rich, orthopyroxene-poor cratonic mantle, such as those of Greenland (North Atlantic craton), have higher Mg/Si than those erupted through the more orthopyroxene-rich cratonic mantle beneath the Kaapvaal, Siberian, and Slave cratons. Incorporation of lithospheric mantle, thus, imparts a local flavour to kimberlite compositions (Pilbeam et al. 2018), for peridotite incorporation (usually 30–50 wt%).

No single kimberlite sample is likely to represent a primitive melt composition because of its hybrid nature. To arrive at any estimate of a parental melt, corrections must be made for the amount of xenocrystic olivine and the associated assimilation of peridotitic phases such as orthopyroxene. Debate centres around two distinct approaches that yield dramatically different parental melt compositions. The common approach uses global or local averages of “minimally contaminated” kimberlites corrected, with varying levels of sophistication (e.g., le Roex et al. 2003; Nielsen and Sand 2008; Kjarsgaard et al. 2009; Soltys et al. 2018), for peridotite incorporation (usually 30–50 wt%).

This approach predicts a broadly highly magnesian (~20–31 wt% MgO) silica-carbonatite parental melt that is water-rich (1%–3%) and CO2-rich (10%–20%), with low to moderate SiO2 (17–32 wt%), low K2O (~0.5%–2%) and very low Na2O (< 0.2 wt%). There is a relatively good agreement between different studies (Fig. 1). The second approach assumes that the minimally serpentinitised Udachnaya East kimberlites (Russia), with their very high Na and Cl contents, are the only unaltered kimberlites from which to construct reliable parental melt estimates (e.g., Kamenetsky et al. 2014). When xenocrystic olivine is subtracted from these compositions, the parental melt becomes a silica-poor and water-poor Ca–Mg-carbonatite with highly elevated levels of Na, K, Cl and S (e.g., Fig. 1). Whereas
a carbonatitic parental melt has long been proposed (see history in Mitchell 1986) and has gained more traction recently (e.g., Nielsen and Sand 2008; Russell et al. 2011; Kamenetsky et al. 2014), an alkali–chloride-rich parental magma remains controversial.

**PROBING KIMBERLITE SOURCES WITH TRACE ELEMENTS AND RADIOGENIC ISOTOPES**

For 50 years, geochemists have used the trace element and isotope geochemistry of igneous rocks to probe the structure and evolution of Earth’s mantle. Kimberlites offer a unique perspective in this regard. Basalts erupting in the ocean basins are comprised predominantly of melts formed at depths of 100 km or less by decompression melting. The aggregated melt composition is, hence, diluted and dominated by this shallow melt source. In contrast, thicker cratonic lithosphere acts as a barrier to decompression melting at shallow depths. Thus, kimberlites erupting through cratons are dominated by melt fractions from much deeper parts of the mantle.

**Trace Elements**

Kimberlites are enriched in incompatible trace elements – elements that strongly partition into the melt from the source region undergoing melting. This is reflected in large enrichments in light rare earth elements (LREEs) over heavy rare earth elements (HREEs) (Fig. 3A). Subtle geographic differences exist: South African kimberlites have generally higher REE abundances and higher LREE/HREE ratios than Canadian Lac de Gras kimberlites (Fig. 3A). Levels of REE enrichment in kimberlites are similar overall to those in lamproites and is consistent with small degrees of melting, likely involving a REE-enriched source region. Notable obvious differences between kimberlites, lamproites and orangeites are manifest in other elements (Fig. 3A). Kimberlites (and ultramafic lamprophyres) are characterized by negative K anomalies on primitive mantle (PM) normalized plots, with low K/Nb compared to lamproites, which generally lack negative K anomalies. Lac de Gras (Canada) and Maniitsoq (Greenland) kimberlites have a more pronounced negative Zr–Hf anomaly compared to southern African kimberlites (le Roex et al. 2003; Tappe et al. 2013), whereas lamproites/orangeites either lack or have strikingly positive Zr–Hf anomalies, with lower Zr/ Hf than kimberlites. Kimberlites have higher Nb and Ta contents and lower Nb/Ta ratios than lamproites (Fig. 3A). These differences, plus the strong enrichment of Ba and Pb in lamproites relative to kimberlites, are seen most clearly in incompatible element ratio systematics (Fig. 3B). Scatter in the Ba/Nb and Th/Nb ratios around the PM-normalized value for kimberlites overlap with the range seen for ocean island basalt (OIB) (Fig. 3C). Higher Ce/Pb and U/Pb ratios are primarily due to LREE enrichment compared with most OIBs. In contrast, Ce/Pb in lamproites and orangeites scatters around the PM value, despite their Pb enrichment, yet their Ba/Nb and Th/Nb values are considerably higher than for the PM and for kimberlites (e.g., Becker and le Roex 2006).

The similarity of key trace element ratios such as Ce/Pb and Ba/Nb in kimberlites and OIBs has been explained by small-degree melting of carbonated peridotite having trace element characteristics similar to typical convecting mantle and modified to varying degrees by small amounts of subducted components (e.g., Tappe et al. 2013). Comparison of kimberlites with experimental melts from carbonated upper mantle peridotite indicate that, whereas the varying negative Zr–Hf anomalies of kimberlites can be reproduced, their high Nb contents and high Nb/Zr cannot. The generally greater trace element variance of kimberlites compared to OIBs could reflect a combination of the digestion of local, variably metasomatized components in the cratonic lithosphere (Fig. 2) and minor crustal contamination. Alternatively, kimberlite trace elements are broadly consistent with a deeper, transition zone origin. Trace element partitioning between carbonate-rich melts and majorite plus Ca-perovskite, which are the main trace element hosts in the transition zone (Dalou et al. 2009), shows that Nb is highly incompatible in majorite and Ca-perovskite whereas Zr and Hf are compatible, better reproducing the observed inter-element fractionations (Fig. 3). Lamproites have strikingly different trace element systematics, supporting an enriched lithospheric source, likely containing significant phlogopite and less carbonate than required for kimberlites.

**Radioisotopic Isotopes**

The radioactive decay systems used to date kimberlites can be used to trace the time-integrated evolution of their mantle sources. Smith (1983) recognized an isotopic dichotomy in rocks with kimberlitic affinity from southern Africa, proposing a two-type classification based upon isotopic composition (Smith et al. 1985): Group I (archeotypal), typically exhibiting a narrow range in isotopic compositions with slightly unradiogenic Sr and radiogenic Nd compared to bulk Earth reference values, and similar to many OIBs; Group II (orangeite) having distinctly more radiogenic Sr, which is indicative of a more enriched source. This distinction shaped much of the discourse over succeeding decades, but the Group I/Group II isotopic classification is now obsolete.

Early isotopic studies of kimberlites focused solely on whole rocks, with their attendant crustal contamination and alteration effects. Heaman (1989) suggested analysing groundmass perovskite (CaTiO₃), which is relatively resistant to weathering, to resolve the alteration problems. The advent of in situ laser ablation inductively coupled plasma mass spectrometry analysis made possible Sr and Nd isotopic analysis of grains as small as a few tens of microns (e.g., Paton et al. 2007). These studies show less radiogenic Sr, and more coherent isotope systematics in kimberlilitic perovskite compared to bulk rocks (Fig. 4).
Coupled Sr–Nd–Hf isotopic variations of kimberlites, lamproites/orangeites and asthenospherically derived magmas (MORB and OIB) (Fig. 5) reveal important source characteristics and mixing systematics. The distinct isotopic character of orangeites is prominent, with significantly more enriched Sr, Nd and Hf isotopic compositions than kimberlites, but overlapping the wide-ranging compositions of lamproites. Kimberlite-borne megacrysts of clinopyroxene, garnet, ilmenite and zircon have radiogenic isotope compositions similar to their kimberlite host (Nowell et al. 2004).

Studies of the Re–Os isotopes in several kimberlite suites show the very strong effect of interaction with lithospheric mantle on kimberlite Os isotope compositions (e.g., Araujo et al. 2001) (Fig. 6), consistent with major element evidence (Fig. 2). Kimberlites with low (<1 ppb) Os typically have Os isotope compositions similar to OIB. With increasing Os content, Os isotopes become more unradiogenic, eventually mirroring the composition of the high Os (~3.5 ppb) cratonic lithosphere they incorporate. At very low Os contents, kimberlites become susceptible to the effects of crustal contamination, or the assimilation of lithospheric metasomes with radiogenic Os. A combination of all these lithospheric contributions can explain the variation of some kimberlites away from convecting mantle Os isotope compositions. The broad overlap between OIBs and those kimberlites less affected by mantle assimilation agrees with the conclusions from other isotopes (e.g., Smith 1983; Nowell et al. 2004) (Fig. 5) that kimberlite sources have a strong sub-lithospheric source input.

**CAN WE CONSTRAIN THE LOCATION OF KIMBERLITE SOURCES?**

Considering the unusual bulk compositions and mineralogy of kimberlites, it is perhaps surprising that they have fairly unremarkable radiogenic isotope characteristics, being similar to most OIBs whose sources are often placed in the lower mantle. Kimberlite isotopic compositions are quite distinct from the “depleted” mantle MORB source. The majority of Mesozoic-to-Eocene kimberlites have Sr–Nd–Pb isotopic compositions that closely resemble the spread seen in OIBs, from typical members of the OIB suite through to more enriched varieties (e.g., Smith 1983) (Fig. 5). The most frequently invoked origin for these enrichments (in both OIB and kimberlites) is an association with ancient subduction events, either via direct incorporation of subducted crust into the source or via metasomatism associated with the subduction process. Pre-Mesozoic kimberlites have much more unremarkable, close to chondritic, Hf–Nd isotope characteristics (Woodhead et al. 2019), indicative of a primitive source.

In contrast to kimberlites, lamproites and orangeites have extreme Sr–Nd–Pb and Hf isotopic compositions (Fig. 5), characteristic of the very long-term, highly variable parent–daughter isotope enrichments observed in mantle lithosphere modified at varying times in the past by subduction-related metasomatism (Nelson 1988). A lithospheric source for these magmas is widely accepted (Becker and le Roex 2006).

The OIB-like Nd–Sr isotopic features of kimberlites have been explained as reflecting an origin in the convecting mantle (Smith 1983) or in lithospheric mantle enriched by OIB-like melts (Becker and le Roex 2006). One notable feature of some Mesozoic and younger kimberlites (Fig. 5) (Nowell et al. 2004; Tappe et al. 2013) is that they describe a Nd–Hf isotope array that is steeper than that of OIB. These characteristics, seen most dramatically in Mesozoic and Cenozoic kimberlites, may result from source variation, such as mixing of sub-lithospheric melts with metasomatically altered rock from the lithospheric mantle (e.g., Tappe et al. 2011). Alternatively, kimberlites variably displaced from the Hf–Nd array may originate from melting a source containing recycled MORB crust or even from enriched OIB domains within subducted oceanic lithosphere in the deep asthenosphere or transition zone (Nowell et al. 2004; Tappe et al. 2013). A variant on this model, for Cretaceous North American kimberlites, invokes kimberlite melt production just above the transition zone due to de-watering of wadsleyite and ringwoodite, triggered by material displaced from the transition zone due to arrival of an incoming slab of subducted oceanic crust (Kjarsgaard et al. 2017).

Heaman et al. (2015) advocate the even deeper source of the core–mantle boundary for Jurassic kimberlite activity in North America, in line with a proposed model for all kimberlites (Torsvik et al. 2010) that links their spatial occurrence at a given geological time with seismic velocity anomalies in the lowermost mantle.

For pre-Mesozoic kimberlites, a deep, convecting mantle source that is in the transition zone or lower mantle and that has been long isolated from subducted crustal components is indicated by the remarkably restricted, almost chondritic, Nd and Hf isotope compositions (Woodhead et al. 2019). The peculiarities of Nd–Hf–Zr trace element systematics
in kimberlites may also indicate a transition zone origin, although more mineral–melt partitioning experiments are needed to evaluate this possibility. The isotopic diversity displayed by younger, Mesozoic-to-Eocene, kimberlites likely reflects a greater input from enriched subducted crustal components that have “contaminated” this source.

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ACKNOWLEDGMENTS

Ken Tainton, Lynton Jaques, Bruce Kjarsgaard and Geoff Nowell provided data used in compilation plots. The latter two, along with Steve Foley, Andrea Giuliani and Jon Blundy, provided helpful reviews.

Figure 6

Whole rock initial Os isotopic compositions (yOs) versus Os concentrations (in ppb) of kimberlites from South Africa, Lac de Gras and Brazil (all as blue dots). The yOs is the difference in % between the kimberlite (corrected to emplacement age for 187Os in-growth) and the average chondrite value. Blue shaded box depicts the field for ocean island basalt (OIB). Red line illustrates the effect of mixing between a kimberlite and cratonic peridotite (Kimb_peridotite), an important process defined in Figure 1. Other lines depict the effects of additional mixing with either crust or mantle metasomatic sulfide superimposed on two different points along the kimberlite-peridotite mixing trend. For data sources and details of mixing scenarios see http://elementsmagazine.org/supplements/.

Figure 1

Os concentration (in ppb) and the difference in % between the kimberlite (corrected to emplacement age for 187Os in-growth) and the average chondrite value. Blue shaded box depicts the field for ocean island basalt (OIB). Red line illustrates the effect of mixing between a kimberlite and cratonic peridotite (Kimb_peridotite), an important process defined in Figure 1. Other lines depict the effects of additional mixing with either crust or mantle metasomatic sulfide superimposed on two different points along the kimberlite-peridotite mixing trend. For data sources and details of mixing scenarios see http://elementsmagazine.org/supplements/.
High-pressure experiments are unconvincing in explaining kimberlites as direct melts of carbonated peridotite because the appropriate minerals do not coexist stably at the kimberlite liquidus. High-pressure melts of peridotite with CO₂ and H₂O have compositions similar to kimberlites only at pressures where conditions are insufficiently oxidizing to stabilize CO₂: they do not replicate the high K₂O/Na₂O of kimberlites. Kimberlite melts may begin their ascent at ~300 km depth in reduced conditions as melts rich in MgO and SiO₂ and poor in Na₂O. These melts interact with modified, oxidized zones at the base of cratons where they gain CO₂, CaO, H₂O, and K₂O and lose SiO₂. Decreasing CO₂ solubility at low pressures facilitates the incorporation of xenocrystic olivine, resulting in kimberlites’ characteristically high MgO/CaO.

**Keywords**: kimberlite, high-pressure experiments, volatiles, petrogenesis, CO₂

**INTRODUCTION**

High-pressure experiments can shed light on several issues surrounding the origin, evolution and modification of kimberlite magmas. Kimberlites have the deepest sources of any mantle-derived magmas, as indicated by their being the main hosts for diamonds and the carriers of the deepest known mantle xenoliths. However, the composition of primary kimberlite melts, their depth of origin, and the mineralogy of the source rocks remain controversial topics. Geobarometry estimates indicate that peridotite xenoliths carried by kimberlites come from as deep as ~255 km (7.8 GPa), showing that the host magma must originate from deeper still. But how much deeper is unknown. There are many examples of inclusions in diamonds from the transition zone and lower mantle, but diamonds are excellent pressure containers and could have been previously transported from great depth via mantle convection to levels above the source of kimberlite melts.

The first problem in resolving the origin of kimberlites is to home in on the composition of the magma. Whereas most igneous rock types can be assigned a simple mineralogical or chemical definition, the cumbersome definition of kimberlite takes up more than two pages of the International Union of Geological Sciences glossary. In terms of petrogenesis, this prevents a clear distinction of kimberlite from other types of deeply derived, volatile- and MgO-rich magmas. Even the term “kimberlite” itself is commonly used for two geochemical groups (Pearson et al. 2019 this issue). Here, we restrict our attention to so-called Group I kimberlites, which may be related to some carbonatite and lamprophyre melts, but are distinct from the Group II kimberlites, lamproites, and other K-enriched magmas that contain substantial amounts of lithospheric components from long-lived non-peridotitic source rocks (Foley and Pintér 2018).

The melting conditions and source rocks that give rise to kimberlite magmas must account for several notable chemical characteristics. Kimberlites are enriched in MgO (20–25 wt%), H₂O and CO₂, but have low SiO₂ (20–32 wt%) and Al₂O₃ (1.5–4.1 wt%) compared to most primary melts of mantle peridotite (Fig. 1). There is a common misconception that kimberlites are alkali-rich, but they only have a high K/Na ratio because of exceptionally low Na₂O. The primary volatile contents are the least constrained of these general characteristics: an unknown proportion of the H₂O may come from late serpentinization (Sparks et al. 2009; Mitchell et al. 2019 this issue). Recent estimates of primary kimberlite magma compositions indicate higher CaO and, thus, lower MgO/CaO (Fig. 1) and lower SiO₂ and H₂O, than many earlier estimates (Soltys et al. 2018; Pearson et al. 2019 this issue).

Traditionally, two experimental strategies have been used to constrain the origin of mantle-derived magmas. In the so-called *forward approach*, potential source rocks are melted at various pressures and temperatures in an attempt to match observed igneous rock compositions. When no match can be found, it must be assessed whether the right combination of conditions are yet to be found or whether assumptions about the identity of the primary magmas and/or source rocks are incorrect. The *inverse approach* starts with the product: a supposed primary melt composition is investigated at high pressures and temperatures using the principle that it must be saturated in all source-rock phases at its liquidus at the correct pressure and temperature of origin. A further experimental approach considered here does not address the origin of magmas per se but their evolution during ascent and at near-surface conditions. Understanding low-pressure processes in kimberlite

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magnas is critical, because changes that occur during transport can severely modify volatile contents and phase relations and, hence, the evolution of the melt composition.

**EXPERIMENTS ON POTENTIAL KIMBERLITE PRIMARY MELT COMPOSITIONS**

There is a long, albeit sparse and inconclusive, tradition of liquidus studies of kimberlite compositions. The main weakness of this inverse approach lies in choosing the primary melt composition to study. If the composition chosen is the product of fractionation or assimilation, or has been generated by polybaric fractional melting or melting of a mixed source, or has the incorrect volatile contents, then no multiple saturation can be expected. If the melting reaction is peritectic, then one or more minerals present in the source may first appear slightly below the liquidus temperature. All that these experiments can then provide is a rough guide as to which minerals may be present in the source. Assuming kimberlites are produced by melting of peridotite at 200–300 km depth, then olivine, garnet, clinopyroxene (Cpx) and orthopyroxene (Opx) should co-exist at the liquidus (Stamm and Schmidt 2017).

The inverse approach has given much less satisfying results for kimberlites than for many other mantle-derived magnas because of the interplay between the effects of pressure and volatile constituents on phase stabilities, and because less is known about original volatile contents. Increasing pressure up to 6 GPa promotes the stability of garnet and pyroxenes relative to olivine, whereas increasing H$_2$O contents does the opposite. Pyroxenes and garnet are also favoured by high CO$_2$/H$_2$O ratios. Thus, the bulk volatile contents, and not just their ratio, must be considered.

Early experiments concluded that kimberlites may originate by melting of phlogopite–carbonate–garnet lherzolite at around 6 GPa (Eggler and Wendlandt 1979). However, this conclusion necessitated extrapolating results from lower pressures and, on closer examination, neither hydrous phases nor carbonates lay close to the liquidus. Many experimental studies prior to 2000 were conducted on kimberlite compositions which, although considered near-primary at the time (e.g., Eggler and Wendlandt 1979; Edgar et al. 1988), had considerably higher MgO/CaO than modern estimates of primary magma compositions. More recently, Girnis et al. (2011) studied four compositions with different H$_2$O/CO$_2$ and volatile contents and concluded that kimberlitic melts may be derived from garnet harzburgite (i.e., no Cpx) at 6–8 GPa, variable H$_2$O/CO$_2$ and high volatile contents (15–25 wt%). Water is required to stabilize olivine: in experiments with CO$_2$ but no H$_2$O, olivine was not stable, and temperatures were unrealistically high. If H$_2$O/CO$_2$ ratios in kimberlite magnas are lower than previously thought, then a number of older inverse experiments must be re-interpreted. These include the lack of pyroxenes and garnet up to 10–12 GPa in the presence of H$_2$O/CO$_2$ ratios that are now thought to be too low (e.g., Mitchell 2004). The conclusions of Ringwood et al. (1992) that kimberlitic magnas must originate in the mantle transition zone (>13 GPa) were based on very MgO-rich compositions and relatively low total volatiles (5 wt% each H$_2$O and CO$_2$): higher CO$_2$ would promote garnet stability, negating this conclusion. The absence of Opx in many experiments may be due to an inappropriate choice of high H$_2$O/CO$_2$: similar considerations about H$_2$O/CO$_2$ may be relevant to studies of Opx dissolution during ascent.

Inverse experiments on kimberlites have generally not accounted for two key variables. The first is that the redox state of the mantle probably decreases with increasing depth: H$_2$O/CO$_2$ ratios and contents have been varied but...
very few experiments have addressed the issue that the asthenospheric mantle beneath cratonic keels is probably too reducing to stabilise CO₂ and carbonate (Frost and McCammon 2008; Yaxley et al. 2017). The second unaccounted for variable is the reaction between ascending kimberlite melts and surrounding mantle rocks, which may help to explain the apparent failure to locate peridotite multiple saturation points.

**MELTING OF PERIDOTITE WITH MIXED CO₂ AND H₂O**

In contrast to other alkaline ultramafic rocks such as lamproites, the source rock for kimberlite melts is widely presumed to be carbonated peridotite: this would be consistent with the radiogenic isotope differences between kimberlite and lamproite magmas (Pearson et al. 2019 this issue). Given that the cratonic lithosphere is thick and that xenoliths from as deep as 255 km occur in kimberlites, then a pressure range of 6–10 GPa is most relevant.

Two main issues plague the interpretation of peridotite melting experiments: (1) appropriate volatile contents and mixtures are uncertain; (2) high-pressure melts with high volatile contents never quench to directly analysable glass. Carbon dioxide and H₂O have universally been presumed to be necessary components in the source because of their high contents in kimberlite rock samples, but possible late-stage serpentinisation and degassing of CO₂ during ascent (Brey and Ryabchikov 1994; Mitchell et al. 2019) complicates the picture. Recent work on the redox state of the mantle at 200–300 km depth indicates it may be too reduced to contain carbonate, having COH species consisting of CH₄ + H₂O instead of CO₂ + H₂O (Frost and McCammon 2008), a possibility yet to be considered in kimberlite experiments. Identifying melt compositions is further hampered by the difficulty in rapidly quenching an experimental melt, which makes melt compositions, especially determining dissolved volatiles, exceedingly difficult to analyse with certainty.

There are many more experimental results available at 6–10 GPa using the forward rather than the inverse approach, but few of these have included both CO₂ and H₂O. The mantle solids is also decreased markedly by the addition of several other components: potassium, fluorine, chlorine and H₂O (Foley et al. 2009; Brey et al. 2009, 2011), meaning that, with appropriate fluxing agents, incipient melting at the base of the cratonic lithosphere may be possible. Nevertheless, the majority of available experimental results are on peridotite with CO₂ alone. It has been claimed that this has little impact on melt compositions (Brey et al. 2009; Sun and Dasgupta 2019), but, in view of the strong and contrasting effects several other components have on melt structures and phase stabilities, the more likely explanation is that differences in melt compositions are real but are yet to emerge from the stratum of uncertainty induced by the quenching problem.

Melts in experiments on peridotite without volatile components show that high MgO, but low SiO₂ and Na₂O, are typical for high pressures. The extremely low Na₂O of kimberlites, however, may be problematical. Melts of depleted, volatile-free garnet harzburgite have lower SiO₂, TiO₂, Cr₂O₃, CaO and Na₂O than melts of fertile peridotites at the same degree of melting. For a variety of peridotite compositions and pressures in the presence of CO₂ and H₂O, initial melts are carbonatitic, progressing to low-SiO₂ silicate melt compositions at higher degrees of melting (Foley et al. 2009; Ghosh et al. 2014). These silicate melts are variously described as kimberlitic (e.g., Brey et al. 2011; Stamm and Schmidt 2017) or ultramafic lamprophyre (UML) (Foley et al. 2009). The distinction between these two kinds of melt is illustrated in a plot of SiO₂/Al₂O₃ against MgO/CaO (Fig. 1), in which kimberlites characteristically exhibit higher ratios of both. The lower SiO₂/Al₂O₃ of UML is due to lower SiO₂, not higher Al₂O₃, consistent with their compositionally transitional status towards carbonatites. The higher MgO/CaO of kimberlites is due to higher MgO, well in excess of 20 wt%, as opposed to mostly 15–20 wt% for UML. Estimated primary kimberlite melts (Pearson et al. 2019 this issue) plot at the low end of the kimberlite compositional range. The reality of the distinction is underscored by the coexistence of UML and kimberlites in the same area (e.g., West Greenland), yet the much-emphasised correlation between SiO₂ and CO₂ in experimental melts (Ghosh et al. 2014; Sun and Dasgupta 2019) does not distinguish between them.

Close matches for Si, Al, Mg and Ca (Fig. 1B) are only achievable at and above 6 GPa (Brey et al. 2008); high MgO/CaO ratios only materialise at 10–20 GPa (Ghosh et al. 2014). However, most of these experiments are H₂O-free, and the K₂O/Na₂O ratios of melts are consistently lower than kimberlites (Fig. 1C). In addition to the relationships shown in Figure 1, other compositional variables do not match between kimberlites and primary melts of peridotite with CO₂ and H₂O, particularly Al₂O₃, K₂O and SiO₂ (Foley et al. 2009; Stamm and Schmidt 2017; Sun and Dasgupta 2019).

In summary, peridotite melting experiments with CO₂ ± H₂O indicate that it is unlikely that kimberlite melts can be produced by batch melting of peridotite alone. A model using melting of peridotite alone can only be retained if recycled assemblages are included in upwelling asthenospheric mantle. Another option is that kimberlitic melts undergo a more complex evolution that involves reaction with the rocks that they pass through, probably with associated redox changes.

**EXPERIMENTS AT CRUSTAL PRESSURES**

Fractional crystallisation and release of fluids close to the surface mean that experiments outlining the low-pressure evolution of kimberlite magmas are essential. However, few experiments on kimberlite or kimberlitic compositions have been undertaken at crustal pressures (<1.2 GPa). Edgar et al. (1988) determined the phase relations of an anaphlitic kimberlite between 4 GPa and 1 GPa with 6.2 wt% H₂O and 4.8 wt% CO₂ (ACO₂ = 0.24). The lower pressure (<2 GPa) part of their phase diagram is illustrated in Figure 2. At 1 GPa (~33 km depth), the liquidus is defined by the crystallization of olivine (~1,425 °C), followed by spinel, then by ol + sp + monticellite (mo), which are joined subsequently by perovskite and then calcite. The lowest temperature phase assemblage is consistent with the microphenocryst mineralogy of a hypabyssal kimberlite (Mitchell et al. 2019 this issue). Importantly, these experiments explain the absence of clinopyroxene (cpx) phenocrysts or microphenocrysts in kimberlite. Because of the reaction relationship cpx + liq₁ ⇒ mo + liq₂, cpx is only stable at the higher P–T conditions of ~8 GPa and ~>1,250 °C (Fig. 2). Additional experiments at higher CO₂ contents (XCO₂ = 0.52) (Edgar et al. 1988) are similar but the phase boundaries are shifted to higher (~100°C) temperatures and dolomite is stable at ~3.5 GPa.

Even fewer kimberlite experiments have been undertaken at very low pressures. These were designed to examine volatile solubilities. Synthetic proxies for an aphanitic kimberlite from Jericho (Canada) and a macrocrystic kimberlite from Bultfontein (South Africa) were studied at 0.1 GPa (~3 km depth) by Sparks et al. (2009) and by Brooker et al. (2011). Both compositions phase assemblages are similar at 1,275°C and 1,250°C and consist of ol + sp + mo + liq (Fig. 2), and contain high (49%–80%) modal
ol + mo + sp. At 0.1 GPa and 1,100°C, the phase assemblage is sp + mo + perovskite + apatite + liq. The absence of olivine can be interpreted as a low-pressure reaction relationship (ol + liq ⇒ mo + liq), which is observed in very fresh and well-preserved kimberlite groundmass where monticellite forms rims on olivine (e.g., Abersteiner et al. 2017). The absence of calcite in these 0.1 GPa experiments, despite high CaO (35–42 wt%) contents, may be due to the high temperatures. This is supported by experiments in calcicarbonate systems at similar low pressures, in which calcite crystallizes only below 1,100°C (Weidendorfer et al. 2017). In spite of limited experimental data, phase relations at low pressures are generally consistent with observed kimberlite mineralogy. The crystallization of predominantly olivine + spinel from kimberlite magma in the uppermost lithosphere probably occurs over a wide pressure range (4.0–1.0 GPa).

**VOLATILE SOLUBILITIES IN KIMBERLITE TO CARBONATITE MELTS**

Volatile solubility measurements on kimberlitic, transitional silicate–carbonate, and carbonatite melts are scarce. Brey and Ryabchikov (1994) presented a thermodynamic model for CO₂ solubility that had two relevant melt compositions (see Fig. 3) that are herein termed “transitional” (13–21 wt% SiO₂) and “kimberlite” (21–27 wt% SiO₂). Also on Figure 3 are experimentally determined CO₂ ± H₂O contents for these types of melt, which are in general agreement with the modelled solubility curves, and a carbonate CO₂ solubility trend. From carbonatites through kimberlite, volatile solubility decreases towards lower pressure, lower CaO, and higher SiO₂ and MgO melt concentrations. Note that any CO₂-bearing primary partial melts are volatile-undersaturated when they leave their source region (Fig. 3). Hence, for an asthenosphere-derived, volatile-undersaturated partial melt, magma ascent must be dominantly controlled by density contrast (Brey and Ryabchikov 1994; Sharygin et al. 2017) until a free fluid is exsolved at the depth of volatile saturation.

The depth at which melts become CO₂-saturated is strongly dependent upon the crystallisation assemblage (Fig. 3, black arrows). Initial crystallization of magnesite or dolomite lowers CO₂ in the melt, whereas crystallization of silicates + oxides, or silicates + oxides + carbonate will (variably) increase it. The experimental results mentioned above favour olivine and spinel, which would strongly increase CO₂ in the melt during transport through the lithosphere. This implies that transitional or kimberlitic melts could be volatile-undersaturated during a significant portion of their transit through the lithospheric mantle. At upper crustal pressures (<0.35 GPa), the results of Brooker et al. (2011) and Mousallam et al. (2016) follow the modelled melt CO₂ solubility curves, although their melt compositions are extremely CaO-rich (35–45 wt%) and do not directly compare to modelled results or to experimental data from higher pressures (CaO < 30 wt%).

**FIGURE 2** Interpretation of pressure versus temperature phase relationships of Wesselton aphanitic kimberlite (Kimberley, South Africa) at 2.0–1.0 GPa, with XCO₂ = 0.24. Phase symbols are as follows: Ap = apatite; Cc = calcite; Cpx = clinopyroxene; I = liquid; Mo = monticellite; Ol = olivine; Pv = perovskite; Sp = spinel. Data from Edgar et al. (1988), Sparks et al. (2009) and Brooker et al. (2011).

**FIGURE 3** Volatile solubility (CO₂, or CO₂ + H₂O) versus pressure for a range of melt compositions. Coloured symbols show experimental volatile solubility data for kimberlite, transitional, and carbonatite melts: data from Edgar et al. (1988), Brooker et al. (2011), Sharygin et al. (2017) and Mousallam et al. (2018). Coloured dashed lines are modelled CO₂ solubility for kimberlite and transitional melts: after Brey and Ryabchikov (1994), with relevant carbonatite melt solubility inferred due to paucity of data. Volatile solubility data for 7 GPa melts (coloured squares at top right) are from Stamm and Schmidt (2017). The black square with arrows (top middle right) shows the compositional trend in relation to CO₂ (arrow direction) that would be produced in the kimberlitic melt by the crystallization of either silicates plus oxides, or silicates plus oxides plus carbonates, or only carbonates.

**REACTION OF KIMBERLITE MAGMAS WITH WALL ROCKS**

Reactions between kimberlitic melts and peridotitic wall rocks are ubiquitous. These are the subject of reaction experiments, wherein two distinct rock types are included in the same experiment and run above the melting point of one rock so that the melt reacts with the solid second rock. The oldest of the relevant observations is that kimberlites show a very good correlation between CaO and CO₂, implying a role for calcite, whereas the stable carbonate in the source peridotite should be magnesite (Bailey 1984). This is underscored by recent appraisals of primary kimber-
lite melt compositions, which contain higher CaO and CO₂ than earlier estimates (Solty et al. 2018). This apparent contradiction is avoided if calcite is present not in the peridotite but in Opx-free assemblages that react with embryonic kimberlite melt. A principal characteristic of kimberlites is that they carry more xenocrystic olivine than any other igneous rock. This olivine is compositionally similar to that in lithospheric harzburgites and may be explained by preferential dissolution of Opx in low-SiO₂ melts (Sharygin et al. 2017).

Reaction experiments have concentrated mainly on reaction between subducted sediments and peridotite as a mechanism to form potassic magmas: few are directly relevant to the origin of kimberlites. The high chlorine contents in some kimberlites may be explained by melts of subducted sediments reacting with peridotite in the lower lithosphere (Förster et al. 2019). Experimental indications that kimberlitic melts may form by reaction of carbonatites with peridotite were presented by Sun and Dasgupta (2019), but their scenario requires active subduction beneath areas of kimberlite production, which is typically not the case.

The introduction of volatiles from assemblages that contain carbonates and hydrous minerals in reaction zones in the lower lithosphere may provide a mechanism by which kimberlite magmas can transport 50 kg xenoliths to the surface. Experiments have yet to adequately account for this fact. The dissolution of Opx leads to an increase in SiO₂, but CO₂ remains in the melt and does not de-gas (Sharygin et al. 2017). Reaction experiments may well be the future of experimental research into kimberlite origin and ascent. This may entail re-interpretation of the isotope groupings: “asthenospheric” may result from reactions between melt and peridotite below the lithosphere; “lithospheric” may merely indicate similar reactions in the lower lithosphere.

**THE ORIGIN OF KIMBERLITE MAGMAS**

There is general agreement that the initiation of melting to form kimberlites must take place below the lithosphere, but the degree to which kimberlites interact with lithospheric mantle is disputed. Experiments have not yet brought a satisfactory solution. Peridotite melting experiments with CO₂ and carbonate at 6–10 GPa produce melts that are ostensibly similar to kimberlites, but these experiments do not explain the high K₂O/Na₂O (Fig. 1C) and redox conditions at 6–10 GPa are likely too reducing to stabilise CO₂ and carbonate.

First-generation reaction experiments and initial results from experiments with CH₄ and H₂O have brought promising results that lead us to the following scenario for kimberlite genesis. The redox profile in and below cratonic mantle is approximately as shown in Figure 4. Upwelling mantle beneath the craton begins to melt under reducing conditions (CH₄ > H₂O) as fO₂ slowly rises due to decreasing pressure. Partial melting increases by 9 GPa and 7 GPa due to increasing H₂O/CH₄ as fO₂ approaches the iron–wüstite buffer. The very limited experimental information to date shows that these melts are likely to be MgO-rich, silicate melts (SiO₂ > 35–40 wt%) that have a MgO/CaO ratio of 3–4 (Fig. 1B) (Jakobsson and Holloway 2008; Litasov et al. 2014). The K₂O/Na₂O ratio of these melts is likely to be much lower than in kimberlites due to the lack of a host for potassium (Fig. 1C) and the compatible nature of Na caused by the stabilisation of the jadeite component in Cpx at these very high pressures.

On encountering the base of the cratonic lithosphere, these reduced “proto-kimberlitic” melts (red line in Fig. 4A) interact with a previously strongly metasomatised and oxidised zone (beige) that has accumulated carbon, CaO, K₂O, and H₂O over time (Foley and Fischer 2017; Yaxley et al. 2017). The repeated metasomatic enrichment and oxidation of this zone lowers its solidus (Fig. 4A,B). This means that interactions between the reduced, asthenospheric proto-kimberlitic melts and the mica- and carbonate-rich mineral assemblages in the basal cratonic lithosphere enables substantial uptake by the melts of Ca and K, and of C (in the form of CO₂), which helps explain both the high K₂O/Na₂O of kimberlites and the correlation of CaO with CO₂. In this scenario, the initial, embryonic kimberlite melt originates below the lithosphere and is not carbonate-rich; it only derives its characteristic kimberlitic chemistry after interacting with the lower lithosphere. The isotopic (asthenosphere-like) uniformity is explained if the assimilated lithospheric material is not very old.

Following interaction, the modified – now kimberlitic – melt is emplaced rapidly through the overlying lithosphere, much of which is more reduced than the metasomatized basal zone of the lithosphere because it is the residue of partial melting in the Archean that fractionated redox states between melt and residue. During this stage, the MgO/CaO of kimberlite magmas increases again due to the uptake of xenocrystic olivine. The low Na₂O of kimberlites may be
partly explained by its uptake in exsolving $\text{H}_2\text{O} + \text{CO}_2$–rich fluid (Soltys et al. 2018), though this would not explain the lack of Na$_2$O-loss from carbonatites and allilikes that are equally, or even more, volatile-rich. Models invoking asthenospheric melts interacting with lithosphere have been proposed before (e.g., Ringwood et al. 1992), but ideas on the nature of the melt and lithosphere have changed. A key difference is the redox contrast between proto-kimberlitic melts and the lower lithosphere. Further reaction experiments and experiments on peridotite under reduced conditions should help clarify and develop these ideas.

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ACKNOWLEDGMENTS

This manuscript has benefitted from comments by Robert Luth, Michael Walter and Andrea Giuliani. SF is funded by ARC grant FL180100134.
Dating Kimberlites: Methods and Emplacement Patterns Through Time

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1811-5209/19/0015-0399$2.50 DOI: 10.2138/gselements.15.6.399

Key to deciphering the origin and tectonic setting of kimberlite magmatism is an accurate understanding of when they formed. Although determining absolute emplacement ages for kimberlites is challenging, recent methodological advances have contributed to a current database of >1,000 precisely dated kimberlite occurrences. Several profound findings emerge from kimberlite geochronology: kimberlites were absent in the first half of Earth history; most kimberlites were emplaced during the Mesozoic; kimberlite magma formation may be triggered by a variety of Earth processes (deep mantle plumes, subduction of oceanic lithosphere, continental rifting); and enhanced periods of kimberlite magmatism coincide with supercontinent breakup.

Keywords: kimberlite geochronology, emplacement patterns, tectonic settings

INTRODUCTION

It is commonly accepted that kimberlite magmas are derived from the deep Earth. However, there is less certainty about the causes of kimberlite magma formation and what controls their geodynamic setting. Answering these long-standing questions has been hampered by a paucity of robust emplacement ages for kimberlites, due to their heterogeneous nature and propensity for alteration (Giuliani and Pearson 2019 this issue). Kimberlites are unusual in that they consist of a mixture of minerals crystallized directly from the kimberlite magma plus a plethora of entrained mantle and crustal rocks and minerals. The capacity of kimberlite magmas to entrain significant quantities of mantle material may be key to the formation of primary diamond deposits and studies of the deep Earth, but this process complicates our ability to accurately determine the timing of kimberlite magma formation and emplacement.

During the past three decades there has been a revolution in our ability to determine precise and accurate dates for kimberlites. This progress has been spearheaded by new technological advances that have substantially reduced the volume of material required to date kimberlites and by new mineral chronometers that specifically target groundmass minerals crystallized directly from the kimberlite magma. Recent technological developments now permit relatively nondestructive in situ geochronology on small (~20 micron diameter) analysis spots by U–Pb laser ablation inductively coupled plasma mass spectrometry (LA–ICPMS) (e.g., Batumike et al. 2008), by U–Pb secondary ion mass spectrometry (SIMS) (e.g., Kinny et al. 1989), by single crystal U–Pb isotope dilution thermal ionization mass spectrometry (ID–TIMS) (e.g., Stamm et al. 2018), and by ⁴₀Ar/³⁹Ar laser probe static mass spectrometry (e.g., Phillips et al. 2017). Here, we review recent developments in kimberlite geochronology, the temporal evolution of kimberlite magmatism, and how kimberlite geochronology is used to constrain their geodynamic settings.

Although many absolute radiometric dating methods have been applied to kimberlite geochronology (with varying degrees of success), there are three chronometers that are routinely employed because they typically yield reliable (accurate and precise) emplacement dates: U–Pb, Rb–Sr, and ⁴₀Ar/³⁹Ar. A comparison of these methods applied to a variety of minerals from Monastery kimberlite (South Africa) is summarized in Noyes et al. (2011). These results give a high-precision weighted mean date (n = 12/15) of 89.21 ± 0.26 Ma for the kimberlite, illustrating the enormous potential for high-precision kimberlite geochronology.

DATING KIMBERLITES: U–Pb GEOCHRONOLOGY

The technique of U–Pb geochronology has been attempted on many minerals isolated from kimberlites and mantle xenoliths (e.g., apatite, baddeleyite, ilmenite, rutile, titanite), with varying degrees of success. Here, we describe the two most commonly used mineral chronometers: groundmass perovskite and mantle zircon.

Groundmass Perovskite

Perovskite (CaTiO₃) is a common accessory mineral in many kimberlites and related rocks and typically occurs as tiny (<100 micron), euhedral–subhedral, orange-brown, cubo-octahedral crystals in the groundmass. Perovskite is ideally suited for U–Pb geochronology because it not only contains elevated levels of U (20–200 ppm by weight) and Th (>500 ppm), but is one of the few dateable minerals that crystallizes directly from the kimberlite magma. Furthermore, perovskite is rare in most crustal rocks, so it is unlikely to be present in entrained crustal material. Dating kimberlites via the U–Pb perovskite method was pioneered in the 1980s (Kramers and Smith 1983; Heaman 1989). There are now more than 1,000 U–Pb perovskite dates available for kimberlites worldwide. There are two main challenges to dating groundmass perovskite: (1) the small grain size, which makes mineral separation and...
analysis by ion beam U–Pb techniques challenging; (2) perovskite contains a significant amount of common Pb (5% to >30% of the total Pb) such that age calculations can be sensitive to the initial common Pb correction (Stamm et al. 2018). Improved accuracy and precision (+0.3 My) of U–Pb perovskite age determinations can be achieved by directly measuring the Pb isotope composition of a co-crystallizing low-U mineral, such as ulvöspinel–magnetite (Stamm et al. 2018).

The amount of perovskite required for an individual analysis has decreased dramatically over the past 20 years, and precise U–Pb ID–TIMS dates can now be obtained on 5–20 microgram aliquots (Ranger et al. 2018; Stamm et al. 2018). Crystals as small as 15 microns in diameter have been successfully separated from kimberlite samples and dated using this technique (Ranger et al. 2018). In situ U–Pb perovskite dating studies of kimberlites employ either LA–ICPMS (Batumike et al. 2008) or SIMS (Kinny et al. 1997) techniques, with analysis spot diameters approaching 20 microns.

Mantle Zircon

Zircon (ZrSiO₄) from the mantle entrained in kimberlite magmas commonly occurs as relatively large crystals (up to centimeter size), which form part of the kimberlite’s megacryst suite (Mitchell et al. 2019 this issue). Occasionally, zircon occurs as inclusions in diamonds (Kinny and Meyer 1994) and as constituents of certain mantle xenoliths, such as mica–amphibole–rutile–ilmenite–diopside (MARID) nodules (Kinny and Dawson 1992). Mantle zircon xenocrysts occur together with diamonds during the final stages of diamond recovery. They often exhibit complex desilicification reaction rims composed predominantly of baddeleyite, which formed during transport and interaction with the kimberlite magma. Dating mantle zircons entrained in kimberlite using the U–Pb TIMS method was pioneered by Gordon Davis (Davis et al. 1976). In order for a mantle zircon to faithfully record the time of kimberlite magmatism it must have resided in the mantle at high temperatures, above the closure temperature for Pb diffusion (~900 °C), before being entrained in kimberlite magma and brought to surface. Where zircons have not been heated above their closure temperatures they may yield ages that significantly predate the time of kimberlite eruption (Kinny et al. 1989). Crustal zircons can also be entrained in kimberlite magmas and these also yield ages significantly older than the time of kimberlite emplacement but can be distinguished by their generally smaller size, morphology, and higher U contents (>100 ppm).

DATING KIMBERLITES: Rb–Sr GEOCHRONOLOGY

Phlogopite [KMg₃AlSi₃O₁₀(F,OH)₂] commonly occurs in kimberlites as macrocrysts (up to centimeter size crystals) entrained from mantle pegmatites, and as microphenoocrysts in the groundmass (Mitchell et al. 2019 this issue). Phlogopite is ideally suited for kimberlite Rb–Sr geochronology because it has high Rb/Sr, which means that the majority of strontium present in the crystal formed from radioactive decay of ⁸⁷Rb. Phlogopite macrocrysts are a favored target for Rb–Sr kimberlite dating because they are large, easy to identify, and straightforward to extract from core/hand samples. Although phlogopite macrocrysts formed in the mantle prior to kimberlite magma genesis, they yield reliable kimberlite emplacement dates because phlogopite has low closure temperature to Sr diffusion (~300°C). Under mantle conditions (>700°C) phlogopite megacrysts will not accumulate radiogenic Sr because it continuously diffuses from the crystal. Therefore, geological time will only be recorded after macrocryst entrainment in the kimberlite magma and cooling to lower temperature conditions in the Earth’s crust. Kimberlitic phlogopite Rb/Sr values vary from ~300 [⁸⁷Rb/⁸⁶Sr ~868) to less than 5. Following the pioneering work of Allsopp and Barrett (1975), subsequent technique modifications have included the exclusion of altered (chloritized) grains and mild acid leaching to remove carbonate (Brown et al. 1989); these approaches have improved the precision and accuracy of Rb/Sr kimberlite dating significantly. For example, Rb–Sr ages with precision levels <1% were determined on phlogopite macrocrysts from fresh kimberlites of the Eocene-to-Late Cretaceous Lac de Gras field in northern Canada (Creaser et al. 2004). Eight phlogopite analyses from the Cobra South kimberlite from Lac de Gras field yielded a high-precision Rb–Sr isochron age of 59.7 ± 0.4 Ma (Creaser et al. 2004).

Reliable Rb–Sr model ages can be determined on single phlogopite macrocrysts with high Rb/Sr because they are insensitive to the initial Sr isotopic composition of the magma. However, dating low Rb/Sr crystals requires an independent constraint on the kimberlite magma initial isotopic composition (e.g., from perovskite) (Paton et al. 2007). This single macrocryst approach has been used to date phlogopite-poor kimberlite pipes. Sakar et al. (2015) investigated the uncertainties in phlogopite model ages using accurate initial Sr isotopic constraints for samples from the Lac de Gras field. They confirmed that phlogopite Rb/Sr macrocrysts with Rb/Sr >200 have age uncertainties of ~0.4%, which increase to ~4% for those with Rb/Sr ratios <75.

DATING KIMBERLITES: ⁴⁰Ar/³⁹Ar GEOCHRONOLOGY

Groundmass phlogopite, because of its high K content and magmatic origin, is the preferred mineral for K–Ar and ⁴⁰Ar/³⁹Ar dating of kimberlites and related rocks. Groundmass grains can be distinguished from phlogopite xenocrysts/phenocrysts by their smaller grain size (usually <200 µm) and the common presence of inclusions of other groundmass minerals, such as spinel.

The K–Ar and ⁴⁰Ar/³⁹Ar phlogopite dating techniques have not been widely applied to kimberlite geochronology, in part because early studies reported anomalously old ages that were attributed to the presence of inherited argon (i.e., pre- or synmagmatic argon). Allosp and Roddick (1984) conducted a systematic ⁴⁰Ar/³⁹Ar study of phlogopite macrocrysts and groundmass phlogopite grains from the Dokolwayo kimberlite (Swaziland) and confirmed the presence of inherited argon in phlogopite macrocrysts. They also demonstrated that groundmass phlogopite that had crystallized from the kimberlite magma contained negligible inherited argon and gave reliable kimberlite emplacement ages. The four main challenges involved in ⁴⁰Ar/³⁹Ar (and Rb–Sr) dating of groundmass phlogopite are as follows: (1) the absence of groundmass phlogopite in some kimberlites and related rocks; (2) the small grain size (often <100 microns), which complicates mineral separation; (3) the difficulties in distinguishing groundmass phlogopite from macrocryst fragments in mineral separates; and (4) the susceptibility of groundmass phlogopite to alteration (chloritization). Some of these challenges have been addressed with recent advances in microanalytical ⁴⁰Ar/³⁹Ar laser probe methods (Phillips et al. 1999) and the availability of multi-collector mass spectrometers, which allow single-grain analyses at precision levels approaching 0.1% (Phillips et al. 2017). For example, mica separated from the Kuusamo...
kimberlites (Finland) yielded identical high-precision Rb–Sr (747 ± 4 Ma) and 40Ar/39Ar plateau (747.8 ± 1.0 Ma) ages (Phillips et al. 2017).

A novel approach to kimberlite geochronology involves 40Ar/39Ar dating of clinopyroxene inclusions extracted from diamonds. These inclusions may contain up to 1.5 wt% K2O, enabling 40Ar/39Ar laser probe dating of single inclusions >100 microns in size (Phillips and Harris 2008 and references therein). This dating method is possible because radiogenic argon, produced from the decay of 40K during mantle residence, diffuses to the diamond clinopyroxene interface (which acts as a crystal defect that prevents argon loss by diffusion) in response to elevated mantle temperatures (>1,000 °C) (Phillips et al. 2004). After entrainment by the host kimberlite and subsequent crustal emplacement and cooling, radiogenic argon is retained in the clinopyroxene inclusions. Extraction of the inclusions from their host diamonds causes loss of the interface/defect (i.e., “mantle residence”), argon. Therefore, 40Ar/39Ar dating of extracted clinopyroxene inclusions has the potential to determine the age of the host kimberlite (Phillips and Harris 2008). One challenge is that some inclusions retain a proportion of their “mantle” (i.e., inherited) argon, such that the 40Ar/39Ar ages may only provide maximum constraints on kimberlite emplacement events. Nonetheless, if sufficient clinopyroxene inclusions are dated, the youngest ages provide reasonable estimates for the age of the host. For example, Phillips et al. (2004) reported reproducible 40Ar/39Ar ages of ~240 Ma for clinopyroxene inclusions from Jwaneng kimberlite diamonds (Botswana), within uncertainty of a previous U–Pb zircon age of 235 ± 4 Ma for this locality (Kinny et al. 1989).

**KIMBERLITE EMBLACEMENT PATTERNS THROUGH TIME**

With improved constraints for kimberlite emplacement events and judicious selection of the most reliable data, it is now possible to address five long-standing questions relating to kimberlite genesis and emplacement patterns through time. 1) How long does it take a kimberlite pipe or field to form? 2) Is there any evidence for kimberlite geochronology studies are now indicating that the time required to build a kimberlite field is protracted. For example, 44 kimberlite bodies from the Chidliak kimberlite field (Baffin Island, Canada) were emplaced over a period of 18 My (157–139 Ma) (Heaman et al. 2015). Furthermore, it has long been assumed that a single kimberlite pipe is emplaced in a geologically short period of time (<1 My) because kimberlite magmas are highly gas-charged and have extremely fast ascent rates from the mantle. However, this view of kimberlite pipe construction is starting to change. For example, high-precision U–Pb perovskite dating of the Renard 2 kimberlite in Quebec has revealed multiple intrusions within a single pipe were emplaced over a period of ~20 My (Ranger et al. 2018).

A compilation of >2,350 published radiometric dates for kimberlites and related rocks worldwide is shown in Figure 1. Some kimberlites have been subject of multiple dating studies; it is estimated that ~1,400 separate intrusions, or approximately 20% of the ~3,500 known kimberlites worldwide (Giuliani and Pearson 2019 this issue), have been dated. A first-order observation is that the emplacement frequency of kimberlite magmatism has varied significantly over Earth history: Proterozoic (16%), Paleozoic (27%), Mesozoic (51%), and Cenozoic (6%). From dating kimberlite emplacement patterns, five conspicuous features emerge. 1) Kimberlites are rare-to-absent in the first half of Earth history. 2) The majority of kimberlites (~85%) are Phanerozoic (~542 Ma). 3) The most prolific era of kimberlite magmatism occurred during the Mesozoic, with ~50% of all dated kimberlites erupted between 248 Ma and 66 Ma. 4) There are at least four broad periods of enhanced kimberlite magma production at 1,200–1,050 Ma, 600–480 Ma, 400–320 Ma, and 170–50 Ma (shaded columns in Fig. 1), of which the Mesozoic (69%) is the most prolific era of kimberlite magmatism. With examples known from southern Africa, North America, and India. 5) Economically significant primary diamond deposits occur in all periods of enhanced kimberlite activity, with the world’s largest diamond mines formed over a period of ~1 billion years: Cullinan (Premier pipe, South Africa) at 1.2 Ga; Mir (Russia) at 365 Ma; Venetia (South Africa) at 528 Ma; Orapa (Botswana) at 118 Ma; Catoca (Angola) at 118 Ma; Orapa (Botswana) at 93 Ma; and Diavik A154 (Canada) at 55 Ma (denoted by diamond symbols in Fig. 1). There is evidence for temporal windows of diamondiferous kimberlite emplacement within specific cratons and kimberlite fields that can be useful for diamond exploration. For example, a total of 52 precise ages have been reported from the highly diamondiferous Lac de Gras kimberlite field (Fig. 2), with up to five pulses of kimberlite activity recognized between 45 Ma and 75 Ma (see summary in Sarkar et al. 2015). A significant discovery from the detailed dating studies of the Lac de Gras field is that the majority...
The paucity of kimberlites in the first half of Earth history is intriguing. There are no known unequivocal Archean kimberlites. If true, this implies that considerable time elapsed before the requisite conditions for kimberlite genesis developed. The existence of Archean kimberlites has been debated for decades, but most purported Archean kimberlites are altered and metamorphosed, thus obscuring their original nature. For example, it is likely that the dated Archean zircons from the metamorphosed Mitzic (Gabon) intrusions (Henning et al. 2003) have a crustal origin. Given the extensive diamond exploration and research activity on several cratons (Kaapvaal in South Africa, Slave in Canada, and Siberian in Russia), if Archean kimberlites exist, they should, by now, have been discovered.

Three main explanations have been invoked to explain the lack of kimberlites in early Earth (Aulbach and Stagno 2016): 1) a hotter early Earth did not favor generation of magmas by low degrees of partial melting in the mantle; 2) a more reducing Archean convecting upper mantle impeded the stabilization of CO₂-enriched fluids/melts; 3) the increase in mantle volatiles (e.g., H₂O + CO₂ fluids) that is required to form kimberlite magmas only occurred after the initiation of deep-subduction plate tectonics. It is possible that a combination of the above factors impeded kimberlite magma formation. This interpretation is consistent with the notion that the onset of significant global oceanic lithosphere subduction occurred at ~2 Ga, when, arguably, the first clearly identifiable global Wilson Cycle can be identified.

At the opposite end of Earth history, there are no known examples of a modern kimberlite volcano—nobody has seen a kimberlite magma erupt! The youngest kimberlite lavas are Quaternary (~12,000 years old), erupted from the Igwisi Hills volcano in Tanzania (Brown et al. 2012).

The youngest known pipes are the ~30 Ma Kundelungu kimberlites in the Democratic Republic of Congo (Batumike et al. 2008).

A compilation of filtered kimberlite ages for Africa, North America, and Russia is shown in Figure 3. The blue shaded regions denote significant periods of kimberlite activity (or “kimberlite barcode”). This compilation demonstrates that there are some contemporaneous periods of kimberlite magmatism within widely separated cratons [e.g., the global kimberlite magmatic events of Heaman et al. (2003)]. For example, a prominent pulse of Jurassic kimberlite magmatism within widely separated geographic regions (continent/country): (A) North America, (B) Russia, (C) Africa. The dates are filtered to exclude nonkimberlites, and only one radiometric date per intrusion is compiled. The light blue shaded regions denote recognized periods of kimberlite magmatism and represent a “kimberlite barcode”.

**Figure 2** Compilation of kimberlite age versus diamond grade in the Lac de Gras (Canada) kimberlite field. In some kimberlite fields the most diamondiferous kimberlites are emplaced within a narrow time span termed here the “diamond window” (dark pink band) between 45 Ma and 56 Ma. A selection of specific named kimberlites within the Lac de Gras field are given.

**Figure 3** Compilation of published kimberlite dates (y-axis) versus kimberlite age (x-axis) grouped according to geographic regions (continent/country): (A) North America, (B) Russia, (C) Africa. The dates are filtered to exclude nonkimberlites, and only one radiometric date per intrusion is compiled. The light blue shaded regions denote recognized periods of kimberlite magmatism and represent a “kimberlite barcode”.

**Figure 4** A compilation of microdiamond grade versus kimberlite age in the Lac de Gras (Canada) kimberlite field. In some kimberlite fields, the most diamondiferous kimberlites are emplaced within a narrow time span termed here the “diamond window” (dark pink band) between 45 Ma and 56 Ma. A selection of specific named kimberlites within the Lac de Gras field are given.
KIMBERLITES AND PLATE TECTONICS

Despite numerous attempts to explain the temporal and spatial distribution of kimberlites, there is no consensus regarding their origin or tectonic setting. Several tectonic processes/events have been postulated to explain kimberlite formation (Kjarsgaard et al. 2017 and references therein), including subduction of oceanic lithosphere, extension of continental lithosphere, and the impact of mantle plumes (either as isolated hotspot tracks or as swarms of plumes generated within the lower mantle). A corollary to increased kimberlite magmatism during periods of plate fragmentation or supercontinent breakup is that periods of low kimberlite magmatic activity appear to coincide with low plate velocities and supercontinent stability (Heaman et al. 2003).

One of the most compelling cases for a temporal link between mantle plume hotspot tracks and the formation of kimberlite magmas is the magmatic record along the Great Meteor hotspot track. This is one of the longest-lived (>230 My) and oldest known hotspot tracks on Earth. It extends for >5,800 km from the northern Atlantic Ocean to Rankin Inlet (Nunavut, Canada) (Fig. 4) and is of similar scale to the ~6,000 km long Hawaii–Emperor volcanic chain in the Pacific Ocean. Magmatism along the continental portion of the Great Meteor hotspot track spans >120 My and includes kimberlites that follow a SE-younging trend.
age progression (Heaman and Kjarsgaard 2000) (Fig. 4). Kimberlite magmatism (~230–120 Ma) dominates the NW portion of the track where the continental lithosphere is thickest, and includes kimberlite fields in Nunavut (Rankin Inlet), Ontario/Quebec (Attawapiskat, Kirkland Lake, Temiskaming) and Upper New York State (Heaman and Kjarsgaard 2000). The southeast segment of the track preserves ~140–110 Ma alkaline-metamorphic Montereign Hills and White Mountains (Quebec, Canada; Vermont and New Hampshire, USA). There is still controversy about the exact location of the Great Meteor track in North America and whether two mantle plumes (Great Meteor and Verde tracks) passed through this corridor in a relatively short time frame. Future high-precision kimberlite geochronology studies of undated kimberlites along the various proposed hot spot tracks will be critical to resolving the link between mantle plumes and kimberlite genesis.

ACKNOWLEDGMENTS

We thank Bruce Kjarsgaard for sharing the original diagram used to construct Figure 4. We also want to thank Andrea Giuliani, Bruce Kjarsgaard, Jan Kramers, and Fu-Yuan Wu for their thoughtful reviews and Jon Blundy for his editorial prowess.

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Kimberlite rocks and deposits are the eruption products of volatile-rich, silica-poor ultrabasic magmas that originate as small-degree mantle melts at depths in excess of 200 km. Many kimberlites are emplaced as subsurface cylindrical-to-conical pipes and associated sills and dykes. Surficial volcanic deposits of kimberlite are rare. Although kimberlite magmas have distinctive chemical and physical properties, their eruption styles, intensities and durations are similar to conventional volcanoes. Rates of magma ascent and transport through the cratonic lithosphere are informed by mantle cargo entrained by kimberlite, by the geometries of kimberlite dykes exposed in diamond mines, and by laboratory-based studies of dyke mechanics. Outstanding questions concern the mechanisms that trigger and control the rates of kimberlite magmatism.

**Keywords:** kimberlite, volcanology, transport, dykes, eruption, xenolith, ascent

### INTRODUCTION

Kimberlite magmas have the deepest origins of all terrestrial magmas (>200 km). They transport substantial loads (>25 vol%) of dense mantle-derived rocks and minerals, including diamond, through the mantle lithosphere to the Earth’s surface. Ascent rates estimated from entrainment of large (radii >10 cm) mantle xenoliths, preservation of mantle temperatures in xenoliths, dehydration rims on olivine xenocrysts, dissolution rates of mantle minerals, and combustion or graphitization rates of diamond are as fast or faster (~1 to 10 s m⁻¹) than those ascribed to other mantle-derived magmas (e.g., Eggler 1989; Sparks 2013). Total transit times through ~150–200 km of relatively cool cratonic mantle lithosphere are estimated at <10 h to ~2 days. Rise rates could be lower if kimberlite magmas are assumed to have significant yield strength. However, to entrain the deepest-seated peridotite xenoliths and suppress the settling out of 10–20 cm xenoliths requires that the initial melts must have high-to-unrealistic yield strengths (1,000–2,000 Pa) (Spera 1984).

There have been no historic eruptions of kimberlite volcanoes to constrain the styles, intensities and durations of eruption. Much of our understanding derives from studies of kimberlite deposits preserved in subsurface bodies (Fig. 1) for which diamond mining operations have contributed a unique and critical body of knowledge (Cas et al. 2008; Field et al. 2008). Remnants of the original volcanoes and surficial kimberlite deposits are less common but, where preserved (e.g., Fort à la Corne in Canada; Igwisi Hills volcanoes in Tanzania), they directly inform on kimberlite volcanic landforms and the nature of the intra- and extracrater deposits.

Here, we provide a summary of emerging ideas concerning the transport, ascent, and eruption of kimberlite magma. We begin with near-surface processes, for which we have abundant geological observations, and move deeper to where data becomes scarcer.

### KIMBERLITE MELT AND MAGMA

Kimberlite is a rock type found at and near the Earth’s surface and is defined on the basis of mineralogy and texture, including the abundance (~15–40 vol%) of mantle-derived xenoliths and xenocrysts (Mitchell et al. 2019 this issue). The nature and composition of the primary kimberlite melts entering the cratonic mantle lithosphere (i.e., *proto-kimberlite*) are obscured by the entrainment of, and chemical interaction with, these large volumes of xenolithic material. Kimberlite magmas are particularly complicated because their componentry, character, and properties may be highly transient and evolve during ascent. Furthermore, the ultrabasic composition and age of kimberlites make them susceptible to post-emplacement alteration (i.e., serpentinization) and textural modification that will involve a loss of primary pore space (Cas et al. 2008; Field et al. 2008; Brown et al. 2012).

Melt compositions estimated from kimberlites that reached the Earth’s surface or the shallow crust are SiO₂-poor, MgO-rich, and are thought to be volatile-rich, being dominated by CO₂ (<15 wt%) with subordinate H₂O (e.g., Price et al. 2000; Sparks et al. 2006). Calculations and experiments suggest densities of 2,600–3,000 kg m⁻³ and viscosities between 0.1 Pa s and 3 Pa s at mantle conditions. However, primary melt entering the base of the cratonic mantle lithosphere may well be more carbonatitic (10–17 wt% SiO₂) and evolve chemically, during ascent, to erupt as “kimberlite”. The properties of the proto-kimberlite melt are, therefore, likely to be different. Work by Dobson et al. (1996) on synthetic Ca–Mg-carbonate melts between 1,350°C and 1,600°C and ~5 GPa indicates that...
proto-kimberlite melts could be 5–10% less dense (2,300–2,800 kg·m⁻³) and 100 times less viscous (6–36 × 10⁻³ Pa·s) than values estimated for erupted kimberlite.

KIMBERLITE VOLCANOES

The classic composite model for kimberlite volcanoes comprises crater, pipe (e.g., diatreme) and shallow seated (hypabyssal) intrusive bodies. However, individual kimberlites are diverse, ranging in geometry from champagne glass–shaped craters (e.g., Fort à la Corne field) to deeply excavated narrow pipes (e.g., Lac de Gras field). These differences in geometry correlate with host-rock geology, eruptive environment, as well as present-day erosion levels (Field and Scott Smith 1999; Field et al. 2008).

Kimberlite Crater and Surficial Deposits

Remnants of kimberlite volcanoes preserve deposits of pyroclastic fallout, pyroclastic density currents, re-sedimented kimberlite, and lavas at Fort à la Corne (Pitari et al. 2008; Leebvre and Kurszlaukis 2008; Scott Smith 2008) or the Igwisi Hills volcanoes (Brown et al. 2012). These occurrences suggest a diversity of eruption environments (subaerial vs. subaqueous), styles (explosive vs. effusive), and types of explosivity (maggmatic vs. phreatomagmatic). They also testify to the range of processes that fill the craters and the pipes.

The Fort à la Corne kimberlite field comprises >70 bodies of volcaniclastic kimberlite hosted within non-volcanic sedimentary rocks. The Fort à la Corne kimberlites erupted explosively from low-to-negative surface relief vents through weak sedimentary host rocks and into a marine setting, forming diverse pyroclastic and volcaniclastic extra-crater and crater-filling deposits. The environmental setting suggests explosive eruptions controlled by shallow phreatomagmatic fragmentation (e.g., Lorenz 1975) which, when combined with the weak surface rocks, favored the formation of wide, near-surface craters and inhibited the excavation of deep vertical pipes (Field and Scott Smith 1999).

The Igwisi Hills volcanoes in Tanzania are the youngest known kimberlites (~10 ka) (Brown et al. 2012). Three vents with low-relief pyroclastic cones (Fig. 1A), craters and extra-crater lavas are preserved and provide unique insights into kimberlite eruption dynamics. The volume of surficial pyroclastic deposits and lava is ~3.5 × 10⁶ m³. The deposits comprise layered fallout of juvenile pyroclasts that can be either scoriaceous or dense. The reconstructed three-stage eruption process is possibly as follows: 1) an initial phase of explosive crater and conduit excavation, as recorded by lithic clast-bearing tuffs; 2) pyroclastic cone formation from a mildly explosive, unsteady, Strombolian eruption; 3) a late-stage effusion to form a lava lake and small volumes of dense to poorly vesicular, viscous, extra-crater lavas (Fig. 1A). The explosive eruptions spanned days to several months; the effusive phase hours to days. This is a common type of eruptive sequence and duration and has been observed at many monogenetic basaltic volcanoes.

Kimberlite Pipe Infill

Many kimberlite deposits occur in deep, subsurface pipes, or diatremes, that feature steep (75° to vertical), smooth, striated walls (Cas et al. 2008) and “root zones” of associated sills and dykes (Fig. 1B). These pipes are the remnant conduits and feeders to subaerial kimberlitic volcanoes (Field and Scott Smith 1999; Field et al. 2008). Contacts between conduit wall rocks and infilling deposits are characteristically sharp, and contacts between units can be near vertical to horizontal (Fig. 1B). Aided by the lithofacies concept, within-pipe deposits are defined by distinctive geological, structural and textural features, such as bedding, grain size, clast lithology and sorting (see Cas et al. 2008). In some instances, deposits within pipes can derive from later or synchronous eruptions of neighboring volcanoes, e.g., the Lac de Gras field (Moss et al. 2008).

The complexity within kimberlite pipes reflects multistage eruptions. Most kimberlite deposits can be divided into two types: volcaniclastic or coherent (Sparks et al. 2006; Cas et al. 2008; Sparks 2013). Volcaniclastic kimberlite can be in the form of massive volcaniclastic kimberlite or variably layered volcaniclastic kimberlite, and include apparently coherent kimberlite deposits (Fig. 1B). The apparently coherent kimberlite–type deposits have pyroclastic origins but form dense and coherent deposits (e.g., Brown et al. 2008), including clastogenic lavas (e.g., the Victor kimberlite in Canada) and welded pyroclastic kimberlite (e.g., Muskox and Jericho kimberlites of Canada), both of which are indicative of relatively high emplacement temperatures of 700–950°C (Pell et al. 2018).

Intrusive Kimberlite Deposits

Coherent kimberlite mainly occurs as shallow intrusive dykes and sills (i.e., hypabyssal kimberlite) either in the root zone of pipes or as late intrusions into the pipe infill (Fig. 1B). Some root zones to kimberlite pipes feature irregular vertical lobes of intrusive kimberlite that have no apparent connection to the surface. These “blind” intrusions (Field and Scott Smith 1999; Field et al. 2008) comprise coherent or volcaniclastic (breccia) kimberlite and are usually connected laterally to the main kimberlite body. They commonly contain xenoliths of local wall rocks and have textures and mineralogy that suggest emplacement from volatile-rich magma. One possibility is that such blind
Recent studies of the Kelvin and Faraday kimberlites (Canada) describe complexly interlayered, xenolith-rich, coherent and volcaniclastic kimberlite within shallow-dipping tubular-shaped dykes (Barnett et al. 2018). These enigmatic bodies (or “chonoliths”) raise mechanical issues because their shapes do not reflect intrusion accommodated by elastic deformation of wall rocks. Instead, their geometry suggests removal of host rock to create space thereby allowing flow and replacement by kimberlite (be it coherent or volcaniclastic). Although it is unclear whether these are part of an “open” volcanic feeder system or are “closed” blind intrusions, the xenolith-rich volcaniclastic deposits clearly suggest explosive magmatic fragmentation.

RECONSTRUCTING KIMBERLITE ERUPTIONS

Reconstructing eruption history, style and duration is relatively straightforward when the kimberlite volcano and its deposits are preserved, such as at Fort à la Corne or the Igwisi Hills volcanoes. It is a challenge to do so when the volcano and its crater facies deposits have been removed (e.g., Lac de Gras field) (Fig. 1B).

The A418 pipe (Northwest Territories, Canada) illustrates the approach required to reconstruct kimberlite eruption history solely from subsurface pipe deposits (i.e., volcanic conduits) (Cas et al. 2008). At the present-day surface, estimated to be ~50–200 m below the original surface, A418 has a diameter of ~125 m (Porritt et al. 2013). The cylindrical pipe tapers down to ~50 m in diameter at ~600 m depth (Fig. 1B) before transitioning to a root zone of narrow dykes. Pipe formation involved fragmentation and excavation of near-surface wall rocks driven by explosive release of magmatic volatiles and, sometimes, augmented by explosive interactions with ground water (Lorenz 1975; Sparks 2013). The volume of excavated crustal wall rock at A418 is ~6–8 × 10^6 m^3. Unlike the Igwisi Hills volcanoes, there are no deposits that record the pipe excavation phase of eruption. However, conservative estimates based on entrainment of ~5–10 vol% wall rock lithics suggest a highly energetic eruption of 0.1–0.2 km^3 (dense-rock equivalent) of kimberlite. Assuming a range of sustained, steady exit-velocities of 100–400 m s^-1, capable of ejecting lithics ~7–10 cm in diameter, and a minimum initial pipe diameter (D ~10 m), the pipe excavation phase would last a minimum of ~2.5–36 h for a gas-charged (~70–90 vol%) eruptive flux. Post-pipe excavation eruptive activity is represented by the deposits that infill the excavated subsurface pipe (Fig. 1B). These suggest a less energetic pulsatory, phreatic/magmatic phase of eruption, expressed by repeated sequences of inwardly dipping, finely bedded pyroclastic surge deposits containing abundant accretionary lapilli (Lorenz 1975; Porritt et al. 2013). The last phase of activity involved intrusion of coherent kimberlite into unconsolidated pipe infill (Fig. 1B).

TRANSPORT OF MANTLE CARGO

One of the defining characteristics of kimberlite is the high proportion of entrained and transported mantle-derived material (e.g., peridotite, eclogite) that represents sampling of the entire (i.e., ~150–200 km) cratonic mantle lithosphere. Xenoliths are typically 1–25 cm but can be ~1 m in diameter (Figs. 2A). Xenocrysts from disaggregated xenoliths (Figs. 2C–D) are dominated by olivine but include clinopyroxene, garnet and ilmenite. Notably, xenocrystic orthopyroxene is rare relative to its abundance in peridotite xenoliths (~7–10 cm in diameter, and a minimum initial pipe face pipe (~1 m in diameter (Lorenz 1975; Porritt et al. 2013). The cylin-drical pipe tapers down to ~50 m in diameter at ~600 m depth (Fig. 1B) before transitioning to a root zone of narrow dykes. Pipe formation involved fragmentation and excavation of near-surface wall rocks driven by explosive release of magmatic volatiles and, sometimes, augmented by explosive interactions with ground water (Lorenz 1975; Sparks 2013). The volume of excavated crustal wall rock at A418 is ~6–8 × 10^6 m^3. Unlike the Igwisi Hills volcanoes, there are no deposits that record the pipe excavation phase of eruption. However, conservative estimates based on entrainment of ~5–10 vol% wall rock lithics suggest a highly energetic eruption of 0.1–0.2 km^3 (dense-rock equivalent) of kimberlite. Assuming a range of sustained, steady exit-velocities of 100–400 m s^-1, capable of ejecting lithics ~7–10 cm in diameter, and a minimum initial pipe diameter (D ~10 m), the pipe excavation phase would last a minimum of ~2.5–36 h for a gas-charged (~70–90 vol%) eruptive flux. Post-pipe excavation eruptive activity is represented by the deposits that infill the excavated subsurface pipe (Fig. 1B). These suggest a less energetic pulsatory, phreatic/magmatic phase of eruption, expressed by repeated sequences of inwardly dipping, finely bedded pyroclastic surge deposits containing abundant accretionary lapilli (Lorenz 1975; Porritt et al. 2013). The last phase of activity involved intrusion of coherent kimberlite into unconsolidated pipe infill (Fig. 1B).

ASSIMILATION AND BUOYANCY

Rapid ascent of kimberlite requires substantial buoyancy and magma overpressure but is hindered by entrainment of large volumes of dense mantle material. Most models for kimberlite ascent invoke an exsolved CO_2–H_2O fluid phase to reduce the magma’s bulk density. Brey and Ryabchikov (1994), for example, suggested a pressure-induced drop in CO_2 solubility at depths corresponding to ~4–5 GPa driving buoyancy-enhancing exsolution of CO_2 fluid within the “diamond window”. Russell et al. (2012) proposed a new “chemical” mechanism for continuous and spontaneous exsolution of CO_2 fluid to support rapid ascent (Fig. 3). They argue that the proto-kimberlite magma entering the base of the cratonic mantle lithosphere was more carbonatitic in composition (see Kamenetsky 2016). The proto-kimberlite assimilates silicate minerals liberated from xenoliths, so causing SiO_2-enrichment of the melt that, in turn, decreases CO_2 solubility, thereby resulting in spontaneous CO_2 exsolution (Figs. 3A) (Russell et al. 2012). The “missing” orthopyroxene (see above) is ascribed to its preferential and rapid assimilation relative to other mantle phases (Fig. 2C). Fueled by exsolution and an increase in buoyancy, the magma accelerates upward for as long as the volatiles remain coupled to the melt. Assimilation ultimately produces a “kimberlite” melt that attains olivine saturation in the shallow mantle and crust (Figs. 3A, 3C), resulting in the crystallization of...
olivine microphenocrysts and in olivine overgrowths on partially resorbed xenocrysts (Fig. 2D) (Brett et al. 2015; Mitchell et al. 2019 this issue). Additional evidence for early and sustained dissolution of mantle silicates is expressed by the irregular, embayed anhedral shapes preserved in cores to many olivine xenocrysts (Fig. 2D).

The Russell et al. (2012) model postulates early, deep-seated exsolution of CO₂-rich fluids long before any significant decrease in lithostatic pressure occurs: potentially, as soon as proto-kimberlite enters the lithosphere (~6 GPa) (Fig. 3A-C). Recently, this hypothesis was tested experimentally, constraining the assimilation-induced exsolution event to ≤3.5 GPa, coincident with the top of the “diamond window” (Stone and Luth 2016). Given the entrainment of material from the deepest part of the cratonic mantle lithosphere (i.e., 150–210 km, or 5–7 GPa), this pressure limit suggests an, as yet, unidentified, deeper buoyancy mechanism, possibly involving very low-density, carbonatitic proto-kimberlite melts.

**KIMBERLITE TRANSPORT IN DYKES**

Magma is transported from source to surface via fractures (dykes) to feed volcanic eruptions. Exposures of kimberlite dykes and sills are typically at depths of 1 km to 3 km and observations on 2-D and 3-D sections show dykes to be segmented, en echelon, and typically thin (~0.6 m) with tapered margins (Kavanagh 2018).

**Dyke Mechanics**

The dynamics of dyke propagation can be described by theory for a fluid-filled fracture intruding an elastic material. This theory constrains the overall 3-D geometry of kimberlite dykes and identifies the specific conditions for dyke-fed kimberlite eruptions. The main driver for dyke ascent is magma buoyancy, which at 300 MPa is particularly large for kimberlite dykes. Initially, the dyke has a penny-shape and is elliptical in cross-section, but this quickly narrows in width and develops a tear-drop cross-section during ascent (see Fig. 4) due to the large and increasing density contrast between the magma and its surroundings during ascent.

The overall volume of a 150 km long, 1 m thick and ~400 m wide dyke would be ~5 × 10⁷ m³, which is ~10 times larger than the volume of material erupted by the Igwisi Hills volcanoes but 5–10 times smaller than that erupted by A418 (see above). However, the erupted kimberlite deposits represent only those magmas that have the favorable properties necessary to reach the shallow crust (<5 km depth): >80% of dykes never erupt (Kavanagh 2018).

**Dyke Damage Zone and the Volatile-Rich Tip**

The propagation pathway of dykes is strongly influenced by the ambient stress field and by the mechanical heterogeneities in the host rock. Stress concentrations at the tip and between dyke segments produce a “damage zone” as the walls are pushed apart by magma overpressure (Fig. 4). The damage zone comprises a series of closely spaced dyke-parallel fractures and breccia between segments, envelopes the full dyke geometry, and is the main source of the entrained xenoliths (Fig. 4).

The dyke tip region is expected to feature a narrow, low-density volatile-filled pocket (Fig. 4). The volatiles can be coupled to the magma or may separate and ascend ahead of the dyke causing chemical conditioning and weakening of wall rocks (i.e., fenitization) and potential precursory volatile-rich phreatic eruptions (McCallum 1976). Alternatively, such degassing may raise the effective liquidus temperature, thereby inducing crystallization, increased magma viscosity and, ultimately, dyke arrest.

**Figure 3** Schematic hypothesis that kimberlite ascent is driven by assimilation-fuelled buoyancy. (A) Compositional evolution of proto-kimberlitic (i.e. carbonatitic) melts driven by assimilation of mantle silicate minerals and driving a chemically induced exsolution of CO₂. Carbonatitic melts (~10–17 wt% SiO₂) assimilate orthopyroxene (Opx) preferentially and are enriched in SiO₂ to become kimberlite and, ultimately, reach olivine saturation. Increasing SiO₂ content also causes a concomitant drop in CO₂ solubility (see inset B) causing exsolution of CO₂-dominated fluid and increasing magma buoyancy. (B) Compositional and pressure dependence of CO₂ solubility across the carbonate–silicate transition; changes in melt composition driven by silicate assimilation can cause a marked drop on CO₂ solubility. (C) Kimberlite evolution as a function of transport from the asthenospheric source, through the cratonic mantle lithosphere (CML), and crossing the graphite–diamond transition (D-G) zone before entering the crust (left panel). Dykes of carbonate-rich parent melt enter the CML and both sample and entrain mantle xenoliths which disaggregate to release xenocrystic minerals which are variably assimilated causing exsolution and, ultimately, olivine crystallization (center panel). The evolution of SiO₂ and CO₂ content (right panel) as a function of transport distance. Exsolution of CO₂ is initially chemical driven (i.e. assimilation) but then driven by decreasing pressure. Initially, Opx and olivine are assimilated, but continued SiO₂ enrichment allows for late-stage crystallization of olivine.

**Dyke Velocity and Eruption Dynamics**

The velocity of magma within rising dykes varies spatially and temporally (Fig. 4) and is highest in the central part of a dyke (Kavanagh et al. 2018). Low-viscosity magmas, such as kimberlite, develop a high-velocity magma “jet” within the dyke which can preferentially transport mantle xenoliths and enhance mixing. Moreover, turbulent flow...
in the volatile-filled head of the dyke provides an environment for efficient pre-eruption milling of xenoliths and xenocrysts (Fig. 2) (Brett et al. 2015; Jones et al. 2019). Competition between turbulence and particle settling ultimately dictates whether dense mantle cargo is entrained or sedimented in the dyke (Fig. 4).

Following Sparks et al. (2006), and using proto-kimberlite properties introduced above, we calculated a characteristic turbulent magma velocity of ~20–90 m·s⁻¹. This suggests that a minimum discharge rate from a 1 m thick and ~400 m wide dyke is on the order of ~10,000 m³·s⁻¹, which is typical of Strombolian to sub-Plinian explosive intensities (comparable to the 1980 eruption of Mount St. Helens, USA) and consistent with inferences from kimberlite deposits. The onset of dyke eruption will be from a short fissure that, due to the penny-shaped 3-D dyke geometry, is much narrower than the dyke in the sub-surface. As the dyke erupts, the source may become depressurized and unstable, potentially inducing further magma ascent via new or existing dykes. The pressure release upon eruption causes elastic recovery of the host rock, closing up the kimberlite dyke from depth to the surface.

At the surface, many kimberlite volcanoes or pipes are associated with precursor dykes, as seen for the Igwisi Hills volcanoes (Brown 2012), the Lac de Gras field (Moss et al. 2008) or the Jericho kimberlite (Price et al. 2002). This type of dyke occurrence suggests that dyke transport of kimberlite magma continues almost to the Earth’s surface. The initial dyke-fed eruptions appear to become rapidly localized (e.g., Jones et al. 2017), thereby focusing the main eruptive flux and forming point-source volcanoes and pipes. Localization can cause a massive change in eruption velocity (for a constant flux) that, under the right conditions (e.g., deep fragmentation, crystalline wall rocks), facilitates the excavation of deep vertical pipes. The excavation of kimberlite pipes, as in other volcanic conduits, is driven by large pressure fluctuations during explosive flow (Costa et al. 2009). Large overpressures can be caused by volatile exsolution or the heating of groundwater and provide a means of excavating near-surface craters and also contribute to pipe deepening. Conversely, large underpressures will likely develop as fragmentation levels deepen, thereby creating conditions for tensile wall-rock failures and conduit widening (Sparks 2013).

**KIMBERLITE PRODUCTION AND ASCENT TRIGGERING**

Kimberlites represent monogenetic volcanic fields and show clustering in both space and time. Kimberlite volcanoes are typically widely distributed on a craton-scale, but also show strong spatial clustering with localized concentrations and elongate footprints at scales of tens of kilometers, suggesting control by either basal lithosphere topography or major lithospheric structures. Temporal clustering has been recognized in all kimberlite provinces (Heaman et al. 2019 this issue). Individual pulses of kimberlite volcanism that span between 10 My and 20 My are common, and periods without kimberlite volcanism can have durations >100 My. Some kimberlite data suggest hot spot trails lasting many tens of millions of years. Minimum rates of kimberlite eruption assessed from geochronology data and from mapping of vents and dykes vary from 1 event per 0.3 My (southern Africa and the Lac de Gras field) to 1 event per 0.08 My (Fort à la Corne, which has 169 bodies emplaced over 13 My). These observations suggest that kimberlite melts can be generated on a craton scale (~1,000 km) at the base of the lithosphere but that individual melt sources have a scale of 10 km to 100 km. Conditions for melt ascent develop over time periods of ~100 ky. We have applied models of melt segregation and accumulation to the consideration of kimberlite production wherein a melt-rich layer segregated from the more permeable asthenosphere accumulates at the base of the lithosphere. This melt layer is buoyant relative to the overlying lithosphere and so is unstable (i.e. Rayleigh–Taylor instabilities develop); instabilities grow with a characteristic timescale that depends on the ratio of the mantle lithosphere viscosity, the buoyancy of the melt, and the width of the melt layer (Seropian et al. 2018). As the instability grows, the pressure difference and strain rate in tension in the mantle at the melt–mantle boundary increases, causing conditions for dyke nucleation and propagation to develop. The potential melt volume will depend on layer width and melt layer growth rate as supplied by porous melt flow in the asthenosphere. Our model results indicate that timescales of episodic kimberlite ascent for layers with widths of 300 m and 30 km are in the range 6 × 10⁵ to 6 × 10⁷ years, respectively. Melt accumulation rates (h) of 10⁻⁵ m·yr⁻¹, taken as representative of asthenospheric melt segregation, imply a corresponding thicknesses (h) of 0.68 m and 6.8 m and accumulated melt volumes of 48 km³ and 4.8 km³ at these times. These calculations give timescales consistent with observations, but volumes are typically larger by at least an order of magnitude more than the volumes of individual kimberlites (3.5 × 10⁻³ to 1 km³). The latter discrepancy might be explained if much of the kimberlite magma stalls to form intrusions within the overlying mantle lithosphere rather than successfully ascending to erupt. More generally,
the difference between the calculated magma volumes versus the field observation volumes reflects uncertainties in the choice of model parameters and the conditions for dyke initiation.

SUMMARY
The styles, intensities, and durations of all volcanic eruptions reflect the chemical and physical properties of the magmas. Kimberlite eruptions are diverse and span most of the styles observed for other conventional magmas. The morphology, composition and properties of kimberlite magmas are transient and evolve during ascent. In essence, the properties of the kimberlite magmas that erupt are inherited during their upward transport (via a dyke mechanism) by processes such as xenolith entrainment, fluid exsolution, mineral assimilation and crystallization. However, the relative timings of these competing processes remain unresolved.

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Brown RJ and 7 coauthors (2012) Kimberlite magmas erupt explosively, indicating the presence of a high-volume fraction of exsolved magmatic fluids. Erupted kimberlite deposits also contain abundant, and often large (>0.5 m), dense xenoliths from the deep mantle. These observations raise important unresolved questions concerning the extent and mechanisms of coupling between the kimberlite melt, mantle xenoliths and large volumes of low-density CO₂-dominated fluids released during dyke ascent. The unresolved question of “Where does fluid exsolution start?” is critical for understanding kimberlite buoyancy and ascent rates.

ACKNOWLEDGMENTS
We thank Rich Brown and an anonymous referee for critical reviews. We also greatly benefitted from discussions with Mathew Field. Support derives from NSERC (JKR), Leverhulme Emeritus Fellowships (RSJS), and the Royal Society (JLK).
Kimberlites are the main source of natural gem-quality diamonds. The intrepid diamond explorer faces three major problems. First, finding a small, usually less than 300 m diameter, Kimberlite, which is often highly weathered. Second, evaluating the quantity of diamonds within a kimberlite that often consists of multiple phases of intrusive and extrusive Kimberlite, each with potentially different diamond grades. Third, evaluating the rough diamonds, the value of which is dependent on carat-weight, shape, colour, and clarity. Modern advances in mantle petrology, geophysics, geochemistry, geomorphology, and geostatistics now complement historical exploration knowledge and aid in selecting prospective target areas, resource estimation, and evaluating Kimberlite-hosted diamond deposits.

Keywords: Kimberlite, diamond, exploration, resource evaluation

INTRODUCTION
Diamond is the hardest known mineral of strategic importance. It is the undisputed “king” of the gem industry (Harlow and Davies 2005). Diamonds are sourced from Kimberlites and, to a much lesser extent, from olivine lamproites and from alluvial deposits derived from these source rocks. Kimberlites are the primary source of these gemstones and provide the majority of the world’s natural diamond production. The scientific importance of diamonds and their inclusions, with respect to understanding the Earth’s mantle, has played an important role in enhancing diamond exploration. Diamond mining provides the samples that advance mantle petrology, which in turn leads to improved diamond exploration. It is a rewarding and integrated spiral of increasing knowledge that was largely sparked in the early 1970s by the vision and leadership of the late John Barry Hawthorne, Chief Geologist in Kimberley for De Beers (see Mitchell et al. 2004 for further details).

Key geological observations from South African alluvial diamond deposits provided the original basis for diamond exploration. In these deposits, the relationship between diamond and other hard, high-density minerals, such as Cr-pyrope garnet, was noted in the 1860s. Subsequently, these “indicator” minerals were found to be associated with diamonds in the Dutoitspan and Bultfontein Kimberlites (Kimberley area, South Africa), discovered in late 1869 (Janse 1995). Modern diamond exploration tactics to find Kimberlite still incorporate the indicator mineral concept (Muggeridge 1995). Until the 1950s, all diamondiferous Kimberlites of economic interest were known from Africa (South Africa, Sierra Leone, Tanzania, Democratic Republic of Congo), and prospecting relied on the detection of indicator minerals observed in stream sediment and soil samples. In the mid-1960s, geophysics was first used successfully in Botswana (de Wit 2018): the contrasting petrophysical properties of volcaniclastic and hypabyssal Kimberlites with the host rocks provided a vital new exploration tool. Indicator mineral and geophysical exploration methods have since been deployed in all continents (except Antarctica), leading to the discovery of Kimberlites in Russia, Australia, India, China, North and South America, Finland, and new discoveries in Africa itself.

EXPLORING FOR KIMBERLITE-HOSTED DIAMOND DEPOSITS
How does one find a Kimberlite-hosted diamond deposit? To start, prospective areas need to be identified. A global map of known cratonic blocks with the main Kimberlite fields superimposed (see Fig. 3 in Giuliani and Pearson 2019 this issue) reveals the first and most basic exploration tool: a 1:1 correlation between Kimberlite-hosted diamond mines and Precambrian cratons. The correlation stems from the thick and cool lithospheric mantle root of cratons where diamonds form and are preserved (see Fig. 2 in Giuliani and Pearson 2019 this issue). This correlation was the basis for the discovery of Kimberlites in Russia in 1954, following on the 1930s concept by Vladimir Stepanovich Sobolev (1908–1982) that large tracts of Russia consisted of old cratonic blocks. Prospective areas with high diamond potential within cratonic regions are deduced by exploration targeting, which integrates regional geology, structure, tectonics, geophysics, topography, remote sensing and geomorphology data sets (Kaminsky et al. 1995; Gurney et al. 2005). More recently, mantle seismic models (Schaefer and Lebedev 2014) provide proxies for present-day lithospheric thickness. Once prospective areas have been identified, detection techniques such as regional indicator mineral sampling and/or geophysics are used to home in on potential Kimberlite targets. The initial objective of exploration is to determine whether Kimberlites are present, if they are diamondiferous, and their size and potential ore tonnage.
Kimberlite geology is the central thread running through diamond exploration, and herein lies the challenge for exploration geologists. Kimberlites do not form simple, monogenetic volcanoes: they form bodies having an exceptionally wide spectrum of shapes and sizes, consisting of multiple phases of intrusive and/or volcaniclastic kimberlites (Russell et al. 2019 this issue). Kimberlites range in size from thin 1–2 m wide dykes and sills, to pipes 50–1,000 m in diameter, with pipes being of primary economic interest due to their higher potential ore tonnage. From an exploration perspective, kimberlite size influences line spacing on any type of geophysical survey, the nature of the kimberlite rock being reflected in petrophysical properties. The size and geometry of any indicator-mineral or geochemical anomaly is not only a reflection of kimberlite body size and shape but also a reflection of the mantle load incorporated and preserved in each distinct kimberlite phase.

**Indicator Minerals: Tracers of Kimberlite and its Precious Diamond Cargo**

Diamonds, mantle xenoliths, and xenocrysts are sampled by the kimberlite magma en route from its deep source to the surface. Importantly, >90% of all diamonds recovered from kimberlites are sourced from the lithospheric mantle, with <10% derived from the asthenosphere, transition zone or lower mantle (Stachel et al. 2005). Based on diamondiferous mantle xenolith and diamond inclusion studies, two main lithospheric diamond parageneses are recognized: peridotite and eclogite. Mantle xenocryst minerals are more abundant than diamonds in kimberlite, hence they are termed “kimberlite indicator minerals” (Fig. 1).

Key kimberlite indicator minerals (KIMs) that belong to the peridotite paragenesis are Cr-spinel, Cr-diopside, Cr-pyrope and olivine (preserved in cold climates only); those for the mantle eclogite paragenesis are almandine–pyrope garnet and omphacite. Additional KIMs include the megacryst suite of minerals e.g., Mg-ilmenite (Fig. 1).

Kimberlite indicator minerals are used in exploration to vector from sediment samples back to their source kimberlite. Most kimberlites erupted tens to hundreds of millions of years ago (Heaman et al. 2019 this issue) and there have been significant changes to the landscape since their emplacement. Landmasses have been uplifted and eroded, been dissected by river drainages, and potentially subjected to multiple glaciations that have eroded and dispersed KIMs across the landscape. Sediment sampling with the objective of recovering KIMs requires a clear understanding of transport processes. In non-glaciated terrains, flat topography dictates the use of loaming (soil sampling), whereas alluvial sampling is applied where stream drainage networks are developed (Muggeridge 1995). In Zimbabwe, the Murowa kimberlites were discovered in 1998 using a combination of alluvial sampling and loaming techniques (Sims et al. 2018). Paleodrainage and cover geology are additional complications. For example, the Cretaceous Orapa kimberlite in Botswana was discovered by recognizing a significant post–Orapa age crustal upwarp and by tracing diamondiferous alluvial samples beyond the headwaters of the present-day drainage divide to their source (de Wit 2018). In glaciated terrains, esker, till, and alluvial sampling are utilized (Golubev 1995). The initial discovery of the Lac de Gras kimberlite field in Canada resulted from esker sampling (Kjaersgaard and Levinson 2002). In an ideal scenario for glaciated regions with a simple flow/transport history, vectoring from till samples back to source is straightforward (Fig. 1). However, sediment samples from glaciated regions characterized by thick overburden and having had complex ice flow/transport and glaciofluvial histories can be complicated to interpret. In such cases, sampling can be ineffective unless the basal till can be accessed by drilling.

Recovery of KIMs is undertaken by producing a heavy mineral concentrate, followed by hand sorting using stereomicroscopes. The distinctive visual characteristics of KIMs (Fig. 1) allows one to discriminate these from equivalent crustal-derived minerals. The mineral chemistry of KIMs is used to verify the visual identification and for paragenetic classification purposes (e.g., garnets of the eclogite, lherzolite and harzburgite parageneses). Further paragenetic refinement is based on compositions of minerals that coexist in diamonds in mantle xenoliths and that are recovered as inclusions in diamond (e.g., Sobolev et al. 1969; Gurney et al. 2005). Determining how kimberlite magmas sample the lithosphere is undertaken by defining pressure ($P$) and temperature ($T$) of KIM formation using thermobarometry. This was originally feasible using only mineral pairs in peridotite xenoliths. More recently, reliable single-grain Cr-diopside xenocryst thermobarometry (Nimis and Taylor 2000) is being used alongside numerical fitting techniques to determine the mantle “paleo-geotherm” at the time of kimberlite eruption (e.g., Mather et al. 2011).

Paleo-geotherm determination defines the thickness of the mantle lithosphere (Fig. 2). More important for diamond exploration is the intersection of the paleo-geotherm with the graphite–diamond transition curve, and with the
mantle adiabat. This constrains the lithospheric diamond stability field with depth (the “diamond window”) (Fig. 2). Trace element analysis on Cr-pyrope and olivine KIMs, coupled with the advent of single grain Ni-in-Cr-pyrope and Al-in-olivine thermometers is used to project the determined temperatures onto the paleogeotherm and establish the derivation depth of the peridotite xenocrysts (Fig. 2).

A simple count of the number of grains that reside within the diamond versus graphite stability fields (Fig. 2), coupled with the paragenetic classification for each grain, allows a first pass estimate of a kimberlite’s “diamond potential” (Sellar 2017). However, in a large field of kimberlites, kimberlite mantle sampling and paragenetic profiles can be highly variable and are often associated with equally variable diamond content e.g., the Orapa field (Botswana) (Preston et al. 2012). In summary, the xenocryst paragenetic and P–T techniques provide a first-order assessment of the mantle load and diamond potential such that drill targets can be identified and prioritized.

**Geophysics: Finding Needles in Haystacks**

Relative to most mineral deposit types, kimberlites are very small features (typically 10s to 100s m diameter) and have little or no alteration halo. As intraplate magmas, they are not genetically related to their host rocks, and have a very limited spatial and geological footprint. In areas with significant cover and/or intensive weathering, geophysical methods allow for direct detection of kimberlites. Geophysical detection of kimberlites is premised on their physical property (magnetic, resistivity or density) contrasts relative to their host rocks. Common geophysical tools used in exploration include airborne and ground magnetics, electromagnetics, and gravity surveys. The objective of these surveys is to generate “anomalies” that are then picked and prioritized for drilling. Anomaly selection is based on criteria such as size, shape, degree of isolation from other geologic signals, and their association with any other relevant geophysical signatures, such as remnant magnetization.

Significant advances in geophysical data acquisition and processing technology have resulted in a high proportion of the post-1990 kimberlite discoveries being made via airborne surveys, which allow for rapid target identification at low costs. An example is the discovery of the Diavik kimberlites, Lac de Gras field (Canada). The application of aeromagnetic surveys alone as a discovery tool can, however, be a challenge. Kimberlites are typically small, isolated, high frequency, short wavelength anomalies. Thus, in geologic backgrounds that exhibit a similar magnetic response, detection is problematic because the kimberlite targets are effectively masked. Conversely, false anomalies may be generated and interpreted as kimberlite. Cross-checking against detailed geological mapping, elimination of man-made signals using high-resolution imagery, and integrating the results from surficial KIMs and sediment geochemistry sampling can help resolve false anomalies. Nevertheless, some ambiguity can only be resolved by drill testing.

**Building a Picture of a Kimberlite Diamond Deposit**

Once kimberlites have been discovered, a 3-D model of each prospective kimberlite is required. The basis for such a model is drill-hole data combined with 3-D inversion of ground geophysical surveys (magnetics, electromagnetics, gravity, magnetotellurics). Any 3-D model must correctly differentiate the internal phases within a kimberlite pipe that may have formed over a time period of 20 My (Heaman et al. 2019 this issue). Diamond grades, size distributions and values can differ significantly between these internal phases in a kimberlite (Kjarsgaard 2007; Field et al. 2008). Application of quantitative componentry analysis is the basis for modern kimberlite drill-core logging: this involves determining the proportions and sizes of olivine grains, juvenile lapilli, KIMs, mantle and crustal xenoliths, coupled with measurements of density, magnetic susceptibility, and geochemistry (using a portable X-ray fluorescence spectrometer). A robust drill-core log is the basis for subsequent sampling for laboratory-based microdiamond, KIM, petrographic and geochemistry studies. Failure to correctly delineate internal kimberlite phases from core logging potentially results in “mixing” of samples across contacts, i.e., one might inadvertently mix different KIM populations, or mix moderate-grade diamond populations with low-grade diamond populations. This could lead to exploration failure.

The 3-D kimberlite geology model provides a basis for understanding how the deposit formed from a magmatic and volcanological perspective. Both phreatomagmatic and CO₂-driven magmatic degassing emplacement processes have been documented (Russell et al. 2019 this issue), but this topic is highly controversial. Notwithstanding, kimberlite magmas are fluids that contain particles, including diamonds, and, hence, emplacement processes are important for understanding diamond size distribution and concentration/dilution. Intrusive processes that can affect diamond distribution include flowage segregation and filter pressing (Kjarsgaard 2007), while volcanic eruption processes can enhance diamond grade and
size by sorting and fines depletion (Harvey et al. 2013). Incorporation of country rock clasts dilutes diamond grade, while sedimentary reworking processes can enhance it. Recent studies have used olivine macrocryst size distribution as a proxy for diamond distribution, on the basis of the comparable density between forsterite-rich olivine and diamond coupled with the high abundance of olivine in kimberlite (Field et al. 2009; Harvey et al. 2013).

**EVALUATION OF DIAMOND DEPOSITS**

Approximately 1,000 kimberlites contain sufficient macro-diamonds to be of economic interest (de Wit et al. 2016). However, only 61 of these 1,000 host active or past-producing kimberlite-hosted diamond mines. Even when present in quantities that are economically viable, the concentration (or “grade”) of diamond in kimberlite is extremely low. Diamond grade is defined as the number of carats per tonne (ct/t), with a carat comprising 0.2 g. The ore value of a diamond deposit depends on both the quantity and quality of diamonds present (Fig. 3). The grade of global economic diamond deposits ranges from 0.025–2.0 ct/t (0.005–0.4 ppm), and less commonly to 5 and rarely 10 ct/t (1–2 ppm). Furthermore, rough diamonds are particulate and individually unique, thus, their size, shape, quality and color can vary from one diamond to the next. Non-gem and near-worthless diamonds (bort) can also be collected along with large high-quality and valuable gem diamonds in the same sample. These features bring about unique challenges in resource evaluation (Kleingeld and Nicholas 2004).

Substantial parcels of diamonds are required to obtain a confident indication of value of the diamonds in a sample (defined in US$/ct) in order to understand a kimberlite’s economic potential. Kimberlites are often complex, multiphase bodies, which exacerbates the challenge of reliable deposit evaluation because each kimberlite phase must be assessed separately for diamond grade and value. Furthermore, diamonds are very brittle and, therefore, prone to breakage during exploration sampling and the commercial diamond recovery processes. Thus, measures need to be put in place to ensure that the diamonds are recovered as intact as possible to enable accurate assessment of their size, shape, quality and color. The methodologies for sampling and defining the grade and value of diamond deposits are, therefore, quite different to many other commodities (e.g., gold, copper, platinum or iron ore). Large high-tonnage and spatially well-distributed kimberlite samples are required in order to directly estimate diamond grade and value; such samples are expensive and often technically very challenging to obtain.

**Diamond Size Distribution: A Key Tool for Economic Evaluation**

Diamonds exist over a wide size range, from tens of microns to very rare stones up to several centimeters across. The diamond size distribution is highly positively skewed, hence, diamond size data require a log-transform for meaningful data analysis and interpretation. The size distribution is assessed by sieving the diamonds using standard sets of sieves and then measuring the number and mass of diamonds per sieve class. Graphical representation of diamond size distribution data is done using two key plots: a grade–size plot that represents diamonds size as well as concentration on a single plot, and a log probability plot (Figs. 4, 5) that is used to assess changes in diamond size distribution only. On a grade–size plot (Fig. 4), the height of the curve reflects diamond grade and the degree of curvature represents diamond size distribution: flatter curves indicate higher proportions of coarser diamonds, whereas steeper curves reflect higher proportions of smaller diamonds. A log probability plot (Fig. 5), which is often used in volcanology and sedimentology grain-size studies, applies the percentage weights of diamonds per sieve class plotted cumulatively on a normal probability scale (inverted). This plot defines the probability of a diamond exceeding a particular diameter (stone) size. The resultant curves provide an indication of the median diamond size, represented by the carat size coinciding with a probability value of 50% (Fig. 5), the variance of the diamond size distribution being reflected by the slope of the curve.

Multiple applications of diamond size distributions are used in exploration. One of the first questions to be answered is whether a kimberlite is diamond-bearing or not. Micro-diamonds (<0.5 mm in size, an arbitrary cut-off) lack commercial value, but form a continuum with macro-diamonds (>0.5 mm), and are used in both early and advanced evaluation (Stiefenhofer et al. 2016). At this stage, diamonds are recovered from 8–15 kg kimberlite samples by hydrofluoric acid, or caustic fusion digestion, a total recovery process akin to an assay. The size frequency distribution of recovered micro-diamond-bearing samples can be used to estimate macro-diamond grade, but only with extreme caution. If the kimberlite warrants additional sampling and macro-diamond recovery, then processing uses the unique physical characteristics of diamond (density, fluorescence, luminescence, atomic number) to separate the diamonds from the kimberlite. However, macro-diamonds may be lost or not recovered, and all material below a specified size (e.g., <1 mm diamonds) is discarded. For macro-diamonds, the diamond size distribution is used to improve grade estimates by correcting for erratic recovery of large diamonds, or for diamond breakage.
Additional relevance of diamond size distribution data include assessing ore value and potential revenue. For example, there is an exponential increase in value with diamond size (for equivalent shape, clarity and color), making the average size of diamond a critical indicator of overall potential value. A very high proportion of this value is derived from the extremely rare larger diamonds, which are inherently difficult to predict or estimate. At the Letseng Mine (extremely low grade, <0.03 ct/t in Lesotho), and the Karowe Mine (low grade, <0.13 ct/t) in Botswana, the ore value is driven by extremely high carat values from large and rare Type II (<10 ppm nitrogen) diamonds. At the opposite end of the size spectrum, decreasing the commercial (mining) bottom cut-off diamond size typically increases the grade but usually decreases diamond value. This trade-off can lead to a decrease or increase in the ore value.

**Early Stage Diamond Evaluation: Should this Kimberlite be Bulk Sampled?**

Given the very high costs of obtaining bulk samples for assessment of diamond grade and value, it is essential to be able to prioritize kimberlite discoveries and ascertain whether further evaluation is warranted. Early stage evaluation utilizes the kimberlite 3-D geology model, which incorporates KIMs and micro-diamond data, plus tonnage estimates for each individual phase. Remarkably, low micro-diamond counts, such as at the Victor Diamond Mine (Wood et al. 2013), do not always mean no, or low-grade macro-diamonds. Furthermore, some of the highest grades and ore values (Fig. 3) are associated with very small (<2.7 ha), low-tonnage kimberlites, such as the Diavik A154S and Internationallay kimberlites; this contrasts with very large kimberlites such as the Jwaneng (54 ha) and Orapa (118 ha) kimberlites in Botswana. Due to high exploration costs (e.g., a 10 kg caustic fusion analysis is $2,500–$5,000), the vast majority of kimberlites are subject only to early stage assessment, and never proceed to the advanced evaluation stage.

**Advanced Diamond Evaluation: Is this Kimberlite Deposit Economically Viable?**

The individually unique nature of diamonds—with carat-weight, shape, color, and clarity being independent of each other—makes resource estimation of kimberlite diamond deposits challenging. Diamonds from high-grade pipes can have low average value (e.g., Mbuji Mayi, Democratic Republic of Congo); conversely, low-grade pipes can have high average values (e.g., Letseng, Lesotho) (Fig. 3). These parameters, coupled with the low concentration of diamond and the importance of diamond size, all exert significant influence on resource estimation (Kleingeld 1987). Any sampling campaign in kimberlite must aim to recover enough diamonds to define the size frequency distribution as well as the spatial distribution of grades within each geological phase. The presence of only one or two high value diamonds can have a significant impact on valuation. Kimberlite bulk sampling for macro-diamonds is undertaken in a staged approach. The first stage is designed to obtain basic grade information and an initial indication of diamond size distribution and quality. This involves diamond recovery from several thousand tonnes of kimberlite, sampled via surface trenching, shallow pits, or large diameter drilling (Kleingeld and Nicholas 2004). Information from this stage is used to design more comprehensive follow-up sampling campaigns with the aim of generating a spatially representative suite of kimberlite samples, and substantially larger diamond parcels (>2,000 ct) to provide a basis for diamond value estimation.
continuous the mineralisation, the greater the complexity of the estimation process and the greater the chances of uncertainty introduced into the estimate (Kleingeld 1987). The application of these three factors is strongly influenced by the kimberlite geology (Nowicki 2014). For example, a massive volcaniclastic kimberlite pipe in-filling phase with an uncorrelated diamond size frequency distribution, and grade variation being largely controlled by variation in country rock dilution, could be considered a “simple” evaluation scenario. In contrast, bedded pyroclastic kimberlite deposits, or re-sedimented volcaniclastic kimberlite deposits, can have quite variable diamond grades and size frequency distributions, either in a systematic or a highly chaotic fashion. This is a much more challenging evaluation scenario and requires a larger dataset of more closely spaced samples (to obtain equivalent confidence levels in the estimate) than for the massive volcaniclastic kimberlite example.

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ACKNOWLEDGMENTS

The authors would like to thank Tom Nowicki (Mineral Services Canada) and Matthew Field (John Wood Group plc) for concise reviews and Graham Pearson, Andrea Giuliani and Jon Blundy for additional comments and editorial handling. Malcolm Thurston and Chris Gordon-Coker (De Beers MRM), Mike Seller, Chris Wallace, Julie Kong (De Beers Exploration Canada), and Rob Preston, Andrew Macdonald and Ingrid Chiu (De Beers South Africa) are thanked for internal reviews. Cristiana Mirece and Mike McCubbing (Saskatchewan Research Council) kindly provided the kimberlite indicator mineral image (Figure 1). Anetta Raths kindly provided the banner image of rough stones from the Diavik Diamond Mine, NT, Canada. Anglo American and the De Beers Group are thanked for permission to publish.
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Dennis Eberl and Colleen Hansel received the 2019 Clay Minerals Society (CMS) awards at the EuroClay 2019 conference, which was held 1–5 July 2019 in Paris (France).

Dr. Dennis D. Eberl has received the Marilyn and Sturges W. Bailey Distinguished Member Award. Dennis earned a BA in geology from Dartmouth College (New Hampshire, USA) in 1965 and a PhD in geochemistry from Case Western Reserve University (Ohio, USA) in 1971. He taught geology at the Northern Illinois University in DeKalb (USA) and at the University of Illinois at Urbana-Champaign (USA) before joining the National Research Program at the US Geological Survey in Colorado (USA) in 1981. He retired in 2011 and now divides his time between Colorado (USA) and Baja California Sur (Mexico). Dennis developed a variety of highly useful analytical computer programs during his career: these include quantitative mineral analysis by X-ray diffraction (XRD) (Rockjock program), the determination of sediment provenance from quantitative mineralogy (SedUnMix program), a theory to describe crystal growth mechanisms from the shapes of crystal size distributions (Galoper program), a method to measure crystallite size by XRD (MudMaster program), a method to calculate the precise chemistry of minerals in mixtures (HandLens program), and the calculation of XRD patterns for mixed-layer illite/smectite from an input of crystallite thickness distributions (StackMan program). These and other techniques were used in geological studies that included the quantitative mineralogy of the Yukon River system (North America), the quantitative soil mineralogy of North America from continental-scale transects, the mineralogy and provenance of North Atlantic bottom sediments, the investigation of antibacterial clays, the invention of a nonpolluting zeo-fertilizer, the mineralogy of hydrothermal illite from the San Juan Mountains (USA), the origin of spring deposits in the Amargosa Desert (USA), and the hydrothermal synthesis of clay minerals.

Dr. Colleen M. Hansel has received Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist Award. Colleen is an associate scientist in the Department of Marine Chemistry and Geochemistry at the Woods Hole Oceanographic Institution (WHOI) (Massachusetts, USA). Prior to joining the scientific staff at WHOI, Colleen was an associate professor at Harvard University (Massachusetts, USA), joint between the Department of Earth and Planetary Sciences and the School of Engineering and Applied Sciences. She obtained a BS in geology at California State University, Sacramento, in 1997, an MS in environmental chemistry at the University of Idaho (USA) in 1999, and PhD in biogeochemistry at Stanford University (California, USA) in 2004. Colleen was a postdoctoral investigator in molecular microbial ecology at Stanford from 2004 to 2006. Over the years, Colleen’s research has centered on the cycling and mineralization of metals within terrestrial and marine systems, using a range of microscopic and spectroscopic techniques. Most recently, Colleen’s research program has focused on coupled elemental cycles and cryptic processes that control the biogeochemistry and health of various marine ecosystems, ranging from coral reefs to the deep biosphere. One particular emphasis is the cycling and sources of reactive oxygen species and the impact of their formation on other elemental cycles and organismal health. To enable this research, Colleen has established a collaborative program to design and develop new in situ submersible sensing technologies to enable measurement of short-lived intermediates, such as reactive oxygen species, over various spatial scales.

Zachary Burton is a PhD candidate in the Department of Geological Sciences at Stanford University and a research assistant at the Search for Extra-Terrestrial Intelligence (SETI) Institute (USA) and the NASA Astrobiology Institute (USA). Zachary’s research with Dr. Stephan Graham at Stanford focuses on the marine geology of continental margins, while his work with Dr. Janice Bishop at SETI/NASA focuses on the analysis of clays, salts, and other sediments in the Antarctic Dry Valleys with the purpose of characterizing these materials as suitable analogues for materials formed and altered under the cold, dry conditions on Mars. He is thankful for the support provided by CMS to further his research on Antarctic clay minerals. In his free time, he writes poetry on innovative space science (“planetary poetry”), which has been featured in The Wall Street Journal.

Bidemi Fashina is a PhD student at the Soil Mineralogy Group in the Department of Soil and Crop Sciences, Texas A&M University. His research is two-fold. First, molecular-level understanding of the mechanisms of clay–organic interactions, having the long-term goal of developing functional clay-based materials that can serve as adsorbents for biotoxins and agricultural chemicals. Second, the description of structural defects in clay minerals to understand the influence of such defects on the properties and functionalities of clay minerals. He uses UV–visible spectrometry to screen the efficiency of clays as sorbents and a combination of X-ray diffraction (XRD), infrared spectroscopy, and molecular dynamics to understand the bonding mechanisms of a given clay–organic complex. He also applies Rietveld refinement analysis to describe the type and abundance of defects in clay minerals.

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CMS 57th Annual Meeting
Pacific NW National Laboratory, Discovery Hall, Richland, WA, USA 15–19 June 2020
Information can be found at http://www.clays.org/

Research and Travel Grant Deadline is 10 February 2020

The 10th biennial Reynolds Cup (2020) competition for quantitative mineral analysis is now open. Information at http://www.clays.org/Reynolds.html
The MAC awards travel and research grants to assist honors undergraduate and graduate students in the mineral sciences. For more information, see www.mineralogicalassociation.ca/. Deadline to apply: 15 January 2020.

Derek Leung is a Masters by Research (MScR) candidate at the University of Edinburgh (UK) under the supervision of Drs. Florian Fussels and Ian Butler. His research project, titled “Microscale Characterisation of Damage Evolution in Curling Stones used in International Competition” aims to understand the mineralogical and textural controls on damage to curling stones by using synchrotron microtomography, image analysis, and petrophysical testing of pristine and damaged curling stone samples. Curling stones only come from two locations in the world: the island of Ailsa Craig (Scotland) and Trefor Quarry (North Wales). Popular media suggest that the rocks from Ailsa Craig and Trefor are one-of-a-kind. But what makes these rocks so special? Laying the groundwork for his MScR project, Derek developed an integrated mineralogical and textural baseline of curling stones used in international-level competition. This research will develop physical criteria (e.g., morphology, color, inclusions, internal textures), and chemical criteria (e.g., major, minor, trace, isotopic) characteristics that will, hopefully, be useful in distinguishing porphyry-related tourmaline from other ore and non-ore environments.

STUDENT TRAVEL/RESEARCH GRANTS

UNDERGRADUATE AWARDS 2018–2019

The Mineralogical Association of Canada Undergraduate Student Awards are given annually to undergraduate students (2nd year of study or higher) at a recognized Canadian university or institute of higher education for excellence in one of the specialties supported by the society: mineralogy, crystallography, geochemistry, petrology, and mineral deposits. Congratulations to the following students who received this award in 2018–2019:

- Peter Baldazzi (Simon Fraser University)
- Alexandre Bénard-Gaudet (Université du Québec à Chicoutimi)
- Johnathan Clarke (University of Waterloo)
- Jayce D. Eadie (University of Alberta)
- Daniel Peter Ferguson (University of Regina)
- Blue Hunter-Moffatt (Carleton University)
- Mélanie King (McGill University)
- Joshua Labrie (Brock University)
- Megan K. Landman (Lakehead University)
- Benjamin A. Myrer (Dalhousie University)
- Deidre Renée Nelson Smith (UBC Okanagan)
- William Pagé (Université Laval)
- Iliajah A. Pidskalny (University of Saskatchewan)
- Taylor M. Robinson (University of Victoria)
- Hannah Sharpe (University of New Brunswick)
- Kayla Soini (Laurentian University)
- Alexis L. Trevors (St Francis Xavier University)
- Miguel M. Vaccaro (Acadia University)

IN MEMORY OF DONALD F. SANGSTER (1935–2018)

It is with great sadness that we report the passing of Dr. Donald F. Sangster on 28 December 2018, age 83. Don was a research scientist with the Geological Survey of Canada for 33 years whose career focused on the geology and genesis of lead-zinc deposits. He was president of the Society of Economic Geologists (SEG) in 1994–1995 and was a long-time MAC member. He was awarded the Duncan R. Derry Medal of the Geological Association of Canada (GAC) (1981), the Silver Medal of the SEG (1984), the Past-Presidents’ Medal of the MAC (1986), and the Logan Medal of the GAC (1998).

LATEST RELEASE IN OUR TOPICS IN MINERAL SCIENCES (Formerly Short Course Series)

Applied Isotope Geochemistry, Topics in Mineral Sciences, Volume 48

Short course delivered at the Research for Future Generations, June 2018, Vancouver (British Columbia, Canada)

EDITORS: Bruce Eglington, Mostafa Fayek and Kurt Kyser
SERIES EDITOR: Robert Raeside
ISSN 2561-6374

Isotope geochemistry is an integral part of the Earth sciences. This subdiscipline reveals the fourth dimension of our science (time), as well as revealing the processes involved in natural systems and the means by which to trace the flux of elements through the geosphere–hydroosphere–biosphere. As such, isotope geochemistry is built on a platform...
Cont’d from page 419

of pure and theoretical science, but is primarily an applied science that adds value to mineral exploration, environmental stewardship, whole Earth ecology, the timing and causes of evolution, paleoclimatic and even food authentication. This short course introduced to the greater geoscience community the utility of using isotopes to understand the processes that govern mass transport in the geosphere. This short course volume is dedicated to both radiogenic and stable isotope applications for the geosciences.

The concept of this book was envisioned by Professor Kurt Kyser (1951–2017), formerly of Queen’s University (Ontario, Canada). The volume begins with the application of isotopes to the exploration of volcanic massive sulfide deposits. The next three chapters focus on the application of radiogenic isotopes to mineral and fluid systems, and Chapter 5 introduces current approaches to data assessment, primarily for detrital zircon samples, and introduces some new approaches which aid in the simultaneous treatment of large sets of data. Chapter 6 applies noble gas isotopes to geothermal systems, and in Chapter 7 heavy metal isotopes are used to trace anthropogenic contaminants in the environment. The final chapter is about the application of clumped isotopes and their utility in obtaining information about paleo-environments. This volume does have some glaring omissions, however: there are no discussions on transition-metal isotopes or on the application of isotopes to understanding clay minerals and the hydrosphere. It is our hope that other researchers will be inspired by this work and that, as techniques continue to evolve, a complementary volume will be organized in the future.

Cont’d on page 421
**Regular Council Members**

**Sergey V. Alexeev** is currently Head of the Hydrogeology and Engineering Geology Department in the Institute of the Earth’s Crust (Irkutsk, Russia). He graduated from the Lomonosov Moscow State University (Russia) in 1981 and received his PhD in 1987. His thesis was entitled “Cryogenesis of Ground Waters and Hard Rocks of the Daldyn-Alakit Region (Western Yakutia)”. He then earned his Doctor of Science degree with the thesis “Cryohydrogeological Systems of the Yakutian Diamond-bearing Province”. From 2013 to present, he has been the Chairman of the Dissertation Council with specializations in hydrogeology, engineering geology, geocryology and ground engineering. His is currently investigating the origin of chloride brines in the sedimentary basins of the Siberian platform and developing a theoretical model for high-salinity groundwater. He uses multiple isotopic tracers to study the evolutionary processes in water–rock systems and found evidence that chloride brines form as a result of the transformation of connate water under closed conditions and slow water exchange. Additionally, isotopic tracers can be used to assess the enclosing rocks’ role in the formation of the chemical and isotope composition of the brine.

**Dirk Kirste** is an associate professor of aqueous geochemistry at the Simon Fraser University in Vancouver (Canada). Dirk graduated with a BSc (Honours) from the University of British Columbia (Canada), an MSc from the University of Waterloo (Canada) and PhD from the University of Calgary (Canada). After graduating, he worked as a post-doctoral researcher with Geoscience Australia and the Australian National University. Dirk’s research is primarily directed towards understanding the processes that control the composition of groundwater and surface water. His research involves both laboratory and field-based work investigating the chemical and isotopic composition of water, minerals and gases. Using variations in the chemistry, he addresses problems in the environment, problems in characterizing and predicting the effects of anthropogenic forcings, and problems in resource exploration and evaluation. He applies a broad range of techniques, including developing field-based sampling and monitoring strategies; applies different analytical methods; designs laboratory-based experimental procedures; and, develops and applies computer simulations.

**Huaming Guo** is a professor of hydrogeology at the China University of Geosciences (Beijing, China). He has had visiting placements at the Karlsruhe Institute of Technology (Germany), US Geological Survey in Denver (USA), and Columbia University (USA). Professor Guo was Chair of the Sino-German workshop in Beijing entitled Geogenic Arsenic in the Environment and was Co-Chair of the 7th International Conference on Arsenic in the Environment “Environmental Arsenic in a Changing World” (or “As 2018”) in Beijing. Currently, he is the co-Editor-in-Chief of the Journal of Hydrology, and Associate Editor of Applied Geochemistry. His three primary research interests are (1) Sources, fate and transport of inorganic pollutants (e.g., arsenic, fluoride, uranium, and chromium) in aquifer systems; (2) Characteristics and mechanisms of arsenic and fluoride adsorption on natural geomaterials; (3) Biogeochemical behaviours of contaminants during mineral–water–microbe–organisms interactions.

**François Chabaux** is a professor at the University of Strasbourg (France). He was awarded a PhD from University Paris 7 (France) in 1993. He was appointed to assistant professor at the University of Strasbourg in 1994, full professor in 1998 and Professor CE in 2012. From 2013 to 2017 he was Director of the Laboratoire d’Hydrologie et de Géochimie de Strasbourg. He is an associate editor of Applied Geochemistry and of Comptes Rendus Geoscience. François has been involved in the development and application of the methodology of U-series nuclides to constrain the timescales of weathering and erosion processes in the critical zone. With his colleagues in Strasbourg, he has investigated the nature of the water–rock interactions that control the chemical composition of waters in watersheds and in aquifers by applying geochemical tracers and, more recently, coupled hydrogeochemical models. An important part of his work was carried out on the Strengbach watershed (Vosges mountains, France), contributing to making this watershed one of the current reference sites of the French critical zone observatory network (OZCAR). François also gave the 2019 IAGC Ingerson Lecture at the 1st IAGC International Conference in Tomsk (Russia).

**Elisa Sacchi** graduated in Earth sciences in 1990 and obtained her PhD in geochemistry in 1995. She has been a researcher (since 2002) and an associate professor (since 2015) at the University of Pavia (Italy) and is currently in charge of teaching geochemistry and environmental geochemistry. She has been awarded numerous fellowships and contracts (Government of Canada Award, University of Torino, Université de Paris XI, Australian Nuclear Science and Technology Organisation) and has worked as a consultant for Italian and international institutions (INFN, ANDRA, OCDE Nuclear Energy Agency, ANSTO) in the fields of radioactive waste disposal and radiological contamination monitoring. Occasionally, she works as an “expert” with the International Atomic Energy Agency. Her main interests are in water, sediment and soil pollution, water–rock interaction and environmental applications of isotope geochemistry. Elisa has authored 50 papers in peer-reviewed journals, written two books, two book chapters and more than 70 contributions to national and international conferences. She is an associate editor for Applied Geochemistry.

**Elisabeth (Liz) Widom** is a professor and isotope geochemist at Miami University (Oxford, Ohio). Liz received a BA from Cornell University (New York, USA) (1984) and a PhD from the University of California Santa Cruz (USA) (1991). She completed a postdoctoral fellowship at the Carnegie Institution of Washington’s Department of Terrestrial Magnetism (Washington, DC, USA), followed by a National Research Council Postdoctoral Fellowship at the National Institute of Standards and Technology, prior to starting a faculty position at Miami University (1997). Since then, Liz has been honored to be a Pemberton Fellow at Durham University (UK) (2005) and a Fulbright Scholar at the Universidad Nacional Autónoma de México (2012). She has served as Department Chair at Miami since 2014, and has held the Janet & Elliott Baines Professorship since 2015. Liz’s research involves the application of trace elements and isotopes (radiogenic and stable) to address a range of geologic problems. Current research foci include investigations of processes and timescales operating in active magmatic systems; the composition and evolution of the Earth’s mantle, with ongoing projects on ocean islands, subduction zones, and intra-plate continental settings; and the application of radiogenic isotope systems to environmental contaminant tracing and nuclear forensics.
The 82nd Annual Meeting of the Meteoritical Society (MetSoc) was held 7–12 July 2019 in Sapporo (Japan). The conference was hosted in Hokkaido University’s Sapporo campus. There were 418 participants from 21 different countries registered for the meeting, including 287 professionals (scientists + exhibitors), 118 student participants, and 13 guests. A total of 289 registrants were MetSoc members. The MetSoc exhibition hosted booths for Japan’s National Institute of Polar Research (NIPR), the Tokyo Institute of Technology’s Earth–Life Science Institute (ELSI), the Japan Agency for Marine–Earth Science and Technology (JAMSTEC), and the analytical instrument manufacturers of JEOL, Cameca, Hitachi High-Tech, Oxford Instruments, and the Isotope Image Laboratory of Hokkaido University. In total, 509 abstracts were accepted for 272 oral, 235 poster and 2 print-only presentations. Oral presentations were scheduled in three parallel sessions from Monday (8 July) to Friday (12 July).

A total of 45 travel awards were allocated to student members, early career scientists, and scientists from low-income countries through generous sponsorships donated by the Barringer Crater Company, the NASA Cosmochemistry Program, the International Meteorite Collectors Association (IMCA), the Planetary Studies Foundation (PSF), Elsevier, the Meteoritical Society’s Endowment and Travel for International Members Fund, Maine Mineral and Gem Museum, O. Richard Norton, Darryl Pitt/Macovich Collection, National Institute of Polar Research (NIPR), and Japan Aerospace Exploration Agency (JAXA).

The conference kicked off on Sunday (7 July) with the pre-conference workshop entitled Workshop: Minerals, Organics, and Water in 3-D View, which was convened by Drs. Akira Tsuchiyama and Aki Takigawa at the University Conference Hall. This was followed by the Welcome Reception at the Hokkaido University Museum. The official opening ceremony took place on Monday (8 July) with greetings by Prof. Masanori Kasahara, Deputy President of Hokkaido University and Mr. Koyu Kishi, President of the Sapporo International Communication Plaza Foundation. The opening ceremony was followed by the Special Annual Lecture, “Tsunami Geology and Geomorphology: Extreme Events in the Earth’s and Human Histories”, which was sponsored by the Meteoritical Society and given by Prof. Kazuhisa Goto of the Department of Earth and Planetary Science, University of Tokyo. The Annual Barringer Invitational Lecture on Monday evening was “The Search for Antarctic Meteorites – Fifty Years from the Discovery of the Yamato Meteorites” and was given by Prof. Kazuyuki Shiraishi of the National Institute of Polar Research. The lecture was open to the public and had a simultaneous translation to Japanese by student member Ms. Kana Ishimaru. This talk attracted a large audience.

The scientific program covered 20 topics. These were organized under the themes of achondrites, carbonaceous chondrites, non-carbonaceous chondrites, chondrules, methods and analytical technique, volatiles, solar system chronology, impacts, Mars, geochemistry of lunar meteorites, organic matter, pre-solar grains, space weathering, differentiated bodies, and nebular dynamics. The program also included the special sessions “Ryugu, Bennu, and Small Bodies”, “Analysis of Lunar Samples: A Celebration of 50 Years Since Apollo 11”, and “50 Years of Japanese Antarctic Meteorites, Allende and Murchison”.

Prof. Hisayoshi Yurimoto, the awardee of the Leonard Medal, gave his lecture on Wednesday morning. Several excursions were conducted to enjoy the nature and culture of Hokkaido on Wednesday afternoon, city bus tour, city walk with sushi lunch, harbor city and stained glass museum (Otaru), whiskey distillery (Yoichi), volcano and lake in Shikotsu area, the Hokkaido Museum, and the Arte Piazza Bibai–Kan Yasuda sculpture park.

The conference banquet took place on Wednesday evening at the Sapporo Park Hotel inside the Nakajima Koen Park, close to downtown Sapporo. Participants enjoyed buffet-style Hokkaido food, Yosakoi Soran dance, and Taiko drumming.

Both poster sessions on Tuesday and Thursday evenings were very well attended, and hopefully many good discussions were had over drinks at the posters.

The conference concluded on Friday afternoon (12 July) with a Farewell Party, where participants met each other at Faculty House Trillium in the Hokkaido University Sapporo campus.

A post-conference excursion to Horoman Peridotite Complex (ophiolites) and Mt. Apoi Geopark was organized for 13–14 July. Dr. Kiyoaki Niida, Director of GeoLab Mt. Apoi, led the tour, and 14 participants enjoyed observing various peridotite rocks and the plate boundary between the North American and Eurasian plates, which formed during a tectonic convergence approximately 13 million years ago.


We would like to thank the numerous colleagues, students, and volunteers whose tireless efforts made it all possible. We also thank the Office for International Academic Support, Faculty of Science, Hokkaido University, which helped participants with visas. We want to emphasize the great support from the members of the Local Organizing Committee, the Scientific Program Committee, and the Travel Award Committee, and from all those who made themselves available as session conveners, student assistants, guides on conference tours and across a multitude of other essential functions.

Hisayoshi Yurimoto
MetSoc 2019 Chair of the Local Organizing Committee

SOCIETY AWARD WINNERS

The society gives four major awards each year. For more information on individual awards, see the Call for Nominations section of the society’s webpage.

The LEONARD MEDAL is the society’s highest and oldest award and is given to individuals who have made outstanding original contributions to the science of meteoritics or closely allied fields. It is named for Frederick C. Leonard who was a founder and the first President of the Meteoritical Society. The 2019 awardee is Hisayoshi Yurimoto, for his fundamental contributions to understanding the micro-distribution of oxygen isotopes in the proto-solar cloud, proto-planetary disk, and in samples returned from asteroids. The citation was given by Sasha Krot.

The BARRINGER MEDAL AND AWARD are sponsored by the Barringer Crater Company in memory of D. Moreau Barringer Sr and his son, D. Moreau Barringer Jr. The award is given for outstanding work in the field of impact cratering. This year, the Barringer Medal and Award is given to Mark Cintala (NASA Johnson Space Center, Houston, Texas, USA) for his fundamental contributions to our understanding of high-velocity impacts as a major geological process throughout the solar system. The citation was written by Fred Hörz and Jennifer Anderson, and delivered by Munir Humayun. The award was accepted on behalf of Mark by Lindsay Keller.
The NIER PRIZE is awarded to a young scientist in the field of meteoritics. The 2019 prize goes to Aki Takigawa of Kyoto University (Japan). Aki receives this award for her significant contributions to our understanding of the refractory dust in stars and in the early solar system through the synthesis of multiple analytical methods. The citation was given by Rhonda Stroud.

The SERVICE AWARD is given to a person who significantly advances the goals of the society. The 2019 award goes to Rainer Bartoschewitz (Bartoschewitz Meteorite Lab, Germany), not only for his effort in advancing the goals of the society but also for the far-reaching impact of his work. His contribution to the society’s goals has been accomplished through his collection of meteorites and extensive outreach activities related to meteorites and planetary science. The citation was written by Klaus Becker and delivered by Jisun Park.

The GORDON MCKAY AWARD is given each year to the student who gives the best oral presentation at the annual meeting of the society. The award honors the memory of Gordon A. McKay and is supported by the McKay Fund, which was established in 2008 as a part of the Meteoritical Society’s endowment. The McKay Award for the 82nd Annual Meeting of the Meteoritical Society in Sapporo goes to Dara L. Laczniak (Purdue University, USA) for her talk in Sapporo entitled “Coordinated Analyses of Ion Irradiated Carbonaceous Chondrites.” The award comes with a prize of US$1,000 and a certificate.

The WILEY-BLACKWELL AWARD is presented for outstanding presentations by students at the annual meeting of the society. Wiley-Blackwell are the publishers of Meteoritics and Planetary Science and, for the 82nd meeting in Sapporo, they sponsored five awards of US$500 each. Laura Bouvier (University of Copenhagen, Copenhagen, Denmark) for her presentation “Probing Magma Ocean Crystallization in Rocky Planets using Zirconium Isotopes – Preliminary Results from Ancient Zircons from Earth and Mars”. Cécile Deligny (Centre de Recherches Petrographiques et Geochimiques, CNRS-UL, Nancy, France) for her presentation “Origin and Timing of Volatile (N, H) Delivery to the Angrite Parent Body”. Marina Martinez (University of New Mexico, Albuquerque, New Mexico, USA) for her presentation “Smooth Rims in Queen Alexandra (Range (QUE) 99177: The Earliest Stages of Fluid–Rock Interactions in the Most Pristine CR Chondrite”. Robbin Visser (Freie Universität Berlin, Berlin, Germany) for his presentation “Manganese–Chromium Ages of Carbonates in Aqueously-Altered Carbonaceous Chondrites and Clasts”. Ke Zhu (Institut de Physique du Globe de Paris, Paris, France) for his presentation “Chromium Isotopic Constraints on the Origin of the Ureilite Parent Body”.

CALL FOR AWARD NOMINATIONS
Please consider nominating a colleague for one of the society’s awards. Nominations should be sent to Secretary Munir Humayun (metsocsec@gmail.com) by 15 January (or 31 January for the Pellas–Ryder Award and the Service Award). For more information and details on how to submit a nomination for any of these awards, please see the latest Newsletter at the society’s website, or e-mail the secretary.

ANNUAL MEETING SCHEDULE
2020 (83rd) 9–14 August, Glasgow (Scotland)
2021 (84th) 14–21 August, Chicago (Illinois, USA)
2022 (85th) Dates to be determined, Perth (Australia)
2023 (86th) Dates to be determined, Brussels (Belgium)

RENEW YOUR MEMBERSHIP NOW!
Please renew by 31 March 2020; after that date, a $15 late fee will be assessed. You can renew online at: http://metsoc.meteoritical-society.net.
GRANITES II: A SUMMER SCHOOL ON MAGMATIC DIFFERENTIATION

On the sunny pink granite coast of Roscoff (Brittany, France), 78 attendees gathered from all over the world (Armenia, Austria, Canada, China, France, Germany, Hungary, Italy, Portugal, Spain, Switzerland, UK and USA) to debate for 5 days (8 to 12 July 2019) the origin of the chemical diversity of magmatic rocks. The burning question was, “What drives the variety of chemical compositions of both volcanic and plutonic rocks?” The main sponsors of this extended summer school, entitled GRANITES II: Magmatic Differentiation (https://granites.sciencesconf.org/), were the CNRS and the VOLTAIRE Labex project coordinated by Bruno Scaillet (Orléans, France).

The Granites II summer school is the second in a series that started in 2017 at Orléans and was led by two researchers from the Institut des Sciences de la Terre d’Orléans (France), Laurent Arbaret and Fabrice Gaillard. For this second edition, Erwan Hallot (University of Rennes I, France) joined the organizing committee and led a field excursion across the famous Ploumanac’h composite granite intrusion of north Brittany, where well-exposed outcrops reveal world-class mingling textures that suggest different degrees of magma differentiation.

Over the five days, prestigious speakers discussed aspects of their own research and added some historical perspectives to a scientific debate that started over 200 years ago and is still not resolved. Thus, Olivier Bachman, Georges Bergantz, Jon Blundy, Wendy Bohrson, John Clemens, Fidel Costa, Marian Holness, Wolfgang Maier, Jean-François Moyen, Othmar Müntener, and Michel Pichavant all shared their knowledge with early carrier researchers (PhD students and postdoc fellows). During the evenings, and after each day’s course, there were vibrant question times which revealed the incredible scientific maturity of the “future Bowen generation”.

The petrological nature of trans-crustal arcs were discussed, the puzzling rarity of cumulative rocks was questioned, the role and amount of water involved in magma genesis/transfer/stoppage/eruption was highlighted, the volcanic-plutonic link was challenged, the different mechanisms of crystal-liquid separation was interrogated and the quantifiable impact of mixing and assimilation was addressed. Following the philosophy of the GRANITES II summer school, the talks were given by specialists in volcanic and in plutonic systems. This diverse approach meant that the early carrier scientists experienced the striking divergences that different researchers take in how to interpret the chemical diversity of magmas. It was agreed that a combination of crystal-liquid fractionation from mafic mantle-derived melts and partial melting of crustal lithologies could account for the chemical diversity of magmas.

Critical challenges for this next “Bowen generation” were identified during a session led by Liz Cottrell (Smithsonian National Museum of Natural History, Washington DC, USA). Liz pinpointed key questions to be addressed regarding the dynamics of solid-liquid separation in magmatic mushes; the timescales of melt extraction, transport and crystallisation; how to constrain sampling bias at all scales; the need to increase fundamental data for phase equilibrium databases, including amphibole, and studying new lower- and mid-crustal sections; and addressing the extent of disequilibrium processes in crystal-liquid reactions and their impact on differentiation paths.

Laurent Arbaret and Fabrice Gaillard
Institut des Sciences de la Terre, Orléans (France)

SFMC GRANTS FOR GOLDSCHMIDT2019

Congratulations to post-doctoral researcher Céline Baudoin and PhD students Axel Denys, Clément Laskar and Marion Turuani for each winning a grant from the SFMC to present their research work at the 2019 Goldschmidt Conference in Barcelona (Spain) last August.

Axel Denys (left) and Céline Baudoin (right)
Marion Turuani (left) and Clément Laskar (right)
MESSAGE FROM THE PRESIDENT, STEPHEN COOK

By the time you are reading this, my penultimate message as President of the Association of Applied Geochemists (AAG), you will have received my letter soliciting nominations for election to AAG Council for the upcoming 2020–2021 term. The approaching council term is a particularly significant one given that it will coincide with the 50th anniversary of the founding of the association in 1970 as the Association of Exploration Geochemists (AEG). The AEG became the AAG in 2003. The council term also coincides, more generally, with a figurative “passing of the torch” from that founding generation of exploration geochemists and their successors to a new generation of applied geochemists who will steer our discipline into the next half-century.

This brings me to the main point of my message, which is to highlight the importance of service to our geochemical community in achieving the above. The AAG is a volunteer organization, relying on geochemists to volunteer their time and energy to staff the Executive, the Council, and the slate of Regional Councilors around the world. The planning and running of symposia, the funding and teaching of educational workshops, and the peer review of scientific papers are just a few of the many collaborative activities of the global geochemical community which would not be possible in the absence of our dedicated volunteers (past, present and future). Of course, many personal benefits also accrue from such service, such as the opportunity to meet and work with many talented colleagues around the world which helps us to grow and develop as scientists.

So, what is required to serve on the AAG Council? Simply, you must be a Fellow in good standing with the AAG. If you are an AAG member with at least six years of post-bachelor’s degree experience, I urge you to submit your application for Fellowship at the first opportunity. Full details of the requirements are available at the AAG website. Becoming a Fellow is a relatively simple procedure and will put you in a position to help influence the activities of the AAG over the coming years and decades. A broad slate of candidates for election to the AAG Council each year ensures that the membership has the opportunity to select a capable and diverse group of men and women to guide AAG’s activities. It is also a sign of a healthy organization, where individuals are prepared to work together for the common good of geochemistry, wherever we may call our home in the world.

To sum up, I urge all Fellows to consider putting their names forward for election to AAG Council for the upcoming 2020–2021 term. Councilors serve a term of two years and may then stand for election to a second two-year term. Half of the council seats come up for re-election every year, providing continuity on the council from one year to the next. Serving on council also provides the experience necessary to potentially serve on the AAG Executive, either as president or in one of the other executive positions, where one can play a guiding role in the association. Many notable geochemists from industry, government, and academia have served terms as president and vice-president of the association over the past half-century. Many of these have been giants of our discipline who have made significant contributions to applied geochemistry in all its forms. William B. Coker (1946–2014; spent much of his career with the Canadian Geological Survey) and Stanley J. Hoffman (d. 1994; Chief Geochemist with BP Minerals for much of his career) are examples of two distinguished former AAG Presidents who played significant roles in my own education as a geochemist over the years.

As a final note, it is with considerable sadness that I must pass along news of the tragic death on 21 June 2019 of Prof. Peter Winterburn in Valparaiso (Chile). Peter was an accomplished scientist in mineral exploration and academia and a good friend to many. He had recently returned to Santiago (Chile) to rejoin Vale, a global mining company, after several years as Professor of Exploration Geochemistry at the Mineral Deposit Research Unit (MDRU) at the University of British Columbia (Canada). The AAG extends its most sincere condolences to Peter’s family. We will provide further details on his life and accomplishments in the next issue of EXPLORE.
It was a great pleasure for me to be offered the opportunity to participate in the prestigious Outreach Program run by the European Association of Geochemistry (EAG) and the Geochemical Society (GS) in 2019. I selected institutions to visit based on the wishes of the EAG and GS to select countries located in northern Africa, notably institutes that hadn’t previously welcomed a researcher as part of the program or those where I have personal contacts.

My first destination was Nouakchott (Islamic Republic of Mauritania), and my second was Cairo (Egypt). My talks focused on meteorites in Morocco in conjunction with meteorites from the country or region that I was visiting, in particular because so many meteorites are collected in the Sahara. Each talk began with a definition of meteorites, meteoritics and planetary science, followed by a discussion of where meteorites come from and how to identify them. I then introduced the importance of geochemistry for classifying meteorites and learning about the history of formation and evolution of the universe and terrestrial bodies in the solar system, including Earth. The geochemical analytical techniques used to study meteorites were also presented. The talks were a great opportunity to connect with local researchers and students who are interested in the topic and would like to develop it in their home countries.

The Outreach Program was a wonderful support for the Africa Initiative for Planetary and Space Sciences (AFIPS), launched in 2017 (https://africapss.org/), and the ATTARIK Foundation for Meteoritics and Planetary Science (www.attarakfoundation.org), two initiatives dedicated to the promotion of meteoritics and planetary science in Africa and the Arab world. Support for AFIPS has also come from the EAG–GS Outreach Program for the organization of two workshops in Africa in 2019 (read about AFIPS in Elements v14n1).
Geochemical Perspectives

Geochemical Perspectives is an internationally peer-reviewed open access journal that publishes invited contributions from leading scientists in the field of geochemistry.

Each issue of Geochemical Perspectives presents a single article with an in-depth view on the past, present and future of a field of geochemistry, seen through the eyes of a highly respected member of our community.

NEW ISSUE

My Stable Isotope Journey in Biogeochemistry, Geoecology and Astrobiology by Marilyn L. Fogel

Marilyn Fogel’s article describes her career in stable isotope biogeochemistry and ecology and how she has studied carbon, nitrogen, hydrogen, and oxygen isotopes as tracers for chemical and biological processes. She’s studied both modern, fossil, and astrobiological materials to understand how biogeochemical cycles have changed over time, in particular how humans might be shaping ecosystems around the globe.

Geochemical Perspectives is provided to all members of the European Association of Geochemistry.

www.geochemicalperspectives.org
www.perspectives.geoscienceworld.org
The Geochemical Society warmly thanks its many dedicated volunteers. Our sincere gratitude goes to the following GS members whose board and committee terms conclude in 2019.

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Meetings in Europe permit some delegates to travel by rail, a more environmentally friendly mode of transport than flying. Train travel is efficient and quite practical in Europe, because of both the high population density and the excellent infrastructure. However, nearly 30% of delegates who came to Barcelona (Spain) this year came from Asia or Australia. Another 22% came from North America. We do not have good data on how many of our European attendees actually took the train (as opposed to flying). Every year, irrespective of where the conference is held, the two largest countries in terms of delegates attending are the US and China.

The Geochemical Society is international. Our members come from >70 countries and have the following breakdown: 50% North America; 28% Asia, Australia, New Zealand, Africa, and the Middle East; 22% Europe. At first glance, Hawai‘i may not seem like a good place to hold Goldschmidt, since nearly everyone has to fly there. But for many scientists from Asia, Australia, and New Zealand, Hawai‘i will present the shortest distance of travel to the conference they have had since the 2016 meeting in Yokohama (Japan). It’s also closer for many people in Western North America than meetings in Europe. From our experience in 2016, we know that more Asian and Australian scientists are likely to attend next year because the venue is easier to reach. This will accomplish the important goal of making Goldschmidt accessible to scientists from all parts of the world, even if some who live farther from Hawai‘i decide not to attend. Note that nearly 800 Japanese scientists participated in the Yokohama meeting, compared to 180 in Barcelona.

As we look into the future, the travel required to reach the conference venue will be a major consideration for the societies. So will energy conservation programs being offered by the convention centers. We are happy to say that the Hawai‘i Convention Center relies largely on passive cooling, and, thus, consumes far less energy than the substantial amounts required to actively cool most other large centers. We are also exploring options such as recording sessions so that people who cannot attend the meeting can still benefit from some aspects of it. We are increasing the options for networking and interaction while at the conference and looking for ways to maximize the overall value of the conference experience.

Travel and human interaction are still very important to the endeavor of science. Figuring out how to achieve this while reducing our carbon footprint is a real challenge that will require many complementary solutions. We look forward to hearing your ideas at gsoffice@geochemsoc.org. Comments sent to this address will be shared with the leadership of both societies.

### SPECIAL ISSUE OF GEOCHIMICA ET COSMOCHIMICA ACTA HONORING THE LIFE-TIME ACHIEVEMENTS OF LAWRENCE A. TAYLOR

Professor Lawrence A. Taylor (1937–2017) was a champion for the study of materials from inner Solar System bodies to understand origins. A >600 page special issue of Geochimica et Cosmochimica Acta (volume 266) is now available and will be freely accessible to all readers from 1 January to 31 March 2020. This collection covers an array of topics that span Prof. Taylor’s diverse interests, including the Moon, Earth, Mars, and asteroidal parent bodies. To view the special issue, please visit: https://bit.ly/2NkQG8.

### THE GOLDSCHMIDT CONFERENCE AND ITS CARBON FOOTPRINT

As recent demonstrations across the world show, there is a growing awareness of climate change and its impacts on human society. Whereas this is not news in our community, it does provoke an examination of how we, as a society of scientists, should contribute solutions.

The Geochemical Society’s largest program is the Goldschmidt Conference, which is developed each year with the European Association of Geochemistry, both societies being co-owners of the conference. In odd-numbered years, the conference is held in Europe with EAG as the lead organizing society; in even-numbered years, the conference is held in North America, with the Geochemical Society as the primary organizer. But about once every 8 years, the GS plans the conference at a venue outside Europe or North America, such as the 2016 meeting in Japan. Each year, 3,000–4,000 scientists from more than 60 countries come together for a week of great science and networking. This gathering leads to vital collaborations, career development, and the formation of new friendships. Because the meeting moves around the world, it also gives delegates opportunities to experience new places and cultures.

A large, international meeting also entails significant consumption of natural resources through the usage of a convention center and delegates’ travel. There is no denying the fact that Goldschmidt has an environmental impact. As more of us consider the carbon footprint of our travel, this raises questions about how the GS and EAG should organize the meeting. First among these inquiries is where should Goldschmidt be held?
Dear friends and members of the DMG,

This year’s DMG Mineralogical Meeting, held September 2019 in Münster, was again a big success. It was a joint meeting with the DGGV (Deutsche Geologische Gesellschaft – Geologische Vereinigung) and so offered a broad variety of geological and mineralogical topics. I thank Heinrich Bahlburg and his team for the local organization. Out of a total of 606 participants, 114 were members of the DMG, 78 from the DGGV, 96 were members of both societies, 223 were non-members, and there were 95 invited speakers plus members of the local organizing committee. So, the mineralogists had a great share of this meeting. About half of them were students, demonstrating that this meeting is a very attractive platform for young scientists. On the other hand, less than 15% of the total number of DMG members attended the meeting, so, we will make every effort to ensure future meetings are even more attractive. Some of our members who work in technical mineralogy and/or crystallography might expect some special topics in their respective fields. We hope to address this at the 2020 European Mineralogical Conference (emc2020), to be held 6–10 September in Cracow (Poland), and at the 2021 European Mineralogical Conference (emc2021), to be held 12–16 September 2021 in Vienna (Austria) as a joint meeting of the DMG together with the Austrian Mineralogical Society (ÖMG) and the Slovakian mineralogical society (Slovenská mineralogická spoločnosť). In 2022, the DMG will celebrate its 100th anniversary of DMG meetings. For this special event we are still seeking a host.

In spite of the stable number of DMG members and the high number of participants at our meetings, it is noticeable that the number of mineralogists in university positions in Germany is constantly decreasing. A preliminary survey among our members revealed that the number of professors in mineralogical disciplines decreased from 114 in 2000 to 79 in 2020, which is a loss of about 30% within 20 years. This tendency is especially pronounced in petrology (from 29 in 2000 to 17 in 2020) and crystallography (from 29 in 2000 to 9 in 2020). This latter discipline will approach zero by 2026 if this trend continues.

So, we have quite a discrepancy between the increasing relevance of our research, as reflected by the high number of contributions at mineralogical conferences, and the decreasing number of scientists in mineralogical disciplines at universities. This is especially striking in the light of the increasing importance of classical fields in mineralogy, such as the investigation of ore deposits and raw materials for future energy generation.

On the whole, there is enough to do promoting our fascinating science, not just for the DMG council and commission members but also for every single member of our society.

In this spirit, I wish you a Merry Christmas and a Happy New Year! See you all in 2020!

Reinhard Fischer (DMG President)

CRYSTALLOGRAPHY AND APPLIED MINERALOGY: WORKSHOP 2020

The next joint workshop of DMG’s Crystallography and Applied Mineralogy sections will take place 11–13 March 2020 in Bad Windsheim (Germany). As always, the major aim of this workshop is to bring students in contact with experienced scientists in order to discuss the students’ recent and future scientific work. For further information contact christoph.berthold@uni-tuebingen.de.

The Third European Mineralogical Conference Cracow, Poland, 6 - 10 September 2020

is organized by the Mineralogical Society of Poland on behalf of other European mineralogical societies:

DMG Deutsche Mineralogische Gesellschaft
MinSoc Mineralogical Society of Great Britain & Ireland
MinSocFin Mineralogical Society of Finland
ÖMG Österreichische Mineralogische Gesellschaft
RMS Russian Mineralogical Society
SEM Sociedad Española de Mineralogía
SFMC Société Française de Minéralogie et de Cristallographie
SIMP Societá Italiana di Mineralogia e Petrologia
SSMP Swiss Society of Mineralogy and Petrology

with participation of:

EMU European Mineralogical Union

Under the theme: Mineralogy in the Modern World the 3rd emc2020 will be focused on presenting current and future challenges in the Earth, planetary and environmental sciences and fostering an exchange of new views and research results between scientists from Europe and beyond. The main themes are: Advanced analytical techniques • Applied mineralogy • Archaeometry • Atomistic and thermodynamic modelling • Education and mineralogy • Environmental mineralogy and low-temperature geochemistry • Experimental mineralogy and petrology • Geobiogeochemistry, geomicrobiology and biomining • Geochemistry • Magmatism and volcanology • Mantle petrology and geochemistry • Metamorphism • Mineral deposits and raw materials • Mineral diversity and evolution • Mineral physics • Mineralogical crystallography • Planetary materials and processes • Radioactive materials

The local organizing committee: Tomasz Bajda and Justyna Topolska.

Contact: emc2020@ptmin.eu
GEOMÜNSTER 2019 – SOME IMPRESSIONS

The joint annual meeting of the German Mineralogical Society (Deutsche Mineralogische Gesellschaft, or DMG) and the German Geological Society (Deutsche Geologische Gesellschaft–Geologische Vereinigung, or DGGV) took place 23–25 September in Münster (Germany) at the GeoMünster 2019 conference. The conference had the title “Earth! Past, Present, Future” and offered a broad spectrum of ~500 presentations and posters within 50 sessions covering 13 scientific themes. Over 600 scientists participated in the conference, including 175 students. An evening public lecture by Prof. Colin Devey (GEOMAR, Kiel), as well as plenary lectures by Marin K. Clark (University of Michigan, USA), Craig Manning (University of California at Los Angeles, USA) and Jim Head (Brown University, USA), complemented the program. The plenary lectures were selected to reflect the broad spectrum of the conference program as well as to address and discuss important fields and methods in the geosciences. The GeoMünster 2019 conference offered a great venue to discuss new research results and to network with internationally renowned scientists.

CHANGEOVER IN DMG COUNCIL

Heidi Höfer (University of Frankfurt) has been the DMG Public Relations Officer since 2002. Her duties will be taken over in 2020 by Birgit Kreher-Hartmann (University of Jena; see right in photo of the GeoMünster 2019 conference) who is presently the speaker of the DMG Mineralogical Museums and Collections Working Group.

DMG SHORT COURSES 2020

In 2020, the DMG will support seven short courses, including a newly developed online class on cosmochemistry. All courses will be aimed primarily at advanced-level undergraduate and graduate students but, as always, are open to more senior researchers as well. Non-local student members of DMG will be eligible for travel support to the amount of €50. Further information can be found at www.dmg-home.org/aktuelles/doktorandenkurse/. The seven short courses and their details are as follows (all locations are in Germany):

5. **Application of Diffusion Studies to the Determination of Timescales in Geochemistry and Petrology**, Institute for Geology, Mineralogy and Geophysics, Ruhr University Bochum, Prof. Sumit Chakraborty, 28 September–2 October 2020, sumit.chakraborty@rub.de, www.gmg.rub.de/petrologie/.
6. **In situ Analysis of Isotopes and Trace Elements by Femtosecond Laser Ablation ICP-MS** [In-situ-Analyse von Isotopen und Spurenelementen mit (MC-) ICP-MS gekoppelt mit Femtosekunden-Laserablation], Institute for Mineralogy, Leibniz University Hannover, Prof. Stefan Weyer and others, 5–9 October 2020, s.weyer@mineralogie.uni-hannover.de.

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Sandra Christin Wind, Ottawa
The next Mineral Deposits Studies Group meeting will be held 6–8 January 2020 at the Natural History Museum, London. The Icebreaker Party will be held on Monday, January 6.

The event is being organized by Dr Jamie Wilkinson (Natural History Museum, London) and the London Centre for Ore Deposits and Exploration (LODE).
**SOCIETY BURSARIES 2020**

The MinSoc invites applications for a number of bursaries.

**Postgraduate Student Bursary**

As part of its objective to advance knowledge of the science of mineralogy and its applications, the MinSoc awards a small number of bursaries to research postgraduate students. These bursaries are intended to allow students to develop, undertake, apply and communicate research in any area of the mineralogical sciences (including crystallography, geochemistry, petrology, environmental science and economic geology). By making these awards, the MinSoc also seeks to encourage the development of postgraduate researchers into the next generation of researchers in mineralogy. The president and council of the society, therefore, recommend and encourage that students registered for a postgraduate research degree in the disciplines of mineralogy, crystallography, petrology or geochemistry apply for a bursary award. Application deadlines and activity cut-off dates are given below.

**Deadline:** 1 May each year, e.g., 1 May 2019 for applications to fund activities taking place between 1 December 2019 and 1 December 2020

**Deadline:** 7 December each year, e.g., 7 December 2019 for applications to fund activities taking place between 1 May 2020 and 1 May 2021

More information and a form are available at: https://www.minersoc.org/postgraduate-bursaries.html.

**Senior Bursary**

The purpose of the Senior Bursary awards is to support academic work by allowing attendance at overseas conferences and meetings; encouraging international collaboration in research of high merit; or supporting fieldwork.

The deadline for receipt of applications is 15 January each year.

A decision will be made by the Awards Committee, with its announcement to be made by no later than 1 March each year.

More information, and a form, are available at: https://www.minersoc.org/senior-bursary.html.

**Hazel Prichard Student Bursary**

The Mineralogical Society of Great Britain & Ireland and the Geological Society are pleased to announce the Hazel Prichard Student Bursary. This bursary, funded by Hazel’s family, honours the achievements of Professor Hazel Prichard (1954–2017; formerly of Cardiff University) in the mineral sciences.

The deadline for applications is 15 February each year.

A bursary of up to £3,000 is available to support an undergraduate or MSc student.

More information available at: https://www.minersoc.org/hazel-prichard-student-bursary.html

Below is a report by Joana Lluch (University of St. Andrews) who was the first winner (2019) of the Hazel Prichard Student Bursary.

“Because of funding from IOM3 and as the winner of the inaugural Hazel Prichard bursary, I was able to travel to the Groote Eylandt mine in Australia, engage in the mine workflow and take samples to perform geochemical studies for my master’s dissertation project which redefined completely the genetic model for this deposit. The Prichard bursary is named in honour of Dr Hazel Prichard, formerly of Cardiff University, and is awarded jointly by the Mineralogical Society of Great Britain & Ireland and the Geological Society in conjunction with their special interest groups: the Applied Mineralogy Group and the Mineral Deposits Studies Group. The Groote Eylandt (GE) manganese deposit is one of the most important sedimentary Mn deposits in the world, located on the Carpentaria Basin, Australia. The deposit is divided into two sub-basins, the northern one (NB), with pisolithic and massive ore, and the southern one (SB), with disseminated carbonaceous ore. The pisolithic NB ore represents deposition on the swash intertidal zone whereas the SB ore was deposited in the subtidal zone. This study shows that the NB ore is not as supergene as previously thought and still conserves primary geochemistry. The deposit shows enrichment in heavy metals and REEs relative to PAAS (Post-Archaean Australian shale) values, with a potential economic source of the latter ones, with concentrations up to 619 ppm. The source of Mn and metals in GE is not continental runoff as previously thought. The deposit shows a Re–Os age of 93.22 ± 3.95 Ma, falling into the second great Oceanic Anoxic Event (OAE2) (~94.4 Ma to ~93.82 Ma) and in the highest Cretaceous sea-level recorded. This study points out the hydrothermal nature of the orebody and relates its formation to the placement of the Caribbean Large Igneous Province. Mn-rich beds are related to minimum detrital inputs reflected by a strong U, Co, Ni, Cu, Zn, Ba and REE enrichment relative to shale values and a strong positive Eu/Eu* anomalies. Redox-sensitive trace elements ratios such as V/(V + Ni) and U/Th together with the absence of Ce/Ce* anomalies show the strong stratification of the water column at the time of deposition from dysoxic to euxinic waters. The Os value for both basins is ~0.71, which reflects the return to radiogenic Os signatures at middle stages of the OAE2 after the dramatic drop produced at its onset. The GE genetic model needs to be redefined to a sedimentary hydrothermal-related OAE2 deposit.”

**MEMBERSHIP REMINDER**

We encourage you to encourage your students to join the MinSoc, starting now! The first year of student membership is free of charge; they just need to sign up (www.minersoc.org/join-now.html).

**SOME RECENT CONTENT IN CLAY MINERALS**

**December 2019**


Natural tuff as an alternative for removing textile dyes (Asucryl red): adsorption properties, kinetic and equilibrium studies. B. Ayaden, N. Benabdeslam, N. Bouzidi, L. Mahtout, M. Bounounala, and M. Djooudi.

Optimization of ultrasonic-assisted copper ion removal from polluted water by a natural clinoptilolite nanostructure through a central composite design. Mohsen Sheydaei, A.B. Gasmsooltanlu, and A. Beiraghi.

Mineralogical study of raw clay samples from Dobrodo, Serbia. M. Milošević, P. Dabić, S. Kovač, I. Kuluđerović, and M. Logar.
EMU RESEARCH EXCELLENCE MEDAL

One of the means by which the European Mineralogical Union (EMU) fosters and encourages research in the mineralogical sciences is to present a silver medal each year. The EMU Research Excellence Medal is presented to early career scientists (no more than 15 years since completing their PhD) who have made significant contributions to research and who are active in strengthening European scientific links. The medal is presented at an awards ceremony during an international meeting, such as the Goldschmidt meeting or a combined meeting of EMU member societies.

The EMU Medal Committee calls upon the member societies and all European mineralogists for nominations; the next deadline is 1 June 2020. The nomination process is quite straightforward and requires only a cover page (available at http://eurominunion.org/wp-content/uploads/2016/12/cover-page-EMU-award.pdf); a cover letter from the nominator outlining the candidate’s qualifications in light of the two criteria for the award; supporting letters from at least two, but no more than four, co-sponsors; a complete candidate CV that includes a full publication list. Nomination packages for 2020 should be sent to the Chair of the Medal Committee, Dr Clare Warren: clare.warren@open.ac.uk by midnight (GMT) on 1 June 2020.

All members of EMU societies are encouraged to consider nominating suitable candidates from among their colleagues, thereby recognising their outstanding scientific contributions to the mineralogical sciences (in the broadest sense).

Please feel free to contact the President of EMU, Michael Carpenter (e-mail: mc43@esc.cam.ac.uk), with questions or suggestions about the EMU Research Excellence Medal.

A New Initiative: Research Excellence Medal Lecture

As a new initiative, the EMU is supporting visits of this year’s winner of the Research Excellence Medal, Dr Katharina Marquardt, to two or three European institutions to present her medal lecture. Dr Marquardt received her award at the Goldschmidt meeting in Barcelona (Spain) and her lecture was, “Olivine Interface Distributions in Static and Dynamic Equilibrium: Effects of Diffusion vs Effects of Dislocation Motion”.

Anyone who is interested in having a visit by the current (or future) medallist to their institution should contact the Secretary of EMU, Dr Jura Majljan (e-mail: JuraJ.Majljan@uni-jena.de), with a proposal of when and where Dr Marquardt would give her lecture. Dr Majljan will decide on the most suitable requests, to fit in also with Dr Marquardt’s schedule.

This is what Dr Katharina Marquardt of Imperial College London (UK) says about her scientific activity:

“I am a mineralogist, Earth scientist and materials scientist working at the intersection of these fields since my doctorate in 2010. After spending several years as a researcher in Earth science departments, I recently moved to the Department of Materials at Imperial College London where I especially enjoy my work on how interfaces influence bulk material properties. I profit from Imperial’s state-of-the-art analytical facilities and the collaborative enjoyable environment I personally require for research. Generally, my work is very interdisciplinary and spans over various disciplines, including geochemistry [Schmidt et al. 2014; Keim et al. 2018], geophysics, materials science [Marquardt et al. 2015, 2017], and includes molecular dynamic modelling [Adjaoud et al. 2012; Wagner et al. 2016] and numerical modeling [Marquardt et al. 2010, 2011; Gardés et al. 2012]. I recently received the prestigious EMU Research Excellence Medal 2018 for my ‘challenging and forefront (research) projects’ and for my ‘contributions that have opened up new horizons’. Hurray!

I teach both electron microscopy (PhD course) and a course on microstructure in 2nd year material science degree. I think that both are so little used or considered in geology, but I think current research is turning more and more towards the study of microstructure and realizing the importance of grain boundaries. Therefore, I consider my most important work to be “The Most Frequent Interfaces in Olivine Aggregates: The GBCD and Its Importance for Grain Boundary Related Processes” (Contributions to Mineralogy and Petrology, 2015, v170: 40.) [GBCD = grain boundary character distribution]. In this work, we precisely describe the state-of-the-art stereological grain boundary plane distribution reconstruction used to understand grain boundary network geometries in rocks. In other words, you may think of this as either an average crystal shape or an average grain boundary network geometry. My study was the first of its kind on natural samples as well as the first on mantle rocks. I know that this work can eventually lead to a greater understanding of grain size evolution (e.g., mantle viscosity) and melt percolation and extraction (geochemical cycles etc) in the Earth’s interior. I hope it will do so!


REFERENCES


Marquardt K and 5 coauthors (2011) Grain boundary and volume diffusion experiments in yttrium aluminium garnet bicrystals at 1,723 K: a miniaturized study. Contributions to Mineralogy and Petrology 162: 739-749


1 Periods of time away from research, for example due to part-time working patterns, parental leave, caring responsibilities, health issues, will be taken into account in the consideration of “time-since PhD” eligibility.
2nd EMU SCHOOL ON MINERAL FIBRES

Following the success of the 1st EMU School on Mineral Fibres, which was held in June 2017, the European Mineralogical Union organized the 2nd EMU School on Mineral Fibres (2019 EMU school) 9–13 September 2019 in Casale Monferrato (Italy). The 2019 school focused on natural occurring asbestos (NOA) from a range of viewpoints, from the geological to the medical, and covered many multi-disciplinary aspects. The chairs of the school, Prof. Alessandro F. Gualtieri (University of Modena e Reggio Emilia, Italy) and Dr Ruggero Vigliaturo (University of Pennsylvania, USA), welcomed 80 delegates from various parts of the world, including Australia and the USA. The school officially opened on 9th September, and, over the 5 days, students attended lectures delivered by 23 keynote speakers. Specific topics included the following: crystal chemistry and the occurrence of mineral fibres and NOA; definitions of “asbestos”, “fibre” and related terms; the genesis of NOA; identifying and classifying mineral fibres; geological assessment and field sampling methods for NOA in rocks and soils; experimental methods for investigating mineral fibres; surface and bio-chemical properties of mineral fibres; protection of workers and the public from potential NOA exposure; asbestos-related diseases and bio-chemical mechanisms that induce adverse effects in the human body; in vitro and in vivo tests to assess cyto/genotoxicity and carcinogenicity of mineral fibres; epidemiological studies of asbestos-related diseases and genetic factors. All presentations were very well received and enjoyed by the delegates. The roundtable discussion on Tuesday, 10 September allowed students and citizens to share information, ask questions to speakers, and take part to scientific discussions moderated by the chairs.

The content of the talks varied from specialist topics, such as the application of scanning electron microscopy and transmission electron microscopy to NOA investigations [e.g., the talk by Dr Jasmine Petriglieri on asbestiform antigorite from New Caledonia and the talk by Dr Mark Bailey on fibrous glaucophane in the blueschists of California (USA)], to multidisciplinary talks during which various aspects of mineral fibre characteristics were linked to health aspects. The talks by Prof. Elena Belluso, Dr Martin Harper and Prof. Alessandro Gualtieri showed that although the world of mineral fibres has been studied for many years, there are no generally accepted definitions of “asbestos” or “fibre”, and there are still controversies about which mineral particles should be classified as “asbestos”. Prof. Gualtieri also presented an innovative model to predict the toxicity of mineral fibres. Drs Ileana Pérez-Rodríguez and Jessica K. E. Choi gave fascinating talks on microbe–mineral interactions. The talk by Dr Daniele Mandrioli on asbestos pathogenicity mechanisms and in vivo tests was well received by all, but especially from those who study mineral fibres from a purely biological and medical point of view. Thanks to Dr Ruggero Vigliaturo, Dr Mark Bailey and Prof. Giancarlo Della Ventura, students gained information about the recent advances in transmission electron microscope and spectroscopy technologies as relevant to the study of mineral fibres. A final highlight was Dr Francesco Turci who gave us great insight into how the surface activity of mineral fibres contributes to their toxicity and pathogenicity.

The social events were highly appreciated, especially the visit to the Eternot Park in Casale Monferrato and the field trip to the Balangero chrysotile mine. The tour guide of the city of Torino gave some background on the history of the first capital of Italy and the city that inspired the “Liberty” style and on Italian artists of the late 800s. The silver service dinner at the Filarmonica (dinner held in a historic building, decorated with fascinating mural frescoes) was an equally memorable experience. None of the social events would have been possible without the fantastic support from our sponsors, to whom the Organizational Committee are extremely grateful. The last day ended with a Farewell Reception at Casale Monferrato Castle, led by the Rotaract Club Casale Monferrato. As happened at the first edition of the school in Modena, there was a friendly atmosphere in Casale that promoted valuable interactions between the students and the lecturers. Additional information on the 2019 EMU school is available on the website emu2019.unimore.it.
It would be difficult to find a researcher who considers that conferences are not an integral part of scientific activity. Conferences are where interesting discussions take place and collaborations are forged that can lead to new discoveries. Conferences are where ideas are exchanged much faster than via publications and do so in a convivial environment. Therefore, no one disputes that it is worth organizing and attending scientific conferences. Thematic conferences that gather specialists together are particularly valuable, a fact recognized by the various European mineralogical societies. In 2012, the German Mineralogical Society (Deutsche Mineralogische Gesellschaft), in cooperation with nine other European mineralogical societies, organized the First European Mineralogical Conference in Frankfurt am Main (Germany). After that conference, it was then decided to organize similar meetings every four years. So, in 2016, the Second European Mineralogical Conference was organized. This time, the duties of the main organizer were taken over by the Italian Society of Mineralogy and Petrology (Società Italiana di Mineralogia e Petrologia) and the conference was held in Rimini (Italy).

More than three years have passed since then. And it is with undisguised pleasure that we, the Mineralogical Society of Poland, would like to announce that this series of European mineralogical conferences is to continue. The 3rd European Mineralogical Conference, designated EMC2020 (or "emc2020"), will take place 6–10 September 2020 in Poland. The conference will be held at the Auditorium Maximum in the Jagiellonian University in Cracow (Kraków), which is a vibrant, academic and tourist-friendly city in the heart of Europe. The Mineralogical Society of Poland will take the role of being the main organizer; however, the most important decisions will be made, as always, in consultation with all our partner European mineralogical societies and with the European Mineralogical Union.

### Contributing Societies

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<tr>
<th>Code</th>
<th>Name</th>
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<tbody>
<tr>
<td>DMG</td>
<td>Deutsche Mineralogische Gesellschaft</td>
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<tr>
<td>MinSoc</td>
<td>Mineralogical Society of Great Britain and Ireland</td>
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<tr>
<td>MinSocFin</td>
<td>Mineralogical Society of Finland</td>
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<tr>
<td>ÖMG</td>
<td>Österreichische Mineralogische Gesellschaft</td>
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<tr>
<td>PTMin</td>
<td>Mineralogical Society of Poland</td>
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<tr>
<td>RMS</td>
<td>Russian Mineralogical Society</td>
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<td>SEM</td>
<td>Sociedad Española de Mineralogía</td>
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<tr>
<td>SFMC</td>
<td>Société Française de Minéralogie et de Cristallographie</td>
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<tr>
<td>SIMP</td>
<td>Società Italiana di Mineralogia e Petrologia</td>
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<tr>
<td>SSMP</td>
<td>Swiss Society of Mineralogy and Petrology</td>
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The theme of EMC2020 is “Mineralogy in the Modern World”, and this should be a platform to exchange ideas and approaches to solving scientific and some broader societal problems. We hope that this meeting will start new collaborations in the realm of mineralogy-related sciences. Details of the scientific sessions are currently being agreed. These sessions will be built around 18 general themes. These are ...

- Advanced analytical techniques
- Applied mineralogy
- Archaeometry, care and preservation
- Atomic and thermodynamic modeling
- Education and mineralogy
- Environmental mineralogy and low-T geochemistry
- Experimental mineralogy and petrology
- Geochronology
- Geochronology
- Geomicrobiology and biomineralogy
- Geochronology
- Mantle petrology and geochemistry
- Metamorphism
- Mineral deposits and raw materials
- Mineral diversity and evolution
- Mineral physics
- Mineralogical crystallography
- Planetary materials and processes
- Radioactive materials

The scientific program of the conference will include three workshops. The first is entitled Inclusions in Metamorphic Minerals: Windows into the Past and will be led by Matteo Alvaro (University of Pavia, Italy), Silvio Ferrero (University of Potsdam, Germany), and Jarosław Majka (Uppsala University, Sweden and AGH-UST, Poland). The second workshop, entitled Seismometamorphism, will be organized by Håkon Austheim (Oslo University, Norway). The third workshop will explore how to model mineral chemistry and will be organized by Mark Tyrer (Coventry University, UK).

Several one- or two-day field trips are also being planned. Conference participants can choose to see the mineralogical peculiarities of the geologically diverse Sudetes region, or can visit the well-known and long-exploited Zechstein copper deposits on the Fore-Sudetic Monocline. These field trips will also allow participants to get acquainted with the geological structure of the crystalline core of the Tatra Massif or the magmatism in the Silesian Basin.

The organizers of the EMC2020 conference are also preparing an attractive social program, which includes the ice-breaker party, a gala dinner and several city tour options, all of which will further enhance your stay in Kraków.

For more information please visit the official conference website: https://emc2020.ptmin.eu/ and/or follow us on Facebook https://www.facebook.com/emc2020ptmin/.

The local organizing committee are Tomasz Bajda, Justyna Topolska, Jakub Kierczak, Krzysztof Szopa, Anna Inglot.

Looking forward to seeing you in Poland!
The Japan Association of Mineralogical Sciences (JAMS) is proud to announce the recipients of its 2019 society awards. The JAMS Award for Young Scientists is awarded to two scientists under 37 years of age who have made exceptional contributions to mineralogical and related sciences. The JAMS Research Paper Award is awarded to the authors of excellent papers that have been published either in the Journal of Mineralogical and Petrological Sciences (JMP) or in Ganseki Kobutsu Kagaku (GKK) in the past three years.

JAMS Award for Young Scientists to Shumpei Yoshimura

Shumpei Yoshimura is an assistant professor at the Department of Earth and Planetary Sciences, Hokkaido University, Sapporo (Japan). He received his PhD from Tohoku University (Japan) under the supervision of Professor Michihiko Nakamura. Yoshimura studies the mechanisms of volcanic eruptions from the perspective of high-temperature experiments on magma vesiculation, degassing, glass sintering, and volatile dissolution and diffusion in the melt. He also carries out numerical simulations of fluid transport in magma and has theorised on the chemical evolution of magma and volcanic gas. Recently, Yoshimura experimentally demonstrated that Cl diffusion in silicic melts is much slower than previously thought. This finding motivated him to inspect Cl spatial distributions in natural silicic lavas in the hope that degassing-related Cl heterogeneity would remain in groundmass glass even if other volatiles had been completely lost or homogenised because of their much higher diffusivity. He observed that the groundmass is highly heterogeneous in its Cl content. Combining this Cl heterogeneity with Cl diffusion calculations, he proposed a new cyclic degassing model as the controlling process behind non-explosive lava eruptions. Yoshimura is now applying this Cl-mapping method to a variety of volatile-related processes, including gas transfer upon magma mixing, in order to understand volcanic eruption dynamics in even more detail.

JAMS Award for Young Scientists to Ayako Shinozaki

Ayako Shinozaki is an assistant professor at Hokkaido University (Japan). She received her PhD from Ehime University (Japan) under the supervision of Professor Hisako Hirai. Using high-pressure and high-temperature experiments, Shinozaki has studied the effects of reduced C–O–H fluids on the stability and phase relation of silicate minerals at mantle conditions. Using laser-heated diamond-anvil cells combined with X-ray diffraction measurements under high-pressure conditions, plus scanning electron microscopy and transmission electron microscopy, Shinozaki found that forsterite and enstatite incongruently dissolve in H2 fluid to form periclase crystals in the MgSiO4–H2 and MgSiO3–H2 systems, respectively. Shinozaki also discovered, from infra-red and Raman spectroscopic measurements, that SiO2 dissolves in H2 fluid to become SiH4 and H2O molecules. This indicates that the dissolution mechanism of silicates in H2 fluid is different from that observed in the MgO–SiO2–H2O systems. In the reduced mantle, C–O–H fluids are expected to contain a substantial amount of H2 in addition to H2O and CH4. The H2 component is likely to enhance the Mg/Si fractionation between the fluid and the solid phases of mantle minerals. Shinozaki is also researching organic materials as a reservoir of light elements in the Earth's interior, in ice satellites, and in meteorites by determining the crystal structures and the chemical reactions of aromatic compounds and amino acids under high-pressure and high-temperature conditions.

JAMS Research Paper Award to Yohei Igami, Akira Miyake, Norimasa Shimobayashi


JAMS Research Paper Award to Yoshihiro Nakamuta


JOURNAL OF MINERALOGICAL AND PETROLOGICAL SCIENCES

The Journal of Mineralogical and Petrological Sciences (JMP) is an international, peer-reviewed open access journal from the Japan Association of Mineralogical Sciences. The journal's impact factor, as reported in the 2018 Journal Citation Reports, is 1.472. The JMPs publishes original articles, reviews, and letters in the fields of mineralogy, petrology, economic geology, geochemistry, planetary science, and instrumental analysis technology. Our journal also encourages and develops a variety of new inter-disciplinary scientific fields, in the hope of new fields blooming in the future. Please feel free to submit a paper to the JMP by going to https://www.jstage.jst.go.jp/browse/jmps.

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Original Articles

Vmsite from the Fuka mine, Okayama Prefecture, Japan – Shoichi KOBAYASHI, Manami YUASA, Mitsuo TANABE, Shigetomo YOSHIDA and Isao KUSACHI

XAFS study of Sb and As in Cretaceous-Tertiary boundary sediments: an index of soiling of the global environment with dust and ashes from impact ejecta falls – Hidetomo HONGU, Akira YOSHISADA, Tsubasa TOBASE, Maki OKUBE, Kazumasa SUGIYAMA and Tsutomu SATO

Na-bearing tremolites as reservoirs of fluid-mobile elements in the mantle wedge: inference from the Ochiai-Hokubo complex (Southwest Japan) in high-P schists – Shoji ARAI, Miki SHIRASAKA, Yoshito ISHIDA and Hidehiko INOUE

FeAl2O4 under ultrahigh-temperature metamorphic conditions: experimental evidence from the sillimanite–Fe2O3 and sillimanite–FeO4 systems – Toshisuke KAWASAKI, Tatsuno ADACHI, Hiroaki OHPFUJI and Yasuhide OSANAI

Minakawaite and platinum-group minerals in the placer from the clinopyroxeneite area in serpentinite mélangé of Kurosegawa belt, Kumamoto Prefecture, Japan – Daisuke NISHIO–HAMANE, Takahiro TANAKA and Tadashi SHINMACHI

http://jams.la.coocan.jp
**President’s Letter**

**MSA: Celebrating the Past; Anticipating the Future**

Those of you who attended the Annual Meeting of the Geological Society of America (GSA) in Phoenix (Arizona, USA; held 22–25 September 2019) may have spotted the above slogan accompanying the Mineralogical Society of America’s (MSA’s) Centennial logo on the doors to the Phoenix Convention Center. There has been much celebration over the past year, with a highly successful Centennial Symposium in Washington DC (USA) in June and Centennial sessions at meetings throughout the year, including a full day of presentations by past MSA presidents at the GSA meeting. (If you missed them, you can access videos of Centennial Symposium presentations on the MSA website.) It is clear from these events that the fields of mineralogy, crystallography, geochemistry, and petrology are as vibrant and relevant today as they were in 1919.

During the coming year, I will use this forum to review the strong foundation on which MSA launches its second century and to discuss some of the upcoming challenges faced by MSA. By building on our strengths and addressing change, we can set our society on a firm course and take advantage of opportunities to become an even more effective international leader in promoting our science. So, let’s start by reviewing MSA’s accomplishments in its first century.

The MSA is the premier professional society for mineralogy and petrology, internationally. It may not be obvious from a society named the Mineralogical Society of America, but the MSA is truly an international organization. Half of its members reside outside of the US, and its committees are composed of members from around the world. Our MSA Lecturers include experts from outside North America, and they make at least one international tour each year. The MSA Fellows and medalists come from across the globe. Our international reach establishes us as a global leader in providing expertise in natural materials.

The MSA promotes mineralogy and petrology by recognizing outstanding fundamental research and public service. The society’s highest honor is the Roebling Medal, awarded for lifetime scientific achievement. The Dana Medal recognizes outstanding contributions by mid-career scientists, and the MSA Award goes to scientists who have published outstanding work prior to their 35th birthday. The society also recognizes appropriate individuals with a Distinguished Public Service Medal. With its awards, MSA promotes important discoveries to the world.

The MSA publishes scholarly research in mineralogy, crystallography, petrology, and geochemistry, broadly defined. American Mineralogist, the international journal of Earth and planetary materials, was established in 1916 and has published some of the most important advances in these fields. Reviews in Mineralogy and Geochemistry provide a concise and comprehensive review of 85 different subject areas to date. The MSA was a founding society of Elements. In addition, MSA publishes textbooks and other monographs, including the Handbook of Mineralogy. Society publications like ours are critical: they are both well respected and accessible.

Activities by the MSA promote scientific literacy and support the next generation of mineralogists and petrologists. Our society provides educational opportunities for all ages, but many activities are targeted to students. MSA Lecturers visit with undergraduates and graduate students on campuses around the world. Students and professionals alike attend MSA workshops and short courses. The MSA hosts educational materials on the web, which are available to all. Students are eligible for Kraus Crystallography and Mineralogy/Petrology Research Grants and also benefit from special membership rates. Activities like these are essential to the future of our discipline.

The MSA is a model organization. If you’ve interacted with MSA headquarters, you know that MSA is excellently managed. For the past 25 years, Alex Speer, our Executive Director, has kept us on track, organizing the membership and the daily work of the society, while, at the same time, transitioning to new practices and building new collaborations. We will miss him dearly and wish him the very best on his retirement at the end of December.

As the summary above suggests, MSA is in a strong position because of the actions of its members over the past 100 years. In the next issue, I will address some of the challenges facing professional societies like ours.

Carol Frost
2020 MSA President

**Notes from Chantilly**

- The MSA Council decided on the 2020 award recipients at its Fall Council Meeting in Phoenix (Arizona, USA). The Roebling Medal is awarded to Andrew Putnis, University of Münster (Germany) and Curtin University (Australia); the Dana Medal to Daniela Rubatto, University of Bern (Switzerland); the MSA Award to Jin Liu, HPSTAR (Beijing, China). Newly elected fellows are Luca Bindi, Craig Schiffries, Melissa Lane, Frank Brenker, Clive Neal, Alan Woodland, Rajdeep Dasgupta, Guoyin Shen, Kimberly Tait, James Gardner, Zhu Mao, and Marian Holness.

- All 2018 and 2019 MSA members have been contacted by mail, electronically, or both about renewing their memberships for 2020. If you have not renewed your MSA membership, please do so. If you have not received a notice by the time you read this, please contact the MSA Business Office. You can also renew online anytime.

**The 2020 MSA Calendar**


**In Memoriam**

<table>
<thead>
<tr>
<th>Manuel Bass (1961 – Fellow)</th>
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<tr>
<td>H. Stanton Hill (1936 – Life Member)</td>
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<td>Edward Jobbins (1961 – Senior Member)</td>
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<td>J. Donald Rimstidt (1975 – Senior Fellow)</td>
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<td>Sheila Seaman (1986 – Member)</td>
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<td>Brian Skinner (1958 – Fellow)</td>
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</table>
2019 MSA Awardees

At its annual meeting, the MSA presented the following awards:

**Roebling Medal**

Peter R. Buseck of Arizona State University (USA) received the 2019 Roebling Medal in recognition of his outstanding and pioneering contributions in mineralogy using transmission electron microscopy (TEM). Dr. Buseck's contributions have included, among many others, aerosol particle research, extensive work in meteoritics, and his investigations of biominalogical questions. Through his efforts, Dr. Buseck established Arizona State University as an international center for high-resolution TEM. He has been inspirational as a mentor to a great number of students and colleagues throughout his career. Many of his students have gone on to stellar careers of their own, a testament to Dr. Buseck's influence, support, and stature as a scientist and visionary.

**Dana Medal**

The 2019 Dana Medal was awarded to Matthew J. Kohn of Boise State University (Idaho, USA) in recognition of his sustained outstanding scientific contributions through original research in the mineralogical sciences. Dr. Kohn is cited for his stellar body of work in such widely varying fields as paleoclimatology and metamorphic petrology. He is known as a broad and deep thinker whose primary focus is on addressing the major unresolved problems in mineralogy, petrology, and geochemistry. Dr. Kohn is also celebrated for developing new tools for analysis, which have changed the scope of what can be studied in the mineralogical sciences. In addition, he has a strong record of service to the community, by editing journals, organizing workshops and symposia, and chairing technical sessions at academic meetings.

**Distinguished Public Service Medal**

The MSA has awarded Rodney C. Ewing of Stanford University (California, USA) its 2019 Distinguished Public Service Medal in recognition of unequaled contributions to public policy, particularly in the area of nuclear waste management. As Chair of the US Nuclear Waste Technical Review Board, he was instrumental in ensuring that the nation’s nuclear waste policies were informed by solid science and concern for the environment.

Dr. Ewing was the driving force behind the genesis of the highly successful *Elements* magazine, which first appeared in 2005 and now has 18 participating societies. The content of *Elements* is designed to appeal to members of the geoscience community across a wide variety of occupations and settings. Dr. Ewing was responsible for overseeing the preservation of the Harding Pegmatite in New Mexico when he chaired the Earth and Planetary Sciences Department at the University of New Mexico. His efforts allowed the site to continue to be available to both the public and students for study and exploration. In addition, Dr. Ewing secured the funding that saved the mineral collection at the University of Michigan (USA).

**MSA Award**

The 2019 MSA Award went to Olivier Namur (Katholieke Universiteit Leuven, Belgium) in recognition of his wide-ranging contributions to mineralogy and for linking these to the large-scale evolution of the Earth, Moon, and Mercury. Dr. Namur has made new and insightful discoveries in the field of layered intrusions. He is known for his excellent fieldwork combined with careful laboratory experiments. Dr. Namur's hallmark is his meticulous collation of geochemical data, which are then subjected to detailed numerical analysis. In addition, he provides mentorship for both graduate and undergraduate students, sharing his knowledge and his creative ways of formulating and investigating complex research problems in petrology and mineralogy.

**Award Nominations**

Nominations Sought for 2021–2022 Awards

Nominations must be received by 1 June 2020.

The Roebling Medal (2021) is MSA's highest award and is given for eminence as represented by outstanding published original research in mineralogy.

The Dana Medal (2021) is intended to recognize continued outstanding scientific contributions through original research in the mineralogical sciences by an individual in the midst of his or her career.

The Mineralogical Society of America Award (2021) is given for outstanding published contribution(s) prior to 35th birthday or within seven years of the PhD.

The Distinguished Public Service Medal (2022) 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. Form required; contact committee chair or MSA home page.

Mineralogical Society of America
Submission requirements and procedures are on MSA’s home page:
http://www.minsocam.org/

**Research Grants**

- The Mineralogical Society of America 2020 Grants for RESEARCH IN CRYSTALLOGRAPHY from the Edward H. Kraus Crystallographic Research Fund with contributions from MSA membership and friends
- STUDENT RESEARCH IN MINERALOGY AND PETROLOGY from an endowment created by MSA members

Selection is based on the qualifications of the applicant; the quality, innovativeness, and scientific significance of the research of a written proposal; and the likelihood of success of the project. There will be up to three US$5,000 grants, with the restriction that the money be used in support of research.

The IMA is honored to present its 2018 Medal of Excellence in Mineralogical Sciences to Gordon E. Brown. Gordon is the Dorrell William Kirby Professor Emeritus of Geology (Stanford University, California, USA) and Professor Emeritus of Photon Science at the Stanford Linear Accelerator Center (SLAC) (California, USA). His contributions to environmental geochemistry, mineralogy and surface science have received international recognition. He has authored or co-authored over 400 refereed publications, achieving a remarkable h-index of 103.

Following his undergraduate years at Millsaps College (Mississippi, USA), Gordon received an MSc (1968) and a PhD (1970) degrees from Virginia Tech (USA). As a postdoctoral fellow (1970–1971) in the State University of New York at Stony Brook (USA) he carried out X-ray studies in minerals, glasses, melts, and at mineral–solution interfaces, as well as in situ X-ray photoelectron spectroscopy studies of mineral reactions with water. The use of synchrotron radiation enabled Gordon’s group to conduct ground-breaking research on molecular-level speciation of As, Se, Hg, U and other contaminants at mine and nuclear waste disposal sites, and on the structure and properties of natural and engineered nanoparticles. Most recently, he and his collaborators have examined CO2 sequestration via mineral carbonation and chemical reactions of fracking fluids with minerals and natural organic matter in oil and gas reservoirs. It is impossible to overestimate the importance of this work to environmental stewardship and to the responsible recovery of hydrocarbons.

Gordon’s research has been recognized through many prestigious awards, including the Hallimond Lecture (Mineralogical Society of Great Britain and Ireland, 1993/4), the Hawley Medal (Mineralogical Association of Canada, 2007), the Clair C. Patterson Award (Geochemical Society, 2007), the Roebling Medal (Mineralogical Society of America, 2007), the Ian Campbell Medal (American Geosciences Institute, 2012), and foreign membership of Academia Europaea (2013).


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**CALENDAR**

**2019**

**December 1–6** Materials Research Society Fall Meeting, Boston, MA, USA. Web page: www.mrs.org/fall2019

**December 9–13** AGU Fall Meeting, San Francisco, CA, USA. Details www.agu.org/fall-meeting

**2020**


**January 26–31** 43rd International Conference and Expo on Advanced Ceramics and Composites (ICACC’20), Daytona Beach, FL, USA. Web page: ceramics.org/event/43rd-international-conference-and-expo-on-advanced-ceramics-and-composites

**February 11–13** Advanced Ceramics and Composites Conference and Exposition on Advanced Ceramics and Composites, Bari, Italy. Web page: www.36thinternationalmineral-deposits-conference.org/2020/

**February 14–19** Asteroids, Comets, Meteoroids Conference, Flagstaff, AZ, USA. Web page: www.hou.usra.edu/meetings/ ACM2020/


**July 21–26** Goldschmidt2020, Honolulu, HI, USA. Web page: goldschmidt.info/2020/

**July 5–7** 9th International Conference on Meteorology and Museums, Sofia, Bulgaria. Web page: www.bgminsoc.bg/


**July 7–10** 2020 COMPRS annual meeting, Palisades, NY USA. Web page: compres.us/events/annual-meeting/2020/2020-comprs-annual-meeting-general-information

**July 14–16** International Archean Symposium, Perth, WA Australia. Web page: 6ias.org/

**July 28–30** 14th International Nickel-Copper-PGE Symposium, Marquette, MI USA. Web page: www.nmu.edu/eegs/symposium-2020

**August 2–6** Microscopy & Microanalysis 2020, Milwaukee, WI, USA. Web page: forthcoming

**August 9–14** Meteoritical Society Annual Meeting, Glasgow, UK. Web page: meteoritical.org/society?_page_id=18

**August 16–20** 260th ACS National Meeting & Exposition, San Francisco, CA, USA. Web page: www.acs.org/

**September 1–5** GEOHEALTH 2020, International Network of Geohalth Scientists (INGS) meeting, Bari, Italy. Web page: geohalth-scientists.org

**September 6–10** EMC2020 – 3rd European Mineralogical Conference, Cracow, Poland. Web page: www.emc2020.ptmin.org/

**September 21–24** 5th International Serpentinite Days Workshop, Sestri Levante (Genova), Italy. Web page: serpentinedays2020.it

**October 4–8** Materials Science & Technology 2020, combined with ACeS 122nd Annual Meeting (MS&T20), Pittsburgh, PA, USA. Web page: forthcoming

**October 5–8** Martian Geological Enigmas: From the Late Noachian Epoch to the Present Day, Houston, TX, USA. Web page: www.hou.usra.edu/meetings/martianenigmas2020/

**October 25–28** Geological Society of America Annual Meeting, Montreal, Canada. Web page: forthcoming


**November 29–December 3** Materials Research Society Fall Meeting, Boston, MA, USA. Web page: www.mrs.org/fall2020

**December 7–11** AGU Fall Meeting, San Francisco, CA, USA. Details forthcoming

**2021**

**April 19–23** MRS Spring Meeting & Exhibit, Seattle WA USA. Web page: www.mrs.org/spring2021


**July 4–9** Goldschmidt2021, Lyon, France. Web page forthcoming

**July 12–16** 17th International Clay Conference, Istanbul, Turkey. Web page: forthcoming

**August 1–5** Microscopy & Microanalysis 2021, Pittsburgh, PA, USA. Web page forthcoming


**August 16–20** Meteoritical Society Annual Meeting, Chicago, IL, USA. Web page: meteoriticalsociety.org/?page_id=18

**October 10–13** Geological Society of America National Meeting, Portland, OR, USA. Web page: forthcoming

**November 28–December 3** Materials Research Society Fall Meeting, Boston, MA USA. Web page: www.mrs.org/fall2021

The meetings convened by the societies participating in *Elements* are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol (more meetings are listed on the calendar she maintains at https://sites.google.com/a/udayton.edu/akoziol1/home/mineralogy-and-petrology-meetings). To get meeting information listed, please contact her at akoziol1@udayton.edu

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Inform *Elements* readers about upcoming short courses, workshops, meetings and conferences. Contact Andrea Koziol (akoziol1@udayton.edu) and Jodi Rosso (jrosso.elements@gmail.com)
Ekati, Canada’s first diamond mine, Northwest Territories (NWT). Copyright © Dominion Diamond Mines

**SCIENTIFIC THEMES**

1. Diamonds
2. Emplacement and Economic Geology of Kimberlites and Related Magmas
3. The Origin and Evolution of Kimberlites and Related Magmas
4. Diamond Deposits – Exploration and Mining
5. Cratonic Mantle – Petrology, Geochemistry and Geophysics

**FIELD TRIPS**

1. Northwest Territories Diamond Mines
2. Kimberlites Across Canada
3. Slave Craton Geology
4. Northwest Territories Kimberlite Drill Core Collection
5. Advances in Drift Prospecting for Kimberlite in Canada

**SHORT COURSES**

1. Geology of Diamonds: Reviews in Mineralogy and Geochemistry
2. The G-Cubed Toolbox: Capturing Full Value from Public-Domain Kimberlitic Indicator Mineral and Microdiamond Data
3. Introduction to Kimberlites: Geology, Terminology, Emplacement and Economics
4. Principles of Rough Diamond Valuation
5. Advances in Drift Prospecting for Diamonds: Using Glacial Processes to Unravel Dispersal Paths

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