Catastrophic Perturbations to Earth’s Deep Carbon Cycle

CELINA A. SUAREZ, MARIE EDMONDS, and ADRIAN P. JONES, Guest Editors

Earth’s Catastrophes: Impacts on Carbon Cycle
Origin and Evolution of Earth’s Carbon
Influence of Large Bolide Impacts
How Large Igneous Provinces Mobilize Deep Carbon
Climatic Transitions: Icehouse to Greenhouse
Perturbing the Biosphere and Mass Extinctions
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Guest Editors: Celina A. Suarez, Marie Edmonds, and Adrian P. Jones

Earth Catastrophes and their Impact on the Carbon Cycle
Celina A. Suarez, Marie Edmonds, and Adrian P. Jones

On the Origin(s) and Evolution of Earth’s Carbon
Sami Mikhail and Evelyn Füri

The Influence of Large Bolide Impacts on Earth’s Carbon Cycle
Balz S. Kamber and Joseph A. Petrus

Deep Carbon and the Life Cycle of Large Igneous Provinces
Benjamin A. Black and Sally A. Gibson

Earth’s Outgassing and Climatic Transitions: The Slow Burn Towards Environmental “Catastrophes”?
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Interpreting the Carbon Isotope Record of Mass Extinctions
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PARTICIPATING SOCIETIES

The Mineralogical Society of Great Britain and Ireland is an international society for those working in the mineral sciences. The society aims to advance the knowledge of the science of mineralogy and engage in other related subjects such as crystallography, geochemistry, geology, and environmental science. The society fosters collaboration through scientific meetings and the publication of scientific journals and monographs. The society publishes Mineralogical Magazine and Clay Minerals. Members receive the society's journals and receive a meeting tree of charge. All members receive Elements.

Website: www.minsoc.org
Contact: business@minsoc.org
Society News Editor: Andrea Kozol
(akozol@huaudays.edu)

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

Website: www.clay.org
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Society News Editor: Katerina Dontsova
(kyriss55@gmail.com)

The Geochemical Society (GS) is an international organization founded in 1956 for geoscientists and scientists involved in the study, practice, and teaching of geochemistry. Geochemical Society’s programs include hosting the annual Goldschmidt Conference, editorial oversight of Geochemistry & Cosmochronology Acta (GCA), supporting geochemical symposia through our Meeting Assistance Program, and offering student development through our Student Travel Grant Program. GS annually recognizes excellence in geochemistry through its medals, lectures, and awards. Members receive a subscription to Elements, special issues of GeoScience Canada, and reduced registration fees for meetings and short courses, and participation in society efforts that supports the many facets of mineralogy.

Website: www.minso.org
Contact: info@minso.org
Society News Editor: Kevin Murphy
(kevint@minso.org)

ElEmEnts October 2019

The International Association of GeoChemistry (IAGC) has been a preeminent international geochemical organization for over 40 years. Its main purposes are to foster cooperation in the advancement of applied geochemistry by sponsoring specialist scientific symposia and the activities organized by its working groups and by publishing its journal, Applied Geochemistry. The administration and activities of IAGC are conducted by its council, comprising a small international executive and a number of members. Day-to-day administration is performed through the IAGC business office.

Website: www.iagc-society.org
Contact: businessoffice@iagc-society.org
Society News Editor: Chris Gardner
(BusinessOffice@IAGC-Society.org)

The Société Française de Crystallographie, the French Mineral and Crystallography Society, was founded on 21 March 1878. The purpose of the society is to promote the promotion of crystallography and crystallography. Membership benefits include the European Journal of Crystallography, reduced registration fees for SMF meetings.

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The Association of Applied Geochemists is an international organization founded in 1970 that specializes in the field of applied geochemistry. The association aims to advance the science of geochemistry as it relates to exploration and the environmental applications of exploration and geochemistry. Membership benefits include the Association of Applied Geochemists’ journal, GeoScience Canada, and reduced registration fees for SMF meetings.

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

Website: www.ptmin.pl
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Society News Editor: Zbigniew Sławowicz
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The Sociedad Española de Mineralogía (Spanish Mineralogical Society) was founded in 1975 to promote the growth of mineralogy, petrology, and geochemistry. The society organizes annual conferences and furthers the tradition of attracting 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 and launched Macla, a new journal focusing on mineralogy, databases, and reviews. Membership benefits include receiving the European Journal of Mineralogy, Macla, and selected book reviews.

Website: www.elsevier.com
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The Swiss Society of Mineralogy and Petrology was founded in 1949 as a federation of academic and industry and amateur societies. The society promotes knowledge in the fields of mineralogy, petrology, and geochemistry and to disseminate this knowledge to the public and to provide a forum for meetings and conferences. The society organizes the annual Swiss Geoscience Meeting and publishes the Swiss Journal of Geosciences jointly with the national geological parcel. Membership benefits include subscriptions to the Swiss Journal of Geosciences and membership in the society.

Contact: bernard.grobet@unifr.ch
Society News Editor: Torsten Vennemann
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The Meteoritical Society is an international organization founded in 1953 for meteoritical scientists, collectors, and educators to advance the study of meteorites and other extraterrestrial materials and their components, comets, and planets. Members receive our journal, Meteoritics & Planetary Science, which includes full-text access to the Icarus, Meteoritical Bulletin, and Icarus. We organize international meetings, workshops, and field trips, and support young planetary scientists through our awards and medals and awards, we recognize excellence in meteoritics and allied fields.

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Society News Editor: Cam Corrigan
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The Japan Association of Mineralogical Societies (JAMS) was established in 2007 by merging the Mineralogical Society of Japan, founded in 1955, and the Japanese Association of Mineralogists, Petrologists, and Economic Geologists, established in 1928. JAMS covers the wide field of mineral sciences, geochemistry, and petrology. Membership benefits include receiving the journal, The Japan Association of Mineralogical Sciences (JAMS), the Japanese Association of Geochemists (JAG), and Klavering. JAMS sponsors the annual meeting of the Association of Geochronology and Geochemical Sciences (AGS), the Gansevoort-Kobayashi-Kagawa (GKK), and Elements.

Website: www.jams.coocan.jp
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Society News Editor: Atsushi Kyono
(kyono@geo.tsukuba.ac.jp)

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 genesis of ore deposits and is affiliated with the International Union of Geological Sciences (IUGS). The society organizes symposia, workshops, and plenary and poster sessions at IUGS Congresses and the IAGOD Biennial Meetings. The IAGOD working groups and commissions promote ore deposits research and sponsor an international speaker series. Membership benefits include reduced fees to our meetings, subscriptions to our flagship journal Ore Geology Reviews and other publications, and a subscription to Elements.

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Society News Editor: David Lenz
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The periodic table of chemical elements is one of the most significant achievements in science because it arranges the 118 known elements in a deceptively simple pattern that reveals their properties. So how did this “Rosetta Stone of Nature” originate? Most likely, you will answer Dmitri Mendeleev, the Russian chemist who in 1869 published a version of the periodic table that we recognize today. His table expresses the periodic law: elements arranged according to the size of their atomic weights show periodic properties. To celebrate the 150th anniversary of this great achievement, the United Nations and UNESCO declared 2019 to be the International Year of the Periodic Table of Elements. But does Mendeleev deserve all the credit? Scientific discoveries rarely arise in isolation; rather contributions from researchers over many years lead to a general picture that eventually emerges. But, sometimes, scientific discoveries are made simultaneously by different researchers. Such is the story of the periodic table.

Among the critical events that led to the discovery of the periodic table was the emergence of atomic theory that had been initially proposed in 1808 by John Dalton, a British tutor and schoolteacher. A key advance was Dalton’s assignment of relative weights to the atoms of elements. But how does one obtain an absolute weight of an atom? In 1811, Italian physicist and mathematician Amedeo Avogadro proposed an idea to calculate atomic weights from gases, but his hypothesis was not widely accepted. It was ~50 years later that Italian chemist Stanislao Cannizzaro resurrected Avogadro’s ideas and showed how atomic weights could be calculated unambiguously. Cannizzaro’s paper, published in a local Pisa (Italy) journal, did not attract many readers and was republished as a pamphlet in 1859. Cannizzaro then attended a conference that would change the course of history of the periodic table. In 1860, the first international chemical congress was held in Karlsruhe (Germany) and 140 of the world’s leading chemists attended. The sole purpose of the meeting was to sort out the basic units of chemical interaction and the proper methods for determining unequivocal atomic weights. Cannizzaro’s defense of Avogadro’s ideas attracted great interest and copies of his pamphlet were distributed. Cannizzaro’s action provided the catalyst for the development of the modern periodic table. Chemists Lothar Meyer, William Odling, and Dmitri Mendeleev all attended the conference and were inspired by Cannizzaro’s work.

It was a French geologist and mineralogist Alexandre-Émile Béguyer de Chancourtois who was the first to arrange the chemical elements in order of their atomic weights. He devised a 3-D spiral graph and plotted the atomic weights on the surface of a cylinder that brought similar elements onto corresponding points above or below one another on the cylinder (Fig. 1). He presented his ideas to the French Academy of Sciences and published his work in 1862. Unfortunately, an original diagram was lost out of the publication, making the paper hard to comprehend. Although de Chancourtois republished his work with the diagram later, it was largely ignored by chemists. After this, he appeared to lose interest in his idea and returned to other scientific endeavors.

More discoveries of the periodic system of elements quickly followed. John Newlands, a British sugar chemist and private chemistry tutor, noticed trends between elements and their weights, and published his “law of octaves” in 1865. Similar to de Chancourtois, Newlands’ work attracted little attention and his pattern did not hold up very well. Four years after Karlsruhe, British chemist William Odling published a table that included 57 elements. However, Odling’s system also failed to have much impact, and he did not pursue it further. Gustavus Hinrichs, a Dane who immigrated to the United States, published a unique periodic system with the elements in a “bicycle wheel” form, with groups of elements displayed as spokes. Lothar Meyer, an influential German chemist, produced several versions of the periodic table from 1864 onwards. Unfortunately, Meyer’s work wasn’t published until 1870, a year after Mendeleev’s 1869 periodic table, so his contributions are overshadowed by Mendeleev.

The history of the periodic table is a remarkable tale, involving discoveries by six diverse individuals over a seven-year period. There were key discoveries and events such as the 1860 congress that accelerated its development. Mendeleev may not have been the first to develop a periodic system of the elements, but he was a master at exploiting it. The discovery of the periodic table, as we currently know it, in 1869 was transformative, because it freed chemical science from associations with the medieval mysticism of alchemy. The periodic table even provided hints of the existence of subatomic structure that would be discovered in the next century.

There are many lessons to be learned from the history of the periodic table. The discoveries of four of the six discoverers of the table were not recognized until many years after they were published.
As we go to press, the Intergovernmental Panel on Climate Change (IPCC) has just released its 2019 “Special Report on the Ocean and Cryosphere in a Changing Climate” (https://www.ipcc.ch/srocc/home/). When the topic is climate change, our reaction is usually “Uh-Oh!”. Calls for clean energy, reduced emissions, and consumer activism are a regular part of news broadcasts or casual conversations. Unlike many of the political storms that currently rage in national forums, climate change is truly an international and global problem.

Our last issue of Elements (August 2019 v15n4) focused on the topic of weathering, clearly demonstrating how climate (and CO₂) links to weathering. The articles in “Catastrophic Perturbations to the Deep Carbon Cycle” take the focus on carbon even further by exploring the passage of carbon among the nonliving and living reservoirs from core to surface. The movement of carbon between the deep Earth and the surface plays a critical role in maintaining the surficial conditions that are necessary for life to exist and thrive. Yet, as demonstrated in this issue, there are ample examples of perturbations to Earth’s steady-state condition. What is learned from the study of natural perturbations to the carbon cycle can be used to help frame and understand the impacts of the human-induced perturbation on Earth’s global system that is currently underway.

Anthropogenic sources of greenhouse gases are the centerpiece of most conversations on the topic, yet, in reality, they are just one part of a very complex system of interdependent parts. The Deep Carbon Observatory (https://deepcarbon.net/) has made it possible for the articles in this issue to be Gold Open Access and they will be readily accessible from the Elements website. So, share the articles and help broaden the climate change conversation with your colleagues, students, and policy makers.

Meyer and Mendeleev were both active in promoting their versions of the periodic table, but Mendeleev is the name we recognize because his more complete version was published before Meyer’s version. And there are lessons to be learned for today’s scientists, young and old: read the literature broadly in fields beyond your immediate specialty; publish broadly and wisely; and be active in promoting your ideas once they have the backing of scientific evidence.

How will the periodic table stand up over the next 150 years? How many new elements will be discovered? Will these elements behave the way the periodic table predicts? Can superheavy nuclei be produced in space? Stay tuned ... the fascinating story of the periodic table continues.

Nancy L. Ross, Principal Editor

REFERENCE

ELEMENTS AT GOLDSCHMIDT2019

The Elements principal editors met in Barcelona (Spain) on Sunday, 17 August 2019, for their annual face-to-face meeting. The all-day meeting took place at the Barcelona International Convention Center, which is just a short distance from the beach. While many vacationers enjoyed the warm summer weather, our Elements editorial team was busy at work. As mentioned in our August 2019 From the Editors column, these meetings are essential for maintaining and/or improving the quality and performance of Elements. Lively discussions have always been part of Elements editorial meetings. This year was no different. Below are just a few highlights.

A New Column in Elements

Each issue of Elements includes approximately six thematic articles that are short, concise reviews of a specific geoscience topic. Articles are written so that technical non-experts are readily introduced to a subject that is out of their field of expertise. Elements authors and editors work incredibly hard to transform articles into this accessible form, which is significantly different from typical journal articles or other scientific comprehensive reviews. That hard work isn’t going unnoticed. Over the past year, Elements has been informally asking members how they use Elements. In addition to general reading pleasure and scientific research, members commonly indicated that they use the magazine as a teaching resource.

During our recent meeting, the editorial team explored possible new initiatives related to geoscience education. It was decided that a new feature column will be included in Elements that focuses on geoscience education. This new column will become a regular part of the magazine along with CosmoElements, Elements’ Toolkit, and Parting Shots.

The editorial team and Elements Executive Committee are watching carefully how this will unfold and how it may or may not affect Elements invited contributors in the future.

Plan S

Open Access publishing is one of the many publishing options available for researchers and is also an option for Elements authors. Late 2018, the so-called “cOAlition S” funders, along with the European Commission and the European Research Council, spearheaded “Plan S.” This plan requires that, beginning in 2021, scientific publications resulting from publicly funded research grants must be published in compliant open access journals or platforms which make the research immediately available without embargo. Elements would fall under the “hybrid journal” category where our content is “subscription” only, but with a purchase option for Open Access. As it stands, publishing in hybrid journals would be prohibited under Plan S. The editorial team and Elements Executive Committee are watching carefully how this will unfold and how it may or may not affect Elements invited contributors in the future.

New Topics in Elements

The editorial team meets biannually to review new proposals of possible topics to include in the Elements lineup. After fruitful discussions and careful consideration, the team selected three proposals for inclusion. Topics to be covered in the February, April, and June 2021 issues will be “Hydrothermal Fluids”, “Exploring Earth and Planetary Materials with Neutrons”, and “Exposed Crustal Arc Sections”. We thank all those who took the time to submit a proposal for our consideration. And, we look forward to working with the organizers of these new issues in the months to come.

As always, the editorial team welcomes the submission of proposals. We will meet again in early 2020 to select additional proposals for the second half of our 2021 lineup. To learn more about submitting a proposal to Elements, visit http://elementsjournal.org/publish-in-elements/

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

EDITORIAL Cont’d from page 295

FOR THE EDITORS

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Benjamin A. Black is an assistant professor of geology at the City University of New York (New York, USA). His interest in the connections between magmatism, outgassing, and environmental crises began during his PhD at the Massachusetts Institute of Technology (Massachusetts, USA) when he first started exploring the 252 Ma Siberian Traps large igneous province (Russia). His current research projects focus on how volatiles such as carbon and halogens impact on the petrology and evolution of large-scale magmatic systems, including impact melt pools and flood basalt provinces.

Marie Edmonds is a professor in Earth sciences at the University of Cambridge (UK). Her current research focuses on cycling of volatiles between the atmosphere and the mantle and the role that magmatic volatiles play in melting, magma genesis, storage and transport, volcanic eruption style and climate modulation over a range of timescales. Dr. Edmonds develops quantitative frameworks to understand complex physical and geochemical datasets in collaboration with a diverse range of geochemists, geophysicists and volcanologists. As an executive committee member of the Deep Carbon Observatory (DCO), she is responsible for overall scientific and intellectual oversight of DCO’s synthesis and integration activities.

Evelyn Füri is a CNRS researcher at the Centre de Recherches Pétrographiques et Géochimiques (CRPG) in Nancy (France). She obtained a diploma degree in Earth sciences from ETH Zurich (Switzerland) in 2004, and she completed her PhD in 2010 at the Scripps Institution of Oceanography in San Diego (California USA). During her graduate work, she studied the noble gas and carbon geochemistry of mantle-derived rocks and fluids. Since first joining the CRPG as a postdoctoral fellow, her research focuses on using the isotopes of H, C, N, and noble gases to explore the origin and evolution of volatile elements on planetary bodies in the solar system.

Sally A. Gibson is professor of petrology and geochemistry at the University of Cambridge (UK). She has studied large igneous provinces for over 30 years. Sally's expertise is based on combining observations from field expeditions to the large igneous provinces of Paraná–Etiéndeka (South America), Deccan (India) and North Atlantic Large Igneous Province with geochemical and geophysical data. A major research focus has been the volatile-rich and the Fe-rich mantle melts that accompany the more voluminous flood basalts. Sally's research group is currently investigating the source of volatiles in mantle plumes and also the capacity of the lithospheric mantle to sequester and release volatiles. She is currently Chair of the UK's Volcanic and Magmatic Studies Group and Vice President of the Mineralogical Society of Great Britain and Ireland.

Hehe Jiang is a recent PhD graduate from Rice University (Texas, USA). She uses geochemistry as a tool to understand the interplay between the deep Earth and Earth's surface processes. She integrates field geology, analytical techniques, and simple geochemical/physical models to reconstruct the evolution of the continental crust, investigate paleohydrologic events in sedimentary basins, and study long-term elemental cycling.

Adrian P. Jones is a professor in petrology at University College London (UK). His laboratory uses experimental high-pressure methods to quantify materials and melting behaviour in Earth’s mantle and investigate the transport of materials to sites of volcanic eruptions. He is particularly interested in the deep earth cycle: where deep carbon is stored and how it is entrained back to the surface in carbon-rich magmas. Dr. Jones is a founding member of the Deep Carbon Observatory and continues to serve on its executive committee.

Balz S. Kamber is a professor of petrology at the School of Earth, Environmental and Biological Sciences at Queensland University of Technology in Brisbane (Australia). He applies geochemistry to understand the elemental cycles that operate on the Earth, with a particular interest in the mass exchange between the deep Earth and Earth’s surface. As a former resident of Sudbury, Ontario (Canada), he has taken an interest in the fascinating geology of large impact structures and their clues for processes that occur in the aftermath of an impact. His group is active in the development of novel analytical methods at the boundaries between chemistry, geology, material science and environmental science.

N. Ryan McKenzie is an assistant professor at the University of Hong Kong. He obtained his BS in geology/paleobiology at the University of California at Los Angeles (USA) in 2006; his MS degree in 2009 and his PhD degree in 2012, both from the University of California at Riverside. He was a Jackson Postdoctoral Fellow at University of Texas at Austin between 2012 and 2014 and a Flint Postdoctoral Associate at Yale University (Connecticut, USA) between 2014 and 2016. Ryan’s research focuses on the dynamic coevolution of various components of Earth’s surface system via field and analytical studies of the sedimentary rock record.

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Joseph A. Petrus is a postdoctoral fellow in the School of Earth Sciences at the University of Melbourne (Australia). He received BSc and MSc degrees in physics from the University of Waterloo and Queen’s University (Canada), respectively, and turned his attention to the Sudbury impact (Canada) for his PhD in Earth science from Laurentian University (Canada). He is particularly interested in applying geochemistry and geochronology to impactites and so better constrain the nature and fate of the rocks involved in large impact events. His research often involves developing and applying novel analytical techniques and data reduction strategies.
Celina A. Suarez is an associate professor in the Department of Geosciences at the University of Arkansas (USA). She received her BS degree from Trinity University (Texas, USA), her MS degree from Temple University (Pennsylvania, USA) and her PhD in 2010 from the University of Kansas (USA). She was a National Science Foundation Earth Sciences Postdoctoral Fellow at Boise State University (USA) where she used rare earth elements, stable isotopes, and infrared spectroscopy to understand bone preservation and diagenesis. Dr. Suarez’s research focuses on using the trace element and stable isotope geochemistry of fossil vertebrates, invertebrates, and paleosols to understand the paleoecology and paleo-climatolgy of ancient continental environments. She is particularly interested in past greenhouse climates and major climate shifts caused by carbon-cycle perturbations, such as the mid-Cretaceous thermal maximum and the end-Triassic extinction.

Bas van de Schootbrugge is an assistant professor in the Geosciences Department at University of Utrecht (The Netherlands). His research aims to understand the evolution of the biosphere in deep time. Dr. van de Schootbrugge focuses on major transitions in Earth history, such as the Toarcian Oceanic Anoxic Event and the end-Triassic mass extinction, because these provide snapshots of severe changes to the biosphere, environmental, and climate. He uses a multidisciplinary approach that combines paleontology with inorganic and organic geochemistry. Central to this work is an understanding of the causes and consequences of widespread ocean anoxia and the deposition of organic-rich black shales. To this end, he analyses organic-walled micro-fossils that provide insight into the response of terrestrial and marine primary producers.

Paul B. Wignall is a professor of palaeoenvironments at the University of Leeds (UK). He studies mass extinctions using a combination of palaeontological, sedimentological and geochemical approaches. He has spent over 25 years studying the Permo-Triassic mass extinction and has interests in extinction studies in general. The link between large igneous province volcanism and mass extinctions has been an especial focus of attention over the past 15 years.

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Deep Carbon Past to Present

Editors: Beth N. Orcutt, Isabelle Daniel, Rajdeep Dasgupta

Publication date: October 2019

Summarizing ten years of research by the Deep Carbon Observatory, this is a comprehensive guide to carbon inside Earth - its quantities, movements, forms, origins, changes over time, and impact on planetary processes - for students and researchers in Earth and planetary sciences. Also available as Open Access on Cambridge Core.

Elements in Geochemical Tracers in Earth System Science is a series of concise, authoritative overviews of the many novel isotope and elemental systems that can be used as 'proxies' or 'geochemical tracers' to reconstruct past environments.

Also of interest...

Published on behalf of the
Mineralogical Society
Earth Catastrophes and their Impact on the Carbon Cycle

Celina A. Suarez1, Marie Edmonds2, and Adrian P. Jones3

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Carbon is one of the most important elements on Earth. It is the basis of life, it is stored and mobilized throughout the Earth from core to crust and it is the basis of the energy sources that are vital to human civilization. This issue will focus on the origins of carbon on Earth, the roles played by large-scale catastrophic carbon perturbations in mass extinctions, the movement and distribution of carbon in large igneous provinces, and the role carbon plays in icehouse–greenhouse climate transitions in deep time. Present-day carbon fluxes on Earth are changing rapidly, and it is of utmost importance that scientists understand Earth’s carbon cycle to secure a sustainable future.

Keywords: impacts, Earth’s origin, extinction, climate change, volcanism, large igneous province

INTRODUCTION

Great strides have been made in quantifying the diverse world of carbon in Earth. Our understanding now encompasses the amount and forms of carbon storage in the Earth’s core, mantle and crust; how carbon is mobilized via melting and outgassing from the Earth’s interior; and the extent and diversity of carbon that is bound in the form of microbial life on the seafloor and in the crust. Much of this work has been carried out under the auspices of the Deep Carbon Observatory (DCO; a global network of over 1,000 scientists on a 10-year quest to better understand all aspects of Earth’s carbon cycle). Important synthetic outputs of the DCO are steady-state models based on groundbreaking new data that can be used to evaluate the contemporary fluxes between carbon reservoirs in the deep Earth and their effects on everything from the evolution of life to the air we breathe.

Armed with this understanding, we can better evaluate perturbations to, or nonlinearities in, the Earth system through deep time. Catastrophic events have caused measurable, perhaps irreversible, changes to Earth’s carbon cycle on land, in the air, and under the sea, as evidenced spectacularly by mass extinction events at significant stratigraphic boundaries associated with major carbon cycle perturbations (i.e., major influxes, or draw-downs, of carbon into, or out of, the surface reservoir). The search for catastrophic causes of perturbations in the carbon cycle ranges from the tipping points reached during slow accretion of tectonic plates into megacontinents, to shifts in atmospheric or ocean circulation, to instantaneous megaenergy events delivered by Earth’s inevitable orbital space encounters with bolides, to large-scale volcanism. These major events are often associated with biological diversity crises and mass extinctions. Deciphering the complex and often faint signals of distant catastrophes requires a multidisciplinary effort and the most innovative analytical technology.

This issue of Elements focuses on large-scale catastrophic perturbations to the modern day “steady state” carbon-centric Earth, exploring the fundamental connections between deep processes and life at the Earth’s surface. Our contributors apply and synthesize what we have learned over the past decade into our current understanding of carbon through deep time while addressing gaps in knowledge and areas of focus for future deep carbon research.

THE DEEP (GEOLOGIC) CARBON CYCLE

The Earth’s carbon cycle is complex and operates on multiple spatial and temporal scales. Biologists, ecologists, and paleontologists tend to focus on the “terrestrial biosphere” portion of the carbon cycle which is encompassed by photosynthetic organisms (plants, algae, some bacteria) acquiring carbon from the atmosphere and ocean; the transfer of carbon to animals that eat those organisms; the death and burial of both organisms, their consumption by scavengers, bacteria, and fungi; and then the regrowth of organisms from the substrate (e.g., plant growth). This

Box 1 FORMS OF TERRESTRIAL CARBON

Carbon exists in a diverse range of solid, fluid and gaseous forms in, and on, the Earth. Some of these phases involve combinations of carbon with oxygen (e.g., carbonate minerals, carbonatite magmas, carbon dioxide), elemental carbon (e.g., diamond, and amorphous carbon), combinations of carbon with iron, combinations of carbon with hydrogen (e.g., kerogen, coal, petroleum, methane and its clathrates), and combinations of carbon with other elements (e.g., silicon, sulfur, nitrogen). Experiments, observations and theory suggest that perhaps >90% of Earth’s carbon resides in the iron alloy core of the Earth, whilst the rest is distributed between the mantle, crust (including sediments), biosphere, and ocean and atmosphere. The oceans and atmosphere combined likely hold <1% of the total amount of Earth’s carbon, yet this carbon has enormous implications for our climate and for the habitability of our planet’s surface.
is a short-term carbon cycle (“surface carbon” in Fig. 1) and operates on a timescale of carbon turnover from tens to thousands of years. The long-term, or geologic, carbon cycle encompasses the emission of CO₂ from volcanic sources (e.g., spreading ridges and volcanoes at subduction zones); carbon drawdown via silicate weathering and the formation of carbonates, or carbon drawdown via the photosynthesis of carbon by phytoplankton and plants; its burial as either organic carbon or inorganic carbonate; its subduction into the mantle; its eventual return to the atmosphere via volcanic and metamorphic outgassing sources. The two cycles are linked via the emissions of carbon to the atmosphere from volcanic and metamorphic sources and via biological weathering of silicates and burial of that organic matter. This large-scale system is kept in balance as long as the influx of carbon into the system (namely carbon from volcanic and metamorphic sources) is approximately equal to the carbon taken out of the system via weathering, burial, and subduction (assuming that the Earth does not receive or lose carbon). When the flux of carbon emissions from deep carbon is significantly altered, for example, it can result in a “perturbation” to both cycles. Figure 2 illustrates current estimates of the fluxes of carbon into and out of the surface reservoir by the long-term (geologic) carbon cycle. Fluxes of carbon from the surface carbon reservoir are shown for the burial of organic carbon and for the subduction of carbon (which includes carbonate in the oceanic crust and mantle and carbonate in sediments) into the mantle. The fluxes in and out of the surface reservoir are large compared to the size of the atmosphere–ocean system, which leads to relatively rapid turnover (residence) times for carbon in the atmosphere–ocean system (~2.5 × 10⁵ years) (Berner 1999).

By analyzing the carbon and carbon isotopic composition (see side bar Fundamentals of Carbon Isotope Geochemistry) of the geological record over time, we can identify major shifts, or perturbations, to Earth’s long-term carbon cycle. Some short-term, rapid events produce perturbations, but the system eventually returns to the steady state (e.g., large igneous provinces). However, a few perturbations have altered the carbon cycle permanently (e.g., the evolution of photosynthetic organisms on land at ~380 Ma). Some of these major shifts perturbed the system so rapidly that organisms could not adapt quickly enough to the associated environmental change, causing mass extinction. At times in Earth’s history, slow inexorable changes in tectonics caused changes in the arrangements of the continents and, hence, in the carbon cycle’s “vigor” through the waxing and waning of arc and continental rift volcanism (Brune et al. 2017). This resulted in large-scale changes in atmospheric CO₂ that persisted for millions of years. Today, the flux of anthropogenically generated carbon, primarily from burning of fossil fuels that formed over millions of years, is contributing to a major perturbation to the carbon cycle (Fig. 2). Indeed, the current flux of CO₂ to the atmosphere via the burning of fossil fuels far outweighs (by >80 times) both the influx of carbon from volcanic and tectonic sources and the outflux of carbon via organic carbon burial and subduction. In order to understand the possible effects of this perturbation, there is a need for scientists to understand other catastrophic perturbations in Earth’s history and to evaluate the sources and sinks of carbon in the Earth system.

**PERTURBATIONS TO EARTH’S DEEP CARBON**

The goal of this issue of *Elements* is to discuss how perturbations to the steady-state carbon cycle of Earth occur, and the consequences for the evolution of life and the planet itself. The concepts of uniformitarianism are well established in the Earth sciences: the idea that the present is the key to the past is fundamental to explaining long timescale geological processes such as orogeny, erosion, continental drift, and sedimentation. There is, however, widespread understanding, borne out of early theories on catastrophism but now based on well-constrained data and models, that high-energy, high-impact events have occurred at intervals through Earth history that have had lasting and important consequence on the Earth’s biosphere and geochemical evolution. We present five articles in this issue aimed at understanding the origins of carbon in Earth via chondritic delivery, cometary bombardment and its timing (Mikhail and Furi 2019 this issue), the effects and implications of bolide impacts on the carbon budget of the Earth (Kamber and Petrus 2019 this issue), the abrupt inputs of carbon associated with the emplacement of large igneous provinces (Black and Gibson 2019 this issue), the tipping points in carbon cycling associated with slow tectonic processes and supercontinent assembly and breakup (McKenzie and Jiang 2019 this issue), and the impacts of carbon cycle perturbations on the biosphere, and mass extinctions (Schobben et al. 2019 this issue).
**Origin and Distribution of Carbon in the Earth**

Mikhail and Furi (2019 this issue) provide an introduction to the origin and distribution of carbon in the Earth. Arguably the greatest perturbation of them all was the violent birth of our solar system at \(-4.55\) Ga. Our planet was born out of a cloud of gas and dust, perhaps relatively poor in carbon. So, where did our planetary budget of carbon come from? How was it distributed in the Earth and how long did it take for the present-day distribution of carbon to be established? Cosmochemical constraints tell us that the inner planets of our solar system first grew “dry”, then came volatile-rich objects (comets and chondritic meteorites) which later contributed much of the volatile inventory of the planet (Marty 2012). Detailed studies of the volatile inventory of the bulk Earth, divided into the different reservoirs, have shown that much of the noble gases reside in the atmosphere and a large fraction of the H, C and N are sequestered into the silicate Earth. This distribution of volatiles is largely due to planetary processing (melting, degassing, differentiation) and the existence of refractory phases in the mantle. The total volatile content of Earth is consistent with the addition of \(-2 \pm 1\)% carbonaceous chondrite material during the main accretionary phase of Earth-forming events, rather than during the late veneer which happened after the main phase of differentiation and which is required to explain the abundance of platinum group elements (Marty 2012).

**Carbon and Bolide Impacts**

A bolide (asteroid or comet) is defined as a meteor brighter than Venus in the night sky, i.e., a fireball. Bolide impacts have been an essential part of the development of the solar system. The frequency and scale of bolide impacts have been an essential part of the development of the Earth. The Earth has also been subjected to more sparsely distributed (in time and space) impacts, but they have had enormous consequences for our habitable environment and for the storage and cycling of carbon and other volatiles in the deep and shallow reservoirs of Earth. The Cretaceous–Paleogene (K–Pg) event, which is widely correlated with the Chixculub (Mexico) impact, occurred 66 Ma ago in the region of the present-day Gulf of Mexico. It released \(-10^9\) Mt of energy on impact (Reimold and Jourdan 2012), a fraction of which was disseminated in providing energy for the dissociation of sedimentary carbonates into gaseous CO\(_2\) and other species (Kawaragi et al. 2009). Carbonate rocks are thermodynamically unstable at the high temperatures that are induced by shock heating and are devolatilized to form carbon-bearing gas species (including both CO\(_2\) and CO). Laboratory experiments and thermodynamic modeling have suggested that CO may be the dominant gas produced during shock devolatilization, which would lead to enhanced O\(_2\) and CH\(_4\) due to photochemical reactions and so lead to a temperature rise of perhaps as much as 2–5°C (Kawaragi et al. 2009). This rise in temperature, even more so than the direct effects of a giant impact, may have led to the sudden collapse of biological systems and contributed to mass extinction. However, there is a large uncertainty associated with this scenario that arises from disagreements surrounding the impact scenario and the impact-driven devolatilization reactions of carbonates (limestones).

Other impacts may also have led to indirect perturbations of the carbon cycle. Impacts may have caused lithospheric decompression melting and associated magma degassing, causing widespread volcanism (Richards et al. 2015), although the links between melting and impacts remain controversial (Ivanov and Melosh 2003). The Sudbury Basin impact (Ontario, Canada), which occurred 1.85 Gy ago (Dietz 1964), is thought to have caused extensive crustal melting, and the igneous complex which developed is perhaps the world’s largest deposit of nickel and copper.

**Carbon and Large Igneous Provinces**

Large igneous provinces (LIPs) are voluminous outpourings of lava onto the surface of the Earth. They have been linked to severe environmental impacts and mass extinctions.
Elements October 2019

Fig. 3. Atmospheric pCO₂ over Earth history in relation to major environmental changes since the Neoproterozoic. These include five large igneous provinces (LIPs): the Viluy (southern Siberia), the Siberian, the Central Atlantic Magmatic Province (CAMP), the Karoo (southern Africa) and Ferrar (Antarctica), and the Deccan (west central India). Also shown are the major tectonic events, five mass extinctions, and large changes in climate regimes. Abbreviations: Ediac. = Ediacaran. ADAPTED FROM MCKENZIE ET AL. (2016).

Critical to the interpretation of such perturbations in the carbon budget of the surface reservoir is a good understanding of how much carbon is brought to the surface by LIP magmas. Up to now, there has been no systematic review of the carbon budgets of LIP magmas: estimating the amount of carbon lost from mantle-derived melts, with very little evidence remaining in the rocks, is a supreme challenge. Black and Gibson (2019 this issue) bring together a range of methods for estimating the primary carbon contents of present-day ocean island basalts, which they use to improve our estimates of LIP-driven carbon emissions. There are many important questions surrounding the impact of LIPs on the surface reservoir carbon budget. How much carbon is released, and at what rate? Does the carbon come from the convecting mantle or from the subcontinental lithosphere? To what extent does large-scale mantle heterogeneity complicate the picture of degassing LIP magmas?

Tectonic Influences on the Long-Term Carbon Cycle

Plate tectonics exerts a primary control on the long-term carbon cycle (Raymo and Ruddiman 1992). Superimposed on the gradual movements of tectonic plates are shorter timescale perturbations in the deep carbon cycle prompted by thresholds and tipping points, or when feedbacks take effect (Fig. 3). So-called “icehouse” conditions governed the Cryogenian, late Ordovician, late Paleozoic and late Cenozoic. These icehouse conditions were interspersed with warm climates, so-called “greenhouse” periods, during the early Paleozoic and early Cenozoic. During the icehouse phases, the planet had ice sheets, of varying extent, and lower pCO₂. The causes of these climate shifts, which occur over million-year timescales (Fig. 3), are thought to be due largely to tectonics. The effects of tectonics on climate may be “sink-driven” [controlled by the drawdown of CO₂ via silicate weathering during and after major orogenic events (Raymo and Ruddiman 1992)] or “source-driven” [the changes in balance between passive and active tectonic margins, which affects the outgassing flux of magmatic and stored lithospheric carbon (Mckenzie et al. 2016)]. There are periods during Earth’s history when these climate changes were extreme. For example, the Earth was almost entirely glaciated during several periods in the Neoproterozoic, producing what has become known as a “Snowball Earth”—a state which persisted for many millions of years, possibly enabled by extreme positive feedbacks involving the enhanced albedo of surface ice sheets (Hoffman and Schrag 2000). The Earth may have escaped the clutches of ice and extreme cold when volcanism resurged above the ice to outgas enough CO₂ to cause global warming and, thus, melt the snowball.

Environmental Disasters and Mass Extinctions

A major feature of catastrophic events is their association with mass extinctions (Mckenzie and Jiang 2019 this issue). Mass extinctions occur when the rate of extinction exceeds the background extinction rate. Background extinction rates have been defined as 0.1–1.0 species extinctions per 10,000 species per 100 years (Ceballos et al. 2017): this is also related to the rate of evolution of new species (origination). Some mass extinctions (e.g., the end-Devonian) may be explained by a lack of origination rather than the extinction of many species. But why do species become extinct?

Four of the five largest mass extinctions are associated with large igneous provinces (LIPs). These LIPs are associated with major carbon cycle perturbations caused by large and rapid influxes of carbon into the system from both mantle and sedimentary sources (Svensen et al. 2009). The rate at which the carbon is input into the atmosphere, and its chemical nature (e.g., CO₂ versus CH₄) is likely to be...
An isotope of an element has the defining number of protons for that element but a different number of neutrons; thus, different isotopes for a given element have different atomic masses. For example, all carbon atoms must have 6 protons, but different isotopes of carbon can have either 6, 7, or 8 neutrons, and so have atomic masses of 12, 13, and 14, respectively. These isotopes are denoted 12C, 13C, 14C. Of the three isotopes, 12C and 13C are stable. Carbon-12 is the most abundant in nature, having an abundance of 98.93% against only 1.07% for 13C. Carbon-14 is radiogenic and decays over short spans of geological time (half-life <6 ky) and so is not present in ancient rocks. It is difficult to measure precisely the absolute abundance of isotopes in natural substances, so the molar abundance ratios (13C/12C) are obtained instead, determined using isotope-ratio mass spectrometry. Stable carbon isotope values are, by convention, stated relative to VPDB (Vienna Peedee belemnite – a belemnite from the Peedee Formation of South Carolina, USA). This is achieved by measuring the certified reference (NBS 19), which has a known carbon isotope offset relative to VPDB. The carbon isotopic values are expressed using the delta (δ) notation in “parts per thousand” (%), and derived from the following equation:

\[ \delta^{13}C = \left( \frac{^{13}C/^{12}C}_{\text{sample}} - \frac{^{13}C/^{12}C}_{\text{reference}} \right) \times 1000 \]

Thus, a sample with a greater 13C relative to the standard is termed “enriched”, and if found to be lesser, is “depleted”. Kinetic and equilibrium effects are important determinants as to why a sample has a given isotopic composition. Isotope fractionation causes partitioning of the stable isotopes between phases, as observed in the different reservoirs of carbon in the Earth (see Figure below). Dissolved inorganic carbon in the ocean, for example, has heavier 13C than the organic carbon of plankton in the ocean because organic matter production during photosynthesis is an enzyme-mediated process, accompanied by a large carbon isotope fractionation that preferentially selects the light 12C isotope and shifts 13C by ~25‰ (on average) over the Phanerozoic. By contrast, carbon isotope partitioning during carbonate mineral precipitation from water causes only a small fractionation, and so limestone values closely approximate the dissolved inorganic carbon values of the contemporary ocean. The removal of inorganic and organic carbon from the ocean-atmosphere system is balanced on geological timescales (>10⁵ years) by carbon release from metamorphism and volcanic outgassing. The combined effect of these latter fluxes, and their isotopic compositions, dictate the size and isotope composition of the Earth’s surface reservoirs. On geological timescales, the oceanic dissolved inorganic carbon pool and the atmospheric CO₂ pool behave as one reservoir, because of the continuous exchange between them.

Figure

Box 2  \textbf{FUNDAMENTALS OF CARBON ISOTOPE GEOCHEMISTRY}

An isotope of an element has the defining number of protons for that element but a different number of neutrons; thus, different isotopes for a given element have different atomic masses. For example, all carbon atoms must have 6 protons, but different isotopes of carbon can have either 6, 7, or 8 neutrons, and so have atomic masses of 12, 13, and 14, respectively. These isotopes are denoted 12C, 13C, 14C. Of the three isotopes, 12C and 13C are stable. Carbon-12 is the most abundant in nature, having an abundance of 98.93% against only 1.07% for 13C. Carbon-14 is radiogenic and decays over short spans of geological time (half-life <6 ky) and so is not present in ancient rocks. It is difficult to measure precisely the absolute abundance of isotopes in natural substances, so the molar abundance ratios (13C/12C) are obtained instead, determined using isotope-ratio mass spectrometry. Stable carbon isotope values are, by convention, stated relative to VPDB (Vienna Peedee belemnite – a belemnite from the Peedee Formation of South Carolina, USA). This is achieved by measuring the certified reference (NBS 19), which has a known carbon isotope offset relative to VPDB. The carbon isotopic values are expressed using the delta (δ) notation in “parts per thousand” (%), and derived from the following equation:

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Figure

The isotopic composition of the Earth’s carbon reservoirs and the processes that modify them. Adapted from Summons et al. (2011).

more important than the absolute amount. Although the sulfate aerosol that is formed from volcanic SO₂, when injected into the stratosphere, has a cooling effect (Robock 2000), the residence time is only on the order of days to years; however, the effects may be prolonged due to frequent injections. Carbon, on the other hand, especially in the form of CO₂, has the ability to warm the planet over hundreds to thousands of years in the long-term carbon cycle because its residence time in the surface reservoir is longer, on the order of 10–10⁴ years. This warming can cause changes to the hydrologic cycle, thermal damage to plants, melting of ice-sheets, disruption to the thermohaline circulation of the ocean, anoxia, and ocean acidification. These components contribute to the habitable environment of communities or ecosystems. Therefore, it is not so much the carbon itself that causes extinction, but its effect on the environment and the life that inhabits it.

Critical to the study of mass extinctions in our planet’s past is the reconstruction of past environments and climates. Most paleoclimate proxies are chemical in nature and measure the isotopic composition or elemental concentration of either minerals or fossils preserved in the rock record. Because we cannot travel back in time with a thermometer, we must rely on proxy measurements using materials that we can analyze chemically and for which that chemical composition is dependent on the climate parameter of interest (e.g., temperature, CO₂ precipitation rate).

FRONTIERS

Deciphering the abrupt perturbations in the carbon cycle over our planet’s history requires forensic studies of geological records combined with technological advances to allow precise dating and analysis of geochemical proxies. Accurate chronologic control of the geological record is needed for evaluation of the timing of species loss associated with LIPs and the extent and duration of carbon isotopic excursions that may be linked to environmental degradation and extinction. Although advances in techniques used to date volcanic material have allowed geologists to constrain ages of volcanic eruptions within ~10 ky resolution or less, our ability to obtain similar precision in the sedimentary record, to tie in with environmental proxies and fossils, is less well developed. Combinations of a variety of relative and absolute dating methods—astrochronology, biostratigraphy, magnetostratigraphy, chemostratigraphy, and geochronology, particularly in lake and ocean sediments—can approach a precision of 10 ky, but it is difficult, time-consuming and expensive. Most challenging is dating continental deposits of fluvial and overbank deposits where deposition is often episodic, with periods of nondeposition, pedogenesis, and periods of rapid deposition.

Models are a good way to link surface and deep reservoirs (Lenton et al. 2018). Of particular promise are plate tectonic reconstructions that allow quantification of elements of the deep carbon cycle, such as mid-ocean ridge carbon flux through time, the carbon in-gassing and outgassing through subduction zones, carbon fluxes produced from mantle plume-related magmatism, and the carbon produced from continental rifting (Brune et al. 2017). There is also great potential for modeling carbon sinks in the crust and lithosphere during orogenic events, as well as drawdown of CO₂ by silicate weathering and during ophiolite obduction. The new generation of surface reservoir carbon-climate models, such as COPSE (carbon–oxygen–phosphorous–sulfur evolution) (Lenton et al. 2018), allow forward modeling of C, S, P, O, and N cycling and can predict isotope records by testing hypotheses against data. A fruitful research direction would be to link carbon isotope box models to plate tectonic reconstructions. Such a link is necessary to understand the complexity of the long-term carbon cycle and the perturbations to the carbon cycle. Then one can understand their effects on the evolution of Earth’s biologic and physicochemical system.
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RELATED TOPICS TO DEEP CARBON CYCLE

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On the Origin(s) and Evolution of Earth’s Carbon

Sami Mikhail¹ and Evelyn Füri²

INTRODUCTION

Earth is unique among the planets in our solar system in that it has liquid water at its surface, it has fostered life, and it has active plate tectonics. Whether these phenomena are linked remains one of the most exciting puzzles in planetary science and is central to the search for habitable exo-worlds. Earth’s clement environment is related to its atmospheric chemistry, which is warm enough to stabilize liquid water at its surface but cold enough to permit plate tectonics (Foley 2015). To understand the chemistry of Earth’s initial atmosphere and how this developed into a habitable environment, we must know the origins of Earth’s carbon.

An important tool for solving for the origin of Earth’s volatiles comes from the stable isotopes of carbon, $^{12}$C and $^{13}$C (Fig. 1), complemented with other isotope systems (e.g., hydrogen, nitrogen, noble gases) (Grady and Wright 2003; Füri and Marty 2015; Marty et al. 2016; Alexander et al. 2017). The carbon isotope signatures of the different solar system objects are strikingly homogeneous (Woods and Willacy 2009) and overlap with the average carbon isotopic value of Earth’s convecting upper mantle (i.e., average $\delta^{13}$C $\approx -5\%_{oo}$).

Multi-element isotope datasets allow scientists to record the isotopic “flavor” of the loosely grouped “volatile elements” as a function of reservoir type. This permits the identification of primordial reservoirs (e.g., solar nebula gas, asteroids, and comets), and it allows us to decipher the cosmic provenance of terrestrial volatiles, including carbon. We can then compare the isotopic signatures of these reservoirs to what we know of Earth and so identify the proportions of the components that make up Earth’s carbonaceous cocktail.

A major caveat is that, throughout Earth’s history, this cocktail has been shaken and stirred by planet-defining events such as differentiation (i.e., core formation), the “giant” Moon-forming impact, and the proposed “late veneer”. As a result, constraining the origin, abundance, and distribution of carbon in the Earth system is not a simple task. Importantly, carbon forms various compounds with many other elements. This means that carbon can, under the right conditions, follow the pathway of the atmophile, lithophile, siderophile, and (very rarely) the chalcophile elements (see Table 1). As a consequence,

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**Figure 1** (top) The broad architecture of the solar system showing the Sun, 8 planets, asteroid belt, and the dwarf planet Pluto. (bottom) The measured carbon isotope values expressed as $\delta^{13}$C for a variety of solar system objects: $\delta^{13}$C = $[(^{13}$C/$^{12}$C$_{sample})/(^{13}$C/$^{12}$C$_{PDB}) - 1] \times 1000$. Abbreviation: PDB = Pee Dee belemnite standard. Error bars for $\delta^{13}$C reflect standard deviations from the mean. The error bars for distance indicate the possible range of formation distances. Abbreviation: AU = astronomical unit (mean distance of the Earth from the Sun). Data from Grady and Wright (2003); Lyons et al. (2018); Woods and Willacy (2009) and references therein.
carbon is incorporated into every layer of the Earth system (Kelemen and Manning 2015). Thus, although carbon is usually grouped as a highly volatile element (alongside hydrogen, the noble gases, the halogens, and nitrogen), the notion that there has been a considerable loss of carbon during planetary accretion and differentiation is potentially inaccurate. The concept of volatility during condensation and evaporation is not directly applicable to the geochemistry of carbon per se. This is because carbon is rarely found solely in its native state (i.e., graphite, diamond, or amorphous). Instead, carbon exists in a variety of materials with different oxidation states (i.e., compounds) that have vastly different physical and chemical properties, such as their boiling points (Fig. 2). Thus, one must be aware that stating a particular volatility value for carbon is inherently inaccurate. Instead, it is more useful to consider the relative volatilities of specific carbonaceous compounds. For example, methane is a highly volatile compound (similar in volatility to argon), which only exists in solid form in the colder regions of the outer solar system, whereas graphite and diamond are the least volatile (most refractory) naturally occurring inorganic carbonaceous materials (Fig. 2) and were preserved in the inner planet-forming region of the solar system.

This article provides an overview of the pathways followed by carbon in the solar nebula and during the accretion and evolution of planetesimals and planets, including the formation of the Earth–Moon system. We also outline what we know of the origin(s) of Earth’s carbon, including how the bulk terrestrial carbon isotope value might have been fractionated, and we highlight the need for robots to boldly go where no robots have gone before in order to address the exciting gaps in our knowledge.

### CARBON IN THE SOLAR SYSTEM

The solar system formed ~4.567 billion years ago from gas and dust during the gravitational collapse of a dense core within an interstellar molecular cloud. A protoplanetary disk (traditionally referred to as the solar nebula) coalesced around the growing young Sun and had a strong thermal gradient across the disk, i.e., temperatures decreased away from the center. It was within this rotating disk that the planets formed. Carbon was present throughout this celestial system: in the hotter regions, it was in the form of gaseous CO, CO₂, and CH₄; beyond the soot line (which is mobile as a function of solar luminosity; Kress et al. 2010), it appears in admixtures of refractory organic molecules and pre-solar C-rich grains; in the cold regions, it occurs as CO₂-, CO-, and CH₄-bearing ices. Cooling led to the formation of protoplanetary dust (i.e., calcium–aluminum-rich phases and Mg-rich chondrules), followed by the accretion of undifferentiated planetesimals. We can still sample such primitive objects in the form of chondrites, some of which are carbon-rich (e.g., CI carbonaceous chondrites of the Urvana type). The presence of a potent heat source in the form of the short-lived radionuclide ²⁶Al (with a half-life $t_{1/2}$ = 0.7 million years) meant that planetesimals that accreted within ~1 million years of solar system formation melted and differentiated (Carlson et al. 2014), creating bodies with metallic cores and silicate mantles and crusts (e.g., asteroid Vesta; Hin et al. 2017). Fragments of these cores and mantles/crusts still fall onto Earth today in the form of iron and achondritic meteorites, respectively.

On average, the achondrites contain low carbon abundances, presumably because the C-carrier phases were destroyed during high-temperature processing. However, the high-energy stages of planetesimal formation did not always entirely remove carbon from a given planetesimal. For example, meteorites from 4 Vesta typically contain 10–30 ppm carbon and have no free carbon phase, whereas ureilites—a rare type of stony (silicate-rich) meteorite—can contain up to 7 wt% carbon and have free carbon phases in the form of graphite and diamond (Grady and Wright 2003). Even iron meteorites, which represent relics of core material from differentiated bodies, show significant carbon abundances (predominantly in the form of graphite inclusions and carbides, but also as dissolved impurities in the Fe–Ni alloy) (Grady and Wright 2003), indicating that the metallic cores of planetesimals had sequestered carbon during core–mantle differentiation.

Further accretion of dust and planetesimals resulted in the formation of telluric (silicate-metal dominated) asteroids, and eventually, the rocky planets of the inner solar system. The terrestrial planets, it is worth noting, presumably formed within the mobile snowline, a virtual limit beyond which water freezes, currently situated at 2.7–3.2 AU (astronomical unit, the mean distance between the Earth and the Sun). The equivalent also exists for carbon, i.e., refractory organic compounds are stable only beyond the soot-line (Kress et al. 2010), whereas CO, CO₂, and CH₄ ices only exist beyond the orbit of Saturn. Thus, it is considered that the planetesimals of the inner solar system were originally carbon-depleted. At greater heliocentric distances, the
process of accretion involved organic carbon-bearing ices (comet-formation), and the birth of the gas giants (Jupiter and Saturn) and ice giants (Uranus and Neptune). The result is a (semi-)stratified solar system, with rocky interior planets and gaseous/icy outer planets.

In between these two planetary families (rocky and gaseous/icy) resides an orbiting array of left-over planetary building blocks known as the asteroid belt (Fig. 1). Despite its apparently well-ordered current orbital architecture, the evolution of the solar system is thought to have been dynamic. To a first approximation, the building blocks of the terrestrial planets were depleted in elements with volatile affinities (Albarede 2009). However, volatile-rich material, isotopically akin to carbonaceous chondrites, from beyond the snow- and soot-lines, could have been scattered into the terrestrial planet forming region due to the inward and outward migration of the giant planets, as proposed in the “Grand Tack” model (Walsh et al. 2011), or simply because the orbits of nearby planetesimals were destabilized by the growth of the giant gaseous/icy planets (Raymond and Izidoro 2017).

CHONDRTIC CARBON—THE OLDEST ARCHIVE

The chondritic meteorites represent the most primitive rocks of the early solar system that can be examined in laboratories today. They are a group of metal-bearing stony objects, which agglomerated at varying distances from the Sun, and they can be divided into three major classes: carbonaceous, ordinary, and enstatite (Fig. 1). Although several groups of the class known as the carbonaceous chondrites contain a large amount of carbon (up to ~3.5 wt%) (Grady and Wright 2003), the name “carbonaceous” is somewhat misleading because some ordinary and enstatite chondrites are more carbon-rich. Most of this carbon is in the form of organic compounds dispersed within the chondritic matrix (e.g., Alexander et al. 2017), but inorganic carbon phases are also present (i.e., graphite, diamond, carbides, and carbonates). The bulk $\delta^{13}$C value of different chondrite classes ranges from $-25\%$ to $+4\%$ (Grady and Wright 2003), a range that encompasses the estimates of the bulk carbon isotope value of Earth’s mantle (average $\delta^{13}$C $\approx -5\%$) (Deines 2002). Furthermore, the hydrogen and nitrogen isotopic signatures of CI chondrites—the richest in water, organics, and noble gases among all meteorites—closely match those of Earth (Füri and Marty 2015). This implies that the major volatile species on Earth were derived from a cosmochemical reservoir that is isotopically similar to the volatile inventory of primitive asteroids and distinct from the icy and volatile-rich cometary bodies and the initial signature of the solar nebula (Marty et al. 2016).

Although chondritic meteorites have never been heated to the point of complete melting, they have all been heated above the sublimation temperature of the most volatile elements, such as the noble gases. This explains why the Sun shows elevated primordial noble gas abundances ($^{20}$Ne, $^{36}$Ar, $^{84}$Kr, and $^{130}$Xe) relative to the chondritic values (Fig. 3), but chondritic meteorites retain solar-like refractory lithophile element abundances (e.g., Mn/Mg). If one compares the abundance of the elements in chondritic meteorites with the solar photosphere (the Sun), then a 1:1 relationship is observed for most elements when normalized to silicon (Fig. 3). Importantly, according to the “chondritic Earth model” (e.g., McDonough and Sun 1995), the bulk composition of the Earth is broadly similar to that of chondritic meteorites. Thus, one can apply chondritic data to estimate the Mn/Mg ratios for the bulk Earth system, or to calculate the size of Earth’s core, where estimates using chondritic Fe/Mg ratios agree with the geophysical constraints. But one cannot use the “chondritic Earth model” to calculate the mass of carbon in the bulk Earth. Chondritic data show that carbon has been fractionated from solar nebular abundances (e.g., C/Mg, but less so than for nitrogen (e.g., N/Mg). However, both carbon and nitrogen were significantly less fractionated than the noble gases (Fig. 3). This is likely, in part, because carbon (and nitrogen) can exist in a variety of redox states with hugely variable boiling points/volatilities (see Fig. 2 for carbon). Therefore, one cannot calculate the carbon abundance for the bulk Earth using chondritic or solar data (i.e., using the C/Mg ratio). In summary, we do not know Earth’s bulk carbon abundance, but we do know that Earth’s carbon sources were fractionated from their initial abundances. In short, Earth’s C/O and C/Si ratios are certainly not solar, chondritic, nor cometary.

PLANET-DEFINING EVENTS IN THE HISTORY OF EARTH’S CARBON

Recent geochemical datasets show that Earth’s volatile elemental ratios (i.e., C/N or C/Si) are nonchondritic, suggesting that elemental fractionation occurred during planetesimal accretion (Hin et al. 2017), core formation (Dasgupta et al. 2009), giant impact(s), impact-induced atmospheric loss (Bergin et al. 2015), or a combination of all these processes (Grewal et al. 2019). Thus, long before plate tectonics began cycling and recycling Earth’s carbon between the surface and the interior, three recognized periods or events were particularly pivotal in the formation and evolution of the terrestrial carbon reservoirs. These events were either internally driven (core formation) or externally driven (the “giant” Moon-forming impact and the late veneer) (Fig. 4), and they modified the distribution of elements within planet Earth. As a result, the distribution of carbon and its isotopes between the terrestrial reservoirs—including the silicate portion that
The first ~1 million years of solar system history experienced significant, and perhaps complete, melting as a result of the energy provided by kinetic and radiogenic heating of star (Carlson et al. 2014). Hence, the terrestrial planets and their building blocks probably experienced at least one magma-ocean stage (of unknown depth), and, upon cooling and solidification, these bodies then differentiated into a metal core, silicate mantle, crust, and a primordial atmosphere. The layering of planets is primarily imposed by density differences; but some elements (and their compounds) find their way into different layers as a function of their chemical properties (ionic charge, radius, electronegativity, and volatility). Carbon is mobile within the Earth system, where the predominant mechanisms driving exchange are diffusion, volcanism, and chemomechanical mixing (i.e., plate tectonics). Thus, Earth’s carbon is in a constant state of flux operating on timescales from seconds to billions of years (Kelemen and Manning 2015). Figure 5 provides a snapshot of the distribution of carbon in the Earth system (today) without estimates for the size(s) of these reservoirs.

Earth’s core could well be the greatest reservoir of carbon, by mass. High-pressure experiments and the presence of carbon in iron meteorites demonstrate that metal–silicate equilibration always results in some fraction of carbon partitioning into the cores of planetesimals and planets (see Wood et al. 2013). Hence, many workers have attempted to constrain exactly how much carbon could have been sequestered into the core during differentiation. There is a driving rationale for this, beyond an interest in carbon geochemistry. Geophysical data has long shown that Earth’s core is a metallic alloy of Fe + ~5% Ni (McDonough and Sun 1995), but its density is too low to be simply a binary Fe–Ni alloy. To explain the density deficit requires that the core must contain 8%–12% of a component with an atomic number less than iron (Z = 26). Carbon has long been considered as one of the lighter elements in the core, along with H, N, O, S, Si (Wood et al. 2013). This is important for understanding the origin of Earth’s carbon if one applies a mass-balance approach because the core makes up >30% of Earth’s mass. Therefore, changing the mass of carbon in the core from a low to a high value would dramatically influence the calculated total carbon inventory of the whole planet. How much carbon is possibly stored in Earth’s core strongly depends on the initial amount of carbon present in the magma ocean, as well on the metal affinity of carbon under core-forming conditions. Over the last decade, experimental studies of the carbon partitioning between Fe–Ni alloy liquid and silicate melt (e.g., Dasgupta et al. 2009; Grewal et al. 2019) have revealed that the behavior of carbon during metal–silicate equilibration is highly sensitive to the composition of the Fe-rich alloy (including the abundance of the light elements H, N, S, and Si) as well as to the pressure (depth of differentiation), temperature, and oxygen fugacity (Wood et al. 2013). Importantly, the debate currently revolves around how much carbon was sequestered into the core, and not if carbon was partitioned into the core (Dasgupta et al. 2009; Wood et al. 2013; Grewal et al. 2019). Assuming that a large amount of carbon was accreted to the young Earth and that this was then sequestered to the core, then a significant amount of the carbon now present in the terrestrial mantle must have been delivered to the Earth after core–mantle differentiation, such as by a large impactor and/or during the accretion of the late veneer.

**Externally Driven Events**

Planet Earth has experienced at least two stages of secondary accretion, defined as events which altered the chemistry of the bulk Earth. The first formed Earth’s Moon; the second provided us with a large fraction of our precious metals (e.g., gold). The “giant” Moon-forming impact occurred within the first 40 to 100 million years of solar system history (Carlson et al. 2014) and was a collision between the proto-Earth and a planet-sized impactor named “Theia”. The impact was so energetic that it caused the bulk silicate Earth to explode from solid rock into a vapor cloud which left a lasting geochemical fingerprint on the volatile element inventory of the Earth–Moon system (Hauri et al. 2017). However, quantifying the effect of the giant impact on carbon geochemistry remains challenging, partly because we do not know the initial or present-day carbon abundance of planet Earth. The Moon-forming impact would have resulted in the melting of most (or all) of Earth’s silicate mantle in order to form a silicate vapor cloud, this event being followed by the formation of a deep magma ocean (Hin et al. 2017; Grewal et al. 2019). This stage of Earth’s history might have resulted in significant outgassing and the formation of a secondary atmosphere. Alternatively, Earth could have gained volatiles from the impactor (Grewal et al. 2019). According to the latter scenario, (partial) accretion of a large differentiated body would explain the major volatile element signature of the bulk silicate Earth. In
either case, carbon was certainly redistributed between Earth’s interior and the surficial reservoirs as a result of the Moon-forming impact.

The so-called “late veneer” was the largest meteor shower in Earth’s history. This bombardment represents the final sweeping up of the residual planetesimal material following the main stage of terrestrial planet formation in the inner solar system. The late veneer hypothesis is required to explain mantle geochemistry. Importantly, the late veneer would have postdated the formation of Earth’s core and the Moon-forming event and at least some stage(s) of atmosphere formation (Fig. 4). The late veneer is considered to have added the “iron-loving” highly siderophile elements (HSEs: Os, Ir, Ru, Rh, Pt, Pd, Re, Au) to the silicate Earth, and represents a contribution of ~0.1–2 wt% of mass chondritic material to Earth (e.g., Chou 1978). However, to explain what we think we know of Earth’s volatile inventory (\( \text{H}_2\text{O}, \text{C}, \text{N}, \text{halogens}, \text{noble gases} \)) requires the addition of ~2 (±1) wt% carbonaceous chondrite–like matter, which is equal to or greater than the mass of material delivered by the postulated late veneer derived using HSE geochemistry (Marty et al. 2016; Alexander et al. 2017). Furthermore, recent findings on the similarity of Ru isotopic compositions of the bulk silicate Earth and of enstatite chondrites suggest that the Earth’s late veneer had an enstatite chondrite–like isotopic signature. This would imply that the late veneer might have been volatile-poor (Fischer-Gödde and Kleine 2017) and that the delivery of terrestrial volatiles was not solely a late-stage event. Accordingly, Earth accreted volatile-rich material, likely sourced from beyond the orbit of Jupiter, during the main sequence of planet building. This accretion was possibly due to either lateral material transport triggered by the growth and/or migration of the giant planets during the earliest history of the solar system (Walsh et al. 2011; Raymond and Izidoro 2017) or during the giant impact phase (e.g., Grewal et al. 2019).

**ASSESSING THE CARBON ISOTOPE VALUE OF THE BULK EARTH**

This article began by highlighting how one can apply carbon isotope data alongside H, N, and noble gas data to constrain the origin(s) of the carbon on Earth, cosmochemically (Fig. 1). Later, we outlined several events in Earth’s early history that can be described as planet-defining, such as core formation, the “giant” Moon-forming impact, and the late veneer (Fig. 4). We also noted that carbon is distributed and redistributed throughout the entire Earth system in the form of various compounds (Fig. 5).

To apply stable isotope geochemistry to trace the source of terrestrial carbon relies on the assumption that the fractionation of volatile element isotopes is negligible during processing of ice and dust in the solar nebula and throughout the accretion/differentiation stages of planetesimal and planet formation. However, and problematically, these redistribution events and processes can all impart equilibrium carbon isotope fractionation. It is now established that the degassing from magma oceans and during high-energy impact events, as observed via moderately volatile isotope systems, can result in stable isotope fractionation (Kato et al. 2015). Thus, degassing of carbon from the magma ocean of low-gravity bodies (planetesimals) could have fractioned the \( ^{13}\text{C}/^{12}\text{C} \) ratio of Earth’s precursor material and of the young Earth itself. Early loss of carbon to space via \( \text{CO}_2/\text{CO} \) escape during degassing of a silicate magma ocean would deplete the magmatic carbon in the heavy isotope and decrease the \( ^{12}\text{C}/^{12}\text{C} \) ratio of the silicate portion of the planet (Horita and Polyakov 2015).

In addition, carbon isotope fractionation between metal–silicate systems preferentially sequesters the lighter isotope into the metallic phase(s) (Horita and Polyakov 2015). Therefore, isotope fractionation during carbon sequestration into the core would affect the carbon isotope composition of our planet, effectively increasing the \( ^{13}\text{C}/^{12}\text{C} \) ratio of the silicate portion of the planet (Mikhail et al. 2014). Thus, although the \( ^{13}\text{C} \) value of the convecting upper mantle is statistically well constrained based on the study of mantle-derived samples, it is conceivable that the \( ^{13}\text{C} \) value of the bulk Earth is different from that of the convecting upper mantle, or that the \( ^{13}\text{C} \) value of the modern bulk Earth might not reflect the initial \( ^{13}\text{C} \) value of the primitive Earth and/or its precursor bodies.

**SUMMARY**

Earth presumably accreted well within the snow line and the soot line, in a volatile-depleted region of the solar system. However, we know that Earth contains carbon, and that the H, C, and N isotopes point to a carbonaceous chondrite source for the terrestrial volatiles. Therefore, it is possible, and likely, that some of the material which formed the Earth originated from larger heliocentric distances. Because a significant fraction of early accreted carbon would have entered Earth’s core during differentiation, the (isotopically) CI chondrite–like volatiles must have been delivered to the terrestrial planet-forming region after core formation. However, the timing and mechanism(s) of carbon delivery remain a matter of debate. We know that Earth accreted a significant fraction of its present-day mass during late accretion events, but the delivery of volatile elements (such as C, N, Ar) during the late veneer cannot dominate Earth’s volatile budget. Earth is still accreting volatile-rich extraterrestrial matter today, with a flux of tens of thousands of kilograms per annum via micrometeorites.

The distribution of carbon in the different terrestrial reservoirs is not fixed, and the geological record is rife with externally and internally driven perturbations. For
example, Earth's surficial carbon reservoirs are perturbed by bolide impacts, some of which had dramatic environmental consequences (Kamber and Petrus 2019 this issue). We are also faced with one significant and inherent limitation: sampling Earth's interior is rife with sampling biases, restrictions, and the influence of surficial material emplaced into the mantle via subduction zone plate tectonics. In short, geological samples originate from depths of less than 100 km (of Earth's 6,371 km radius) and only a few minerals (chiefly diamond) show tentative evidence for a deeper mantle origin. The most obvious limitation is that we will never obtain samples of Earth's core.

Owing to the uncertainties outlined in this article, we use caution and choose not to make bold and biased claims as to our positioning for the relative proportions of the celestial components which make up Earth's cosmic cocktail. The long-standing enigma of the origins of Earth's carbon is a dynamic problem, which is much larger in scope than planet Earth itself. The answers are undoubtedly going to rely on a collaborative approach requiring advances in experimental, analytical, and computational technologies between geochemists, geophysicists, planetary scientists, and cosmochemists. The least studied, but accessible, part of the puzzle focuses on the provenance and distribution of carbon throughout the solar system. For example, samples from primitive carbon-rich asteroids are going to be returned to Earth in the early 2020s by two dedicated space missions: Hayabusa2, from Japan's JAXA, and OSIRIS-REx from USA's NASA. The milligram-sized samples, alongside data from cometary missions (Europe’s ESA Rosetta Mission), will provide exceptional, essential, and priceless information on the nature of carbon in the early solar system. This will enable a more robust assessment of the formation of Earth’s volatile reservoirs. To build upon the wealth of current and future terrestrial geoscientific datasets, we propose that such internationally collaborative planetary exploration missions, inclusive of sample-return objectives, are the best way forward to determine the relative proportions of the cosmic cocktail and to solve the origin(s) of Earth’s carbon.

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The Influence of Large Bolide Impacts on Earth’s Carbon Cycle

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INTRODUCTION

Large bolide impact events have become rare. At most, there is one strike of one ~10 km object every 100–200 million years (My). But the rich history of former bombardment is evident on the surfaces of inner solar system bodies, as well as from the few preserved impact features on Earth itself (e.g., Reimold and Jourdan 2012). Impact basins more than 1,000 km across exist on our planetary neighbours and they are pockmarked with thousands of smaller impact features. Counting crater numbers and measuring the sizes of craters on images of the Moon’s surface qualitatively shows that most of the very large basins formed early in the history of the solar system. Dates for lunar samples constrain the bulk of the bombardment to have occurred within the first ~700 My since planet formation. Importantly, however, significant events capable of producing basins hundreds of kilometres in diameter also happened in more recent history. It is instructive to study how these could have disrupted the complex interplay between biology and geology on Earth; that is, how they have affected the global biogeochemical carbon cycle.

The Earth’s geological history is subdivided into eons, eras and periods (Fig. 1). For the older eras, these subdivisions were defined with the appearance or disappearance of dominant rock types, whereas most boundaries of the younger eras and periods coincide with the rapid disappearance of organisms (mass extinctions). Many scientists suggest that the Earth has recently transitioned into a new period – the provisionally termed “Anthropocene” – this is defined to reflect the planet-wide effects of human activity. The Anthropocene could be described as a gigantic combustion experiment in which reduced, energy-rich forms of C (e.g., coal, oil, gas, wood) are oxidized to CO₂, with additional significant atmospheric emissions from industrial and land-use activity. The cumulative atmospheric CO₂ release since AD 1750 is ~2,000 Gt (Boden et al. 2009). For comparison, the bolide strike that formed the ~66 Ma Chicxulub structure (Mexico) released between 425 Gt and 1,400 Gt of CO₂ (Artemieva et al. 2017; Brugger et al. 2017). Thus, some large bolide impacts are comparable to the Anthropocene effect in terms of the rapid disruption of the carbon cycle and the potential for exceeding the currently unknown critical degree of perturbation (e.g., Rothman 2017). However, during the most intense bombardment period on the early Earth, the surface was poor in the C- and S-rich sediments that exert the greatest control over climate perturbation. Time, therefore, provides a natural narrative for a review of environmental consequences.

IMPACTS ON THE VERY EARLY EARTH

The Hadean Eon (4,567 Ma to ~3,850 Ma) is the oldest eon of Earth’s history, and it witnessed by far the largest number of impacts. Unfortunately, the Hadean geological record is very sparse and significant uncertainty exists about Earth’s evolution during that time. Nevertheless, three key questions are of great scientific importance because of their enduring legacy for the remainder of Earth history. They all relate to the Hadean impact history (e.g., Grieve and Stöffler 2012):

1. Did the Hadean bombardment deliver volatile elements, including water and carbon, to the early Earth?
2. What happened to the Earth’s vanished primordial crust?
3. Was life on Earth already established during the Hadean?

The delivery of extraterrestrial material to Earth happens with two dominant size classes of objects: the tiniest, and the largest. The fully formed Earth was struck by a few hundred bolides capable of causing very large (>100 km) impact basins (Bottke et al. 2012), and these objects contained at least one-third of the delivered extraterrestrial...
matter. At the other end of the spectrum, cosmic dust, having particle diameters in the micrometre range, constitutes the second significant source of extraterrestrial matter (Peucker-Ehrenbrink et al. 2016). Of the two types of impactors – comets and asteroids – comets are predominantly composed of volatile species (O, C, H, N), whereas asteroids include undifferentiated chondritic bodies that also contain ~1.1 wt% H and ~1.8 wt% C (e.g., Alexander et al. 2012), with organic molecules. Although intuitively, this suggests that the delivery of such matter to Earth during the Hadean might have contributed to the build-up of the hydrosphere and to the surficial C reservoir, this simple logic is complicated by impact physics.

Comparing the delivery of extraterrestrial elements of a refractory nature (i.e., with a high boiling temperature) to those of a volatile character (low boiling temperature) shows that most of the volatile cargo would be lost from cosmic dust upon its atmospheric entry (Peucker-Ehrenbrink et al. 2016), except for particles <35 μm which experience limited frictional heating. Impacts of larger bodies at velocities in excess of ~15 km/s cause at least partial vapourization of the target and intense heating to >10,000 K of the vapourized material (e.g., Collins et al. 2005), and this leads to the formation of a silicate vapour plume. The behaviour of the various chemical elements in these plumes, particularly atmospheric escape versus condensation and fallback to the Earth, is currently not fully understood. The isotopic systematics of light elements and noble gases suggest that late addition to the Earth from comets is unlikely to have been volumetrically important for water, nitrogen and carbon (Alexander et al. 2012). Current evidence favours an origin of the terrestrial volatiles by early capture during planetary accretion rather than by late addition during very large impact events.

Regardless of the origin of volatiles, the rate at which the lunar surface was bombarded (and, by analogy, the Earth) can be reconstructed by combining crater density statistics with the known ages of rocks from the Moon’s surface (e.g., Reimold and Jourdan 2012). The largest uncertainty in this flux estimate arises from the paucity of samples returned from the older, more heavily cratered dark side of the Moon and the few direct dates for large lunar impact basins (e.g., Bottke and Norman 2017). There are two end-member models for the bombardment flux: one that envisages a spike in very large impacts between 3,850 Ma and 4,200 Ma (the late heavy bombardment, or LHB) versus one that favours an exponentially decaying flux (the “accretion tail scenario” of Morbidelli et al. 2018). With currently available data, modelling cannot unequivocally rule out either scenario. One of the strongest pieces of evidence in favour of the LHB remains the U/Pb age line of lunar highland samples (Tera et al. 1974) that was originally used to advance the concept of a late bombardment. This line is interpreted to date the timing of volatile element loss and homogenization. The age conspicuously coincides with the more widespread preservation of terrestrial rocks, i.e., the Archaean–Hadean boundary (Fig. 1). If future lunar data confirm the existence and timing of the LHB, one of the most significant environmental consequences of very large bolide impacts on Earth could have been the destruction of the protocrust. On Mars and Mercury, the ancient protocrusts persisted, despite bombardment, but the LHB on Earth may have been effective at crust destruction if the crust-mantle system had reached a vulnerable state, due, for example, to build-up of internal heat (e.g., Kamber 2015).

**ARCHAEOAN IMPACTS AND THE EARLIEST CARBON CYCLE**

With no supracrustal rocks of Hadean age preserved, the question of putative Hadean life and its effects on the carbon cycle cannot be studied directly. By contrast, the
Archaean sedimentary record does contain samples with remains of organic (reduced) carbon, as well as carbonate, and there is clear evidence that the Archaean Earth was struck by very large bolides. No unequivocal Archaean impact basins have been found to date. Instead, the evidence for impacts comes from so-called spherule layers within sedimentary sequences (e.g., Simonson and Glass 2004). These tell-tale sediment layers are millimetre-to-metre thick, laterally continuous, and contain spheres of various compositions, some with evidence for quench cooling, high pressure minerals, or shock features. The first important inference drawn from their distribution in time (Fig. 1) is that the Earth continued to be bombarded with large bolides well beyond 3,850 Ma (e.g., Lowe et al. 2014) and that the Archaean witnessed more large impacts than the later eons (e.g., Bottke et al. 2012). Because many spherule beds are enriched in iron-loving (siderophile) elements, it has also been possible to incontrovertibly prove that some layers have had a contribution to their formation from a vapourized asteroid, for example via the isotope composition of Cr (e.g., Kyte et al. 2003).

A particular advantage of studying spherule beds is that they are preserved within a stratigraphic context (Simonson and Glass 2004). This provides additional sedimentary information and geochemical evidence of potential environmental disruption. Most of the well-preserved Archaean spherule beds from the Kaapvaal Craton (southern Africa) and the Pilbara Craton (western Australia) show evidence for sedimentary redistribution caused by currents and/or waves (e.g., Lowe et al. 2014). The consistent occurrence of spherules within reworked eroded local detritus rather than the pure deposits of constant thickness expected from fallout, strongly suggests that reworking was a consequence of the impact itself via tsunamis, impact-induced turbidity currents, or bottom return flows.

Johnson and Melosh (2012) concluded that most of the spherule bed-forming bolides were 20–50 km in diameter and would have excavated transient craters of up to 100 km deep and final basins reaching several hundred kilometres in diameter. To date, no such basin has actually been discovered. One interesting area of future research is the question of shock-metamorphism of the lithospheric mantle during impact. This may have led to burial of impact effects, as well as the crust–mantle boundary. In terms of environmental and carbon isotope consequences, the impact that caused the 2,629 Ma spherule layers in Western Australia and South Africa is particularly instructive because it is found within carbonate (mostly dolomite), which is conducive to chemical and isotopic analysis. According to Johnson and Melosh (2012), the corresponding impact basin would have been ~100–150 km in diameter and, thus, represent a significant event. The carbon isotope values for reduced carbon across the spherule bed do not show an incontrovertible trend, but nonetheless indicate a significant general shift towards lighter carbon from $^{13}\text{C}$ of ~42‰ to ~48‰ (Eigenbrode and Freeman 2006). By contrast, the shallow marine carbonate $^{13}\text{C}$ ($\delta_{\text{carb}}$) values remain near 0‰ across the spherule bed, but these data were obtained at a more limited spatial resolution that may not have captured the disruption of the global biogeochemical carbon cycle. More detailed isotopic studies across spherule beds are needed to explore to what extent the balance between the buried sedimentary reduced carbon and the dissolved oceanic carbon was disrupted by these impact events.

Carbonate is a less dominant sediment type in the Archaean supracrustal rock record than in the Proterozoic and the Phanerozoic. Therefore, it is impossible to produce a continuous global carbonate carbon isotope record that would cover all the ~15 known Archaean spherule layers to test how representative the 2,629 Ma event was. Notwithstanding this limitation, it is evident from the existing global compilation (Fig. 1) that the presently documented fluctuations in Archaean $\delta_{\text{carb}}$ were much less pronounced than in the Palaeoproterozoic and Neoproterozoic (e.g., Krissansen-Totton et al. 2015). Regardless of the potential of very large bolide impacts to temporarily disrupt the ancient carbon cycle, the apparent stability of the cycle itself, as well as the similarity of the predominant Archaean $\delta_{\text{carb}}$ with modern carbonate carbon, is astonishing. The oldest carbonates occur in the Isua Greenstone Belt (Southwest Greenland). They are between 3,710 Ma and 3,810 Ma and, although not universally accepted as sedimentary in origin, some appear to have yielded $\delta_{\text{carb}}$ close to the modern-day value of zero, and they have co-existing very light carbon preserved in putative biogenic graphite (Schidlowsky et al. 1979). Due to the pervasive metamorphic overprint of the Isua rocks, some doubt remains as to whether the recorded carbon isotope values truly reflect the sedimentary system. Regardless, many more paired reduced carbon and $\delta_{\text{carb}}$ values have been reported for younger Archaean sedimentary rocks, leaving little doubt as to the stability of the early terrestrial carbon cycle (e.g., Krissansen-Totton et al. 2015).

**PROTEROZOIC IMPACTS AND THE OCEAN– ATMOSPHERE SYSTEM**

Of the six largest preserved terrestrial impact structures, three are Proterozoic in age: the 2,023 Ma Vredefort impact structure (South Africa); the 1,849 Ma Sudbury Basin (Canada) and the 580–590 Ma Acraman crater (South Australia) (Fig. 1). Due to deep erosion of the Vredefort structure and the lack of a confirmed corresponding impact layer, it is impossible to reconstruct the environmental consequences of Earth’s largest preserved bolide impact. By contrast, both the Sudbury and Acraman events preserve remnant impact structures, as well as corresponding impactite layers in the sedimentary record. These two impact events are, therefore, more conducive to studying putative global environmental consequences.

The impact layer corresponding to the Sudbury Basin is found up to 700 km away in the Fe-rich sedimentary strata of the Lake Superior region of North America (e.g., Cannon et al. 2010). The layer is a breccia containing lithic fragments (some shocked), devitrified glasses of various kinds, as well as accretionary lapilli (Fig. 2); this layer differs from the Archaean spherule beds described in the previous section. Of critical importance is that the breccia layer occurs within a Palaeoproterozoic sedimentary context (Fig. 2). The bolide is believed to have hit a foreland basin covered by relatively shallow water (e.g., Ubide et al. 2017), and the main excavated rocks were quartz-rich sandstones of the >2,200 Ma Huronian Supergroup and Archaean basement. These contained very little carbon. However, Petrus et al. (2015) argued that the bolide was likely a 15 km diameter comet (density of 0.6 g/cm$^3$). If similar in composition to comet Halley, which has 18.4 wt% C (Delsemme 1988), the Sudbury object would have contained 195 Gt of C and, if fully vapourized, would have released ~700 Gt of CO$_2$, or about one-third of the CO$_2$ perturbation of the current Anthropocene experiment (Fig. 3A).

In the lead-up to the impact, the continental foreland basin of the Lake Superior region was ferruginous, with thick banded-iron formations being deposited. Cannon et al. (2010) noted that the Sudbury impact layer nearly always caps the iron formations and other ferruginous sediment (Fig. 2) and that deposition continued with different mud-sized detritus. No re-occurrence of the dominant deposition of iron formation after the impact has yet been observed. There is, thus, strong regional evidence that the Sudbury impact event caused a sharp change in basin water conditions >700 km away. Noting that the disappearance of Palaeoproterozoic banded iron formation at ~1,850 Ma is a global phenomenon (Fig. 1), and further observing strong
evidence for tsunami deposits within some of the impact layers at variable water depths, Cannon et al. (2010) proposed that the Sudbury impact could have pervasively changed the regional, and probably the global, oceanic stratification, bringing to an end the long-lasting dominantly ferruginous state of the early Palaeoproterozoic deep oceans. The physical reasons for the inferred change remain to be established, however. It is currently unknown how an event such as the Sudbury impact could have disrupted the global oceanic iron supply and started the fickle oceanic states of the remaining Proterozoic.

The Sudbury Basin itself preserves the best-exposed and most accessible stratigraphy through a very large impact basin on Earth. It may originally have measured 170–200 km across but thanks to its remnant now being folded, there is an unparalleled opportunity to study transects from the shocked basement into the differentiated melt sheet and across the basin fill (e.g., Ubide et al. 2017) without the need for drilling. Of particular interest is the 1,300 m thick unit that overlies the crystallized melt sheet. It consists of breccias and tuffs that collectively are far too thick to represent the fallback from the impact. Instead, the first 300 m of chaotic breccias most likely formed through a fuel-coolant interaction, when seawater flooded onto the superheated melt sheet (e.g., Ubide et al. 2017). The remaining stratigraphy is characterized by sustained deposition of subaqueous volcanic products (bombs, lapilli and ash) that are more mafic than the average target rocks. The observation of on-going igneous activity within a subaqueous impact basin led Ubide et al. (2017) to speculate whether it could represent deeply sourced magmatism.

Numerical impact modelling (e.g., Collins et al. 2005) demonstrates that the depth of the transient cavity (created within less than a few seconds) nearly linearly increases with increasing bolide diameter (Fig. 3B), whereas the final depth of even a 500 km diameter basin is less than 3 km. The divergence in depth between transient cavity and final depth of even a 500 km diameter basin is less than 3 km. The consequence of subaqueous events could, therefore, be sustained, of very large impacts, one very different environmental impact basin on Earth. It may originally have measured 170–200 km across but thanks to its remnant now being folded, there is an unparalleled opportunity to study transects from the shocked basement into the differentiated melt sheet and across the basin fill (e.g., Ubide et al. 2017) without the need for drilling. Of particular interest is the 1,300 m thick unit that overlies the crystallized melt sheet. It consists of breccias and tuffs that collectively are far too thick to represent the fallback from the impact. Instead, the first 300 m of chaotic breccias most likely formed through a fuel-coolant interaction, when seawater flooded onto the superheated melt sheet (e.g., Ubide et al. 2017). The remaining stratigraphy is characterized by sustained deposition of subaqueous volcanic products (bombs, lapilli and ash) that are more mafic than the average target rocks. The observation of on-going igneous activity within a subaqueous impact basin led Ubide et al. (2017) to speculate whether it could represent deeply sourced magmatism.

Numerical impact modelling (e.g., Collins et al. 2005) demonstrates that the depth of the transient cavity (created within less than a few seconds) nearly linearly increases with increasing bolide diameter (Fig. 3B), whereas the final depth of even a 500 km diameter basin is less than 3 km. The divergence in depth between transient cavity and final basin (Fig. 3B) necessitates an ever-increasing material flow during the rebound and collapse of the original cavity. It has been proposed (e.g., Jones et al. 2003) that the vertical component of this material flow could give rise to secondary decompression melting. In areas of unusually high continental heat flow (e.g., Sudbury) and on weak plates (e.g., ocean basins), one environmental consequence of very large impact events could, therefore, be sustained, deeply sourced magmatism and the associated release of volatiles.

Regardless of this possibility, a final noteworthy aspect of the Sudbury crater fill is the progressive enrichment of the breccias and tuffs in reduced carbon. Studying the chemistry of the fine-grained ash-sized matrix of the crater fill, O’Sullivan et al. (2016) demonstrated that the crater basin was likely cut off from the open ocean and so developed a distinctive water chemistry within it. These authors also note that the sustained magmatic activity within the basin supported base-metal deposition similar to volcanogenic massive sulfide ores, which otherwise occur at oceanic spreading sites. Apart from the destructive forces of very large impacts, one very different environmental consequence of subaqueous events could, thus, be the formation of enclosed “ponds” (similar in shape to atolls), which contained chemical “factories” (hydrothermal systems) producing organic molecules as potential building blocks for life. Whereas life had long been established by 1,849 Ma, similar Hadean or early Archaean subaqueous impact basins should be considered as possible birthplaces of life and the kick-start of the terrestrial carbon cycle.

The ~590 Ma Acraman impact occurred during a period of intense fluctuations in the carbon cycle in the late Neoproterozoic Era (Fig. 1). The possibly 85–90 km diameter impact structure is now deeply eroded, but the corresponding impact layer can be traced for >500 km (Williams and Wallace 2003). Palaeomagnetic data suggest a low latitude impact, which could potentially increase any resultant environmental effects. But in terms of the on-going Neoproterozoic fluctuations in carbon isotopes (Fig. 1), the Acraman event seems to have been relatively minor, with only a small excursion towards a more negative reduced carbon isotope value; however, the detailed isotope stratigraphy is currently missing. Grey et al. (2003) pointed out that the Acraman impactite layer coincides with a marked change in fossil plankton (acritharch) successions and may have been more significant in terms of radiation than the preceding worldwide Marinoan glacial event (Cryogenian Period). The main target lithology of the Acraman impact were acidic volcanic rocks poor in carbon. There may have been limited disruption of the global carbon cycle, although detailed carbon isotope stratigraphy is unavailable.
THE CHICXULUB (MEXICO) IMPACT: A SPECIAL CASE OF BOMBARDING A PRODUCTIVE MARINE PLATFORM?

The remaining three largest terrestrial impact structures are Phanerozoic in age. The possible causal relationship between a large bolide impact and a Phanerozoic extinction event has been widely discussed in the literature, but there are two very clear observations (e.g., Fig. 1). One is that there have been more significant extinction events during the Phanerozoic than there are very large impact structures to account for them; the second is that there were large impact events [e.g., the 215 Ma Manicouagan crater in Quebec (Canada)] with no correlative mass extinction. Against this backdrop, the exceptional coincidence between the K–Pg [formerly known as the K–T] extinction event and the ~180 km diameter, 66 Ma, Chicxulub impact structure in Yucatan stands out. It is still being debated whether the environmental effects of the bolide strike on their own were responsible for extinction or whether the Earth was struck at a time when its biology had already been pushed close to a tipping point by volcanic degassing and dropping sea-level. Regardless, it is widely agreed that the Chicxulub impact caused planet-wide climate disruption, as supported by the geological context of the impact site. In the late Cretaceous, the Yucatan Peninsula was a partially emerged platform composed of calcium carbonate and evaporite deposited on older sediments, themselves sitting on Precambrian basement. The bolide excavated through this “fertile” stratigraphy at a site partly on land and partly submerged.

From a carbon cycle perspective, the presence of thick carbonate beds at the target site is of greatest relevance (Fig. 3A). The potential quantity of CO₂ devolatilized to high atmospheric altitude from bolides is dwarfed by that modelled to be ejected from a thick carbonate platform (Artemieva et al. 2017). On a 500–1,000 year timescale, the effects of releasing 425–1,400 Gt of CO₂ into the atmosphere (Artemieva et al. 2017; Brugger et al. 2017) is climate warming, but in the case of Chicxulub – where limestone, sulfate and seawater were the target – the short-term effect was dramatic SO₂-driven cooling with global annual mean surface air temperatures dropping by more than 20°C, recovering only after 30 years (Brugger et al. 2016). The bolide strike may also have caused massive wildfires and/or stratospheric emission of smoke from combustion of hydrocarbons within the target marine platform (oil and gas are produced to the north and west of the impact site). The nature of recovered molecules from incompletely combusted hydrocarbons preserved in the impact layer supports the idea that the bulk of the soot was released from reduced carbon contained within the impacted target rocks, amplifying SO₂-driven cooling along the equator and causing droughts (e.g., Kaiho and Oshima 2017). All this is consistent with the extinction patterns.

The K–Pg event, thus, emphasizes a further aspect of impacts on the terrestrial surface, which is lithologically and geochemically highly diversified and evolved. Less than one-sixth of the current planetary surface has a suitable make-up to cause strong stratospheric cooling if hit by a large bolide (Kaiho and Oshima 2017); significant direct disruption of the global carbon cycle seems only likely from impacts onto thick carbonate targets.

**SUMMARY**

Bolide impacts have affected the Earth’s carbon cycle in a multitude of ways. The widely held view that there are direct effects to the carbon cycle through environmental devastation and mass extinction, such as has been popularized with the K–Pg boundary event, is probably exceptional rather than the rule. Most of the consequences of large impacts have been indirect. On the Hadean Earth, intense bombardment may have contributed to the destabilization of the original crust, thereby possibly promoting
plate motion that has become an integral part of carbon cycling through plate destruction. Subaqueous early impact basins may also have been self-contained production sites of organic molecules that could have been potential cradles for life.

Throughout the Archaean, Earth continued to be occasionally bombarded by large bolides, as inferred from thick beds of spherules that must have splashed down from giant melt and vapour plumes. The existing Archaean sedimentary carbon isotope record does not appear to show fluctuations of the magnitude seen in later times; however, the record is of limited temporal resolution. In general, partitioning of carbon between the reduced and oxidized pools has remained surprisingly constant. The much more pronounced carbon isotope excursions of the Palaeoproterozoic and Neoproterozoic do not coincide with known impact events. Instead, the two very large events, at 1,849 Ma and 590 Ma, are traceable in the sedimentary record and are associated with the end of the deposition of banded iron formations and the radiation of acritarch plankton, respectively. If future work demonstrates these to be causal relationships, they would illustrate the indirect influence of large impacts on the carbon cycle through the reorganisation of the ocean’s redox state and the disruption of biological evolution.

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Most Phanerozoic mass extinctions are not coincident with very large impact events. The Chicxulub event, occurring at the K–Pg boundary, caused a moderate carbon isotope excursion and greatly disrupted the budget of climate-active gases in the atmosphere. This, in turn, led to a short-term abrupt cooling and a medium-term strong warming (e.g., Brugger et al. 2016). The lesson drawn for the Anthropocene is that the release of several thousand Gt of CO2 into the atmosphere may not leave a marked carbon isotope signal in the geological record. Instead, the Anthropocene is more likely to leave its legacy as a mass extinction from greenhouse-induced climate change on a biosphere already at a tipping point caused by habitat loss.

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Deep Carbon and the Life Cycle of Large Igneous Provinces

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INTRODUCTION

Large igneous provinces (LIPs) are defined as the geologically rapid emplacement (over 10^5–10^6 years) of hundreds of thousands to millions of cubic kilometers of lava at the surface and the associated intrusive bodies (e.g., Coffin and Eldholm 1994). They are dominated by thick successions of lavas known as flood basalts. These vast igneous provinces have formed several times throughout Earth’s history, on almost all of the major continents and also in the oceans. Large igneous provinces are often found far from plate boundaries. Detailed studies of individual LIPs have shown that they are formed of igneous rocks with diverse compositions, ranging from tholeiitic basalts, to occasional rhyolites, to strongly alkaline magmas such as lamproites and carbonatites.

The generation and emplacement of LIP magmas is linked to rapid, large-scale outgassing of volatile species, including sulfur, water, halogens, and carbon dioxide [e.g., Self et al. 2006; see also the December 2005 (v1n5) issue of Elements]. This surface outgassing is facilitated by extensive subterranean magmatic plumbing systems that form important pathways for the transfer of mantle and crustal carbon to the atmosphere (e.g., Ridley and Richards 2010; Black and Manga 2017). Among magmatic gases, carbon dioxide (CO₂) is particularly vital to the life cycle of LIP magmatism and its climatic consequences (Cui et al. 2013; Jones et al. 2016). The centrality of CO₂ in the environmental perturbations that coincide with some LIPs (e.g., Courtillot and Renne 2003)—such as the Deccan Traps (India), Siberian Traps (Russia), Karoo–Ferrar (southern Africa and Antarctica, respectively), Ontong Java Plateau (Pacific Ocean), Columbia River Basalt Group (northwestern USA), and the Central Atlantic Magmatic Province (northwest Africa, southwest Europe, northeast and southeast North America)—renders LIP-driven climate stress an important paleoclimatic analog for the present-day climate. However, the origins, budget, isotopic composition, and fate of LIP carbon remain pressing and challenging questions due to the evanescence of CO₂ in carbon-saturated mafic magmatic systems (e.g., Self et al. 2006; Armstrong McKay et al. 2014; Hartley et al. 2014; Saunders 2015; Black and Manga 2017).

HOW DO WE KNOW LIPS RELEASE CARBON?

Water, CO₂, sulfur, and halogens are among the most abundant constituents in volcanic gases. While some fraction of these gases is released during volcanic eruptions, the remainder may be discharged diffusely through crust, unaccompanied by volcanic eruptions. This cryptic degassing can form an important part of the overall gas release budget, especially for CO₂ (Armstrong McKay et al. 2014). Furthermore, if the establishment of lithospheric plumbing systems during the initial development of a LIP precedes the onset of flood basalt volcanism at the surface, or if intrusive magmas solidify after the last eruptions, cryptic degassing could either precede or postdate active volcanism.

Because no LIPs are forming at the present day, studies of recent, analogous, volcanic activity (e.g., Burton et al. 2013; Pfeffer et al. 2018) provide an important source of information about the release of LIP carbon. Eruptions of tholeiitic flood basalt lavas may bear similarities to present-day fissure eruptions in Hawai‘i (Kilauea Volcano) and Iceland (Laki and Holuhraun Volcanoes). The smaller-volume alkaline magmas associated with some LIPs may have had similar origins to those in the East African Rift (e.g., Foley and Fischer 2018).

At sites of present-day volcanism, both eruptive and cryptic CO₂ release can be constrained through ground-based and airborne measurements (e.g., Burton et al. 2013). More direct constraints on carbon in LIP magmas can potentially be provided by petrologic and geochemical methods, but such data are scarce and require cautious interpretation. Blebs of melt trapped inside growing crystals (commonly known as “melt inclusions”) can record magmatic water, CO₂, sulfur, and halogen concentrations at the time of entrainment and prior to eruption (e.g., Self et al. 2006). However, any CO₂ that has already exsolved at the time of melt entrainment cannot be reliably reconstructed.
Alternatively, trace element ratios such as CO$_2$/Nb and CO$_2$/Ba from un-degassed samples can be used to infer original CO$_2$ content for partly degassed, primitive magmas (e.g., Hartley et al. 2014). This is because Nb and Ba exhibit a similar incompatible behavior to CO$_2$ during mantle melting but do not degas (e.g., Rosenthal et al. 2015).

**HOW MUCH CARBON DO LIP MAGMAS RELEASE?**

Although all LIPs consist of a wide variety of magma types, estimates of volatile contents have mainly been derived for tholeiitic flood basalts. Estimates for carbon in flood basalts, based on volatile and trace element concentrations of melt inclusions, are summarized in Figure 1. Most previous estimates of the CO$_2$ content of flood basalts have relied on analogous, well-studied basaltic systems, such as Kilauea and Laki, to arrive at concentrations of 0.5–0.9 wt% CO$_2$ in flood basalts (e.g., Self et al. 2006; Saunders 2015). Given that in continental settings, flood basalt magmas may require several weight percent of dissolved water and/or exsolved CO$_2$ to be sufficiently buoyant to erupt through low-density felsic continental crust (Lange 2002), these CO$_2$ concentrations may be underestimates.

Alternative estimates of the CO$_2$ concentrations in flood basalt magmas have been derived from olivine-hosted melt inclusions. These are rare and typically found in primitive flood basalts, so they may not necessarily be representative of the main phase of more fractionated tholeiitic magmatism. Moreover, analyses of CO$_2$ in olivine-hosted melt inclusions in tholeiitic magmas (e.g., Black et al. 2014) reflect only the dissolved amount, which forms an indeterminate fraction of the total CO$_2$ released per km$^3$ of magma. Thus far, measurements of CO$_2$ in olivine-hosted melt inclusions from flood basalts have overlooked the CO$_2$ in shrinkage vapor bubbles (which may dominate the total CO$_2$ content) and so are minimum estimates. If LIP magmas reach CO$_2$ saturation at high pressures, CO$_2$ concentrations in melt inclusions represent lower limits on initial concentrations. Consequently, it is not surprising that CO$_2$ measurements for melt inclusions in the Siberian Traps (Black et al. 2014) (Fig. 1) are lower than the estimates for flood basalts based on measurements from Hawai’i and Iceland (Self et al. 2006; Saunders 2015).

The use of volatile/nonvolatile trace element ratios (such as CO$_2$/Nb and CO$_2$/Ba) to estimate original CO$_2$ concentrations must be applied with care to flood basalt magmas. This is because processes such as recharge, assimilation, and fractional crystallization in crustal magma chambers can significantly modify concentrations of strongly incompatible trace elements. Primitive high-MgO lavas, known as picrites, may sidestep this issue and thereby provide a window into initial CO$_2$ concentrations. Using this approach, Ba and Nb concentrations in picrites from the Siberian Traps (Sobolev et al. 2009) and the North Atlantic Igneous Province (Kent et al. 2004) suggest original melt CO$_2$ concentrations between 0.1 and 2 wt% CO$_2$. This large range for flood basalts (Fig. 1), along with the current lack of data for more alkaline magmas, emphasizes the need for further direct constraints on carbon in LIPs.

**WHERE DOES LIP CARBON COME FROM?**

Large igneous provinces occupy broad areal extents, up to $10^6$ km$^2$ (Coffin and Eldholm 1994), and are widely believed to have resulted from the impingement and lateral spreading of upwelling high-temperature mantle plume heads with diameters of up to 2,000 km at the base of the lithosphere (White and McKenzie 1995). According to their site of emplacement, LIPs may be categorized as oceanic or continental. Large igneous provinces emplaced on the continents may draw carbon from three main reservoirs: the convecting mantle, the subcontinental lithospheric mantle, and sedimentary rocks and fluids in the crust (Fig. 2). The main source of carbon for oceanic LIPs is the convecting mantle.

Carbon dioxide behaves highly incompatibly during mantle melting (e.g., Dasgupta and Hirschmann 2010), meaning that it partitions almost entirely into the melt phase. Consequently, the initial CO$_2$ concentrations of magmas are determined by the carbon concentration of their mantle source and by the degree of partial melting (Fig. 3). The high $^{3}$He/$^{4}$He ratios in some LIP magmas suggest their parental melts are formed from deep-sourced, primordial material brought up in mantle plumes. In addition to primordial carbon, mantle plumes are also likely to contain carbon that has been recycled, due to subduction and subsequent entrainment of oceanic crust by the plume. However, the fate of carbon during plate tectonic recycling is not well known (e.g., Dasgupta and Hirschmann 2010; Kelemen and Manning 2015). Furthermore, while some LIP melts have incompatible trace element and Sr, Nd, Pb and Hf isotopic ratios similar to oceanic basalts, and they appear to be derived solely from a mantle plume source, the geochemistry of many LIP melts testifies to additional contributions from the overlying lithosphere (e.g., Gibson et al. 2006).

Variations in the depth and degree of melting in upwelling mantle plumes associated with flood basalts are well-established, for example, from incompatible trace element ratios that reflect the presence or absence of garnet in the residue during melting (e.g., White and McKenzie 1995; Sobolev et al. 2011). Numerical models indicate that the extent of partial melting that occurs during upwelling of mantle
Plumes is primarily controlled by the temperature of the convecting mantle and the thickness of the overlying lithosphere (e.g., White and McKenzie 1995). If the lithosphere becomes thinner through the course of LIP magmatism, due to synenplacement extension or erosion (e.g., White and McKenzie 1995; Elkins Tanton and Hager 2000), the amount of melting will be lowest at the earliest stages of plume impact and the carbon concentration in these melts will be high (Figs. 3 and 4) (Sobolev et al. 2011; Black and Manga 2017). Because the lithosphere is of nonuniform thickness, the amount of melting in the plume will also vary spatially at any given time, and regions of preexisting thinning or weakness will focus plume upwelling and melting (Fig. 4) (e.g., Gibson et al. 2006).

### The Tempo of Carbon Release and the Life Cycle of LIPS

Large igneous provinces are commonly emplaced over several million years, but the main pulse of flood basalts volcanism occurs on timescales of a million years or less (e.g., Courtillot and Renne 2003 and subsequent geochronological studies). The flux of CO$_2$ is, therefore, likely to vary during LIP emplacement (Fig. 5) and through the course of individual LIP eruptions. Both the evolving CO$_2$ flux and $\delta^{13}C$ depend on magma emplacement rates, melting conditions, carbon sources, and flushing of CO$_2$ through the magmatic system as a fluid phase that is not bound to magma transfer. All of these factors are likely to shift through the life cycle of a LIP.

The tempo of magma emplacement can be constrained through studies of geochronology, physical volcanology, paleomagnetism, radiogenic isotope systems, or proxies such as mercury deposition. These lines of evidence retain significant uncertainties, but they do generally support the existence of short-timescale variations in volcanic activity superposed on gradually shifting long-term mean volcanic fluxes (e.g., Self et al. 2014 and references therein).

Geochronologic studies show that low-degree, incompatible trace element–rich, lithospheric melts often pre- and postdate the main phase outpourings of flood basalts (e.g., Gibson et al. 2006). If lithospheric removal occurs during LIP emplacement, this could also trigger a pulse of devolatilization from both the foundering lithospheric material and the residual subcontinental lithosphere under a steeper geotherm (e.g., Elkins Tanton and Hager 2000; Gibson et al. 2006) (Fig. 4). Thermomechanical transitions may modulate the depths of magma storage and, therefore, the country rock lithologies that are to be subjected to heating and devolatilization (Burgess et al. 2017); crustal metamorphism also requires heating of large volumes of rock, and outgassing from the cold upper crust may, therefore, lag behind the onset of volcanism (Black and Manga 2017).

On the timescales of individual eruptions, carbon outgassing can be decoupled from volcanic flux, for example when CO$_2$ partitions into a fluid phase. Ground-based measurements of the Holuhraun (Iceland) fissure eruption of 2014–2015 revealed that CO$_2$/SO$_2$ ratios in the volcanic
Early phase in LIP formation

Late phase in LIP formation

**Figure 4** Mantle plume–lithosphere interactions through the life cycle of continental large igneous provinces (LIPs) can influence the melting regime of the convecting mantle and the subcontinental mantle lithosphere. (1) During the initial impingement of a mantle plume (‘red’) beneath thick continental lithosphere (yellow and brown), low-degree partial melts from metasomatized lithospheric mantle predominate (panel A). (2) Over the course of LIP magmatism, the lithosphere undergoes significant thinning through extension (e.g., White and McKenzie 1995; Gibson et al. 2006) and/or foundering (Elkins Tanton and Hager 2000; Sobolev et al. 2011). Panel (C) illustrates that formation of tholeiitic basalts through adiabatic decompression melting in the mantle plume imposes a maximum lithospheric thickness during main-phase flood basalt magmatism of ~70 km. Panels (B) and (D) show experimentally determined solidus curves for mantle melting and reveal how the conductive thermal gradients in the lithosphere steepen at the base of the lithosphere following mantle plume impact. This conductive heating triggers low-degree melting of the lithospheric mantle and the formation of carbonated silicate melts in the late-stages of LIP formation. Abbreviations: \( T_p \) = mantle potential temperature; MBL = mechanical boundary layer. Modified from Gibson et al. (2006).

Plume were higher by a factor of 10 during the earliest days of the eruption (Pfeffer et al. 2018). Flipping the causal relationship, evolving CO\(_2\) concentrations during fractionation of magmas in the deep crust have also been hypothesized to exert control over the eruptionability of flood basalt magmas. Carbon dioxide may, therefore, play a role in shaping the tempo of volcanic activity and outgassing (Lange 2002; Black and Manga 2017).

OUTGASSING OF LIP CARBON AND THE ROLE OF DEEP INTRUSIVE MAGMAS

The depths at which LIP magmas become saturated in an exsolved CO\(_2\)-rich phase, and the mobility and fate of the exsolved fluid, are critical to understanding their overall carbon outgassing history. The proportion of a magmatic volatile—one that is initially dissolved in the melt—that reaches the atmosphere can be thought of as the outgassing efficiency. For CO\(_2\), it is commonly assumed that the outgassing efficiency is close to 100% for extrusive flood basalt magmas, due to the very low solubility of CO\(_2\) in basaltic melt at 1 atmosphere pressure (e.g., Self et al. 2006). In conjunction with an assumed CO\(_2\) content of 0.5 wt% in a primitive basaltic melt, this efficiency implies an approximate CO\(_2\) yield of 14 Mt/km\(^3\) erupted magma (Self et al. 2006). Importantly, if the CO\(_2\) outgassing efficiency deviates significantly from 100%, carbon isotope fractionation due to partial degassing may shift the net \(^{13}\)C of the carbon that is released.

Estimates of CO\(_2\) outgassing that are based solely on emplacement rates of flood basalts do not account for the potential flux of CO\(_2\) from associated intrusive magmas. Outgassing from CO\(_2\) saturated magma bodies in the permeable upper crust may take place through gradual, passive degassing in conjunction with emissions during eruptions (e.g., Burton 2013). In the less permeable lower crust and lithospheric mantle, dike formation and magma ascent may provide one of the only avenues for CO\(_2\)-rich exsolved fluids to reach the surface. In this case, CO\(_2\) initially exsolved at depth could “flush” shallower magmas, increasing CO\(_2\) release beyond what would be expected from the volume of erupted flood basalts (e.g., Armstrong McKay et al. 2014). The hypothesis of large-scale CO\(_2\) flushing in the complex magmatic plumbing systems associated with flood basalts receives some support from studies of Icelandic fissure eruptions. Comparison between trace element concentrations and melt inclusion CO\(_2\) content from the 1783–1784 Laki (Iceland) fissure eruption suggests that ~60% of the initial CO\(_2\) cargo was degassed in the lower-to-middle crust (Hartley et al. 2014).

The importance of deep intrusive degassing depends on the relative volumes of intrusive and extrusive magmas. Based on petrology and seismic imaging of high-velocity layers near the Moho, Ridley and Richards (2010) infer that the ultramafic cumulates that may underly LIPs are comparable in volume to the erupted lavas. A range in intrusive/extrusive ratio of 0.5 to 4 implies that 30%–80% of LIP magmas do not erupt. The efficiency of which these deep intrusive magmas degas and transfer CO\(_2\) to the atmosphere is uncertain; Hartley et al. (2014) estimated a 40–60% degassing rate of intrusive magmas in the Laki plumbing system, but this rate could be higher if crystallization in deep magma bodies drives further CO\(_2\) exsolution. Assuming homogeneous CO\(_2\) content, 50% intrusive degassing, and efficient transfer of CO\(_2\) to the atmosphere via flushing through the magmatic system and eruption, the magmas that do erupt could carry 1.25 to 3 times their native CO\(_2\) content assuming an intrusive/extrusive ratio of 0.5 to 4. This “excess carbon” load is, in some ways, analogous to the “excess sulfur” released from some arc volcanic eruptions that tap a sulfur-rich exsolved phase (e.g., Armstrong McKay et al. 2014 and references therein).
The relative contributions and timings of CO₂ release from the convecting mantle, mantle lithosphere, and crust during large igneous province (LIP) emplacement. (Upper graph) The degree of melting varies during the life cycle of a LIP. (Lower graph) The relative contributions and timings of CO₂ release from different reservoirs may vary from LIP to LIP. Carbon dioxide from the crust is likely to be characterized by a different carbon isotope composition than CO₂ from the mantle. The carbon isotope composition of the lithospheric mantle is uncertain. Moho = Mohorovičić discontinuity, which occurs ~8 km beneath oceanic crust and ~32 km beneath continental crust.

**Box 1**

**CARBON ISOTOPE RECORDS AND MANTLE CARBON ISOTOPE RATIOS**

The δ¹³C in marine carbonates and organic matter reflects the balance between the addition and removal of carbon (with specific δ¹³C values) to the ocean–atmosphere system. Fluctuations in δ¹³C are, therefore, often interpreted as changes in the carbon being added to, or removed from, the oceans and atmosphere.

The isotopic composition of carbon in LIP magmas is important because the negative marine carbon isotope excursions that are recorded in marine sediments coinciding with the emplacement of some LIPs (e.g., Schobben et al. 2019 this issue) indicate major perturbation of the global carbon cycle by LIPs. However, δ¹³C of LIP magmas can also be influenced by the carbon isotope composition of the crust from which they were derived. For example, melting of mantle plume component rich in recycled oceanic crust has been hypothesized as a source of isotopically light carbon (Sobolev et al. 2011). Mantle carbon isotopes are fractionated during open-system degassing. Assimilation or heating of crustal carbon reservoirs (coals, hydrocarbons, organic-rich shales) can lead to release of very isotopically light carbon (e.g., Ganino and Arndt 2009). If multiple reservoirs contribute carbon during LIP emplacement, the δ¹³C values, as well as the flux of carbon, may evolve through time. Thus, determining the isotopic composition of carbon outgassed during LIP magmatism remains an important question for future work.

**Figure 5**

Schematic illustration of the evolving contributions of CO₂ from the convecting mantle, mantle lithosphere, and crust during large igneous province (LIP) emplacement. (Upper graph) The degree of melting varies during the life cycle of a LIP. (Lower graph) The relative contributions and timings of CO₂ release from different reservoirs may vary from LIP to LIP. Carbon dioxide from the crust is likely to be characterized by a different carbon isotope composition than CO₂ from the mantle. The carbon isotope composition of the lithospheric mantle is uncertain. Moho = Mohorovičić discontinuity, which occurs ~8 km beneath oceanic crust and ~32 km beneath continental crust.

**HOW DOES LIP CARBON INFLUENCE THE ENVIRONMENT?**

The fluxes of CO₂ during LIP magmatism, and, consequently, the viability of CO₂ as a significant driver of climate change, have been the subject of debate (e.g., Self et al. 2006 and references therein; Saunders 2015; Black and Manga 2017). Perhaps the best evidence for major perturbation of the global carbon cycle by LIPs comes from carbon isotope records (see Box 1). In brief, these lines of evidence indicate four major aspects of carbon cycle disruption: (1) strong warming coinciding with some LIPs (e.g., the Siberian Traps and the North Atlantic Igneous Province) (see Saunders 2015), with more ambiguous evidence in other cases; (2) spikes in atmospheric pCO₂; (3) negative carbon isotope excursions (e.g., Cui et al. 2013; Schobben et al. 2019 this issue); (4) ocean acidification. Taken together with geochronology aligning these environmental changes to LIP magmatism (Courtillot and Renne 2003), the most straightforward interpretation is that they were primarily caused by carbon release related to LIP emplacement, possibly supplemented with light carbon from clathrates or from the metamorphism of sedimentary organic material (Box 1). Accurately determining the CO₂ budget of diverse LIP magmas is critical to testing hypotheses regarding the causal links between magmatism, warming, and carbon cycle perturbation.

On the timescales of silicate weathering and water–rock reactions, LIPs may play an important role as carbon sinks, because CO₂ reacts with calcium and magnesium in basalts to form carbonate minerals (e.g., Jones et al. 2016; see also August 2019 issue, v15n4, of *Elements*). By analogy to mid-ocean ridge settings, where the balance between net outgassing and net sequestration of carbon is uncertain (e.g., Burton et al. 2013), the capacity for LIP carbon sequestration on longer timescales may rival the magnitude of potential outgassing (Jones et al. 2016). This balance, and the timescales of atmospheric CO₂ drawdown, may depend on the extent of subaerial versus submarine volcanism in a given LIP and the potential for water–rock reactions in hydrothermal systems.

**SOME IMPORTANT QUESTIONS FOR FUTURE WORK**

1. What is the carbon isotope composition of carbon released during LIP magmatism, and how does this relate to fractionation during degassing, interaction with carbon-bearing country rocks, and the initial composition of magmatic carbon?

2. What role does deep CO₂ exsolution play in regulating ascent and eruption of LIP magmas, and what fraction of CO₂ exsolved at depth reaches the atmosphere?

3. How do alkaline and carbonatite magmas relate to and physically interact with tholeiitic magmas, and what do alkaline magmas tell us about the influence of CO₂ and other volatiles on the petrologic evolution of LIP magmas?

4. How do LIPs contribute to storage and liberation of volatiles, especially carbon species, in the subcontinental lithospheric mantle?

5. On the 10⁵–10⁷ year timescales of silicate weathering, does LIP emplacement lead to prolonged warming, transient warming followed by cooling as silicate weathering proceeds, negligible climate change, or predominant cooling? If the long-term climatic consequences differ between LIPs, what controls these outcomes (discussed further by McKenzie and Jiang 2019 this issue)?

**CONCLUSIONS**

Large igneous provinces are dominated volumetrically by vast outpourings of flood basalt lavas and their intrusive equivalents. The frequent association of alkaline and carbonatite magmatism with flood basalts in LIPs attests to the petrologic importance of carbon during the generation of LIP magmas, though when and how plumbing systems associated with diverse magma types interact with each other is an unresolved question. Previous estimates of the CO₂ content of flood basalts range from 0.5 wt% to 0.9 wt% CO₂. Revised estimates of the CO₂ content of Hawaiian (Kīlauea) and Icelandic (Laki) basalts, along with incompatible trace elements from flood basalt picrites, suggest that primitive flood basalt magmas may commonly carry
Based on the shifting contributions of deep convecting mantle, lithospheric mantle, and crustal sources (Figs. 4 and 5), together with the variable flux from deep intrusive magmas, the CO$_2$ flux from LIP magmas probably evolves through the entire magmatic cycle. As a consequence, LIP carbon emissions are unlikely to scale directly with volumetric eruption rates, which offer, at best, a partial picture of the tempo of carbon outgassing. Nevertheless, gross estimates based on erupted volume provide a starting place for situating LIPs in the context of the global carbon cycle. For a total LIP magma volume of $10^7$–$10^9$ km$^3$ emplaced over $10^5$–$10^6$ years, and carrying $10$–$100$ wt% CO$_2$, the mean annual flux would be 30–3,000 Mt CO$_2$/year, with the potential for orders of magnitude deviation from this mean rate over the course of the magmatic cycle. The Laki fissure eruption released an estimated 300–900 Mt CO$_2$ over the course of 6 months (Hartley et al. 2014). For comparability, potention-day global subaerially released CO$_2$ from volcanoes has been estimated at 500–600 Mt CO$_2$/year (Burton et al. 2013; Kelemen and Manning 2015). During geologically brief intervals of intense outgassing, LIPs are likely to dominate the global flux of deep carbon to the atmosphere.

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Earth’s Outgassing and Climatic Transitions: The Slow Burn Towards Environmental “Catastrophes”?

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On multimillion-year timescales, outgassing from the Earth’s interior provides the principal source of CO₂ to the ocean–atmosphere system, which plays a fundamental role in shaping the Earth’s baseline climate. Fluctuations in global outgassing have been linked to icehouse–greenhouse transitions, although uncertainties surround paleo-outgassing fluxes. Here, we discuss how volcanic outgassing and the carbon cycle have evolved in concert with changes in plate tectonics and biotic evolution. We describe hypotheses of driving mechanisms for the Paleozoic icehouse–greenhouse climates and explore how climatic transitions may have influenced past biotic crises and, in particular, how variable outgassing rates established the backdrop for carbon cycle perturbations to instigate prominent mass extinction events.

Keywords: carbon cycle, outgassing, weathering, climate, biodiversity, mass extinction

LONG-TERM CARBON CYCLE

Earth has transitioned between two major baseline climate states throughout its history: icehouse (or Ice Age) intervals that consist of generally cool climates with well-developed polar ice sheets, and warm greenhouse intervals devoid of ice caps. Transitions between icehouse and greenhouse intervals are largely influenced by the partial pressure of atmospheric carbon dioxide (pCO₂). The transfer of carbon between the solid Earth (endogenic system) and the ocean–atmosphere (exogenic system) on million-year timescales is governed by the long-term carbon cycle. The pCO₂ is a result of the balance between the rate of CO₂ inputs through magmatic/metamorphic degassing and the rates of carbon removal via silicate weathering and organic carbon burial (Berner 2004) (Fig. 1). Due to the small size of the surface carbon reservoir relative to the inputs from the solid Earth, a negative feedback between silica weathering and temperature is required to stabilize atmospheric CO₂ and climate on timescales of longer than 10^5 years (Walker et al. 1981). Thus, steady-state pCO₂ levels are determined by the input and the relative strength of the silicate weathering feedback mechanisms (Berner 2004).

Solid Earth carbon degassing occurs at mid-ocean ridges, rifts, volcanic arcs in subduction zones, orogenic belts, and large igneous provinces (Fig. 1). The global volcanic flux of CO₂ probably varied significantly throughout geologic time. Changes in subduction zone length, in the volume of a mantle plume, and/or in the global oceanic crust production rate can result in at least a two-fold increase in volcanic CO₂ inputs (Lee et al. 2013). Variation in the CO₂ input would, therefore, play a fundamental role in changing long-term baseline climate states. These tectonic/magmatic processes also contribute to modifying the climate–silicate weathering feedback strength, which is influenced by the exhumed supply of weatherable minerals, dissolution kinetics, and hydrologic conditions (Hartmann et al. 2014; Maher and Chamberlain 2014; Jiang and Lee 2019). The long-term carbon cycle stabilizes planetary climate due to the temperature sensitivity of silicate weathering—at high temperatures weathering rates increase and rapidly draw CO₂ out of the atmosphere, so cooling the climate. Because surface temperature is, in part, controlled by pCO₂, the relation between CO₂ inputs and the weathering feedback can be represented as the curve in Figure 2. In general, we expect a positive correlation between the input or output with steady state pCO₂, with the slope of the curve representing the feedback strength. With linear
Since the Cryogenian Period (716–635 Ma), Earth has shifted between numerous icehouse–greenhouse states (Fig. 3). The Cryogenian was one of the most extensive icehouses, being characterized by two Snowball Earth events when ice sheets reached paleo-shorelines in equatorial regions. The first of these Snowball Earth events, known as the Sturtian glaciation, occurred ~716 Ma, and the second was the Marinoan glaciation that terminated ~635 Ma. Subsequent relatively short-lived, yet expansive, glaciations included the Ediacaran Gaskiers glaciation (~580 Ma) and the Hirnantian glaciation at the end of the Ordovician Period (~440 Ma). The Late Paleozoic icehouse extended from the Carboniferous to the late Permian, and our current Cenozoic icehouse climate was initiated.

**ICEHOUSE–GREENHOUSE CONDITIONS IN DEEP TIME**

>Schematic illustration of climate states having varying weathering feedback and outgassing conditions.

Low outgassing rates combined with kinetically limited weathering regimes allows Earth to reach a state where extensive icehouse (or snowball) conditions can be achieved. Conversely, elevated outgassing combined with supply-limited weathering (i.e., a negligible silicate weathering feedback) can push Earth into a runaway greenhouse. **Adapted from Lee et al. (2019).**

weathering feedback, the system remains regulated and runaway processes cannot happen. However, global or regional weathering processes can be either “rate-limited”, wherein an excess of weatherable minerals are available and the weathering rate is limited by kinetic rate, or “supply-limited”, which occurs when all weatherable substrates are exhausted and the weathering rate is limited by the supply of fresh materials. As such, the negative feedback mechanism may not scale linearly with exogenic CO2 content. For example, in a low pCO2 scenario, temperature could drop below some threshold where weathering kinetics become negligible because surface temperatures are, in part, controlled by pCO2. As a result, the system reaches a threshold of atmospheric pCO2 such that weathering rates are insensitive to CO2, and further decreases in carbon input combined with ice albedo effects could result in runaway icehouse conditions. Similarly, silicate weathering may become supply-limited even with high temperature and high pCO2, where the system reaches a threshold above which increased CO2 does not result in increased weathering. This can result in runaway greenhouse conditions (Fig. 2).

Therefore, “thresholds” in the silicate weathering feedback exist, above or below which weathering rates become insensitive to pCO2, leading to failure of silicate weathering feedback in climate regulation (Foley 2015; Kump 2018). Crossing these thresholds would move the planet to a new steady state with different feedback parameters. For example, in a low pCO2 scenario, temperature could drop below the water freezing point where weathering kinetics become sluggish, or even cease completely. If the system maintains low CO2 input, the planet would remain ice-covered and be dominated by runaway ice-albedo feedback. In a globally supply-limited scenario, the system reaches a threshold above which increased CO2 does not result in increased weathering, thus rapid emission of large quantity of CO2 may exhaust the capacity of the long-term climate regulator associated with silicate weathering, resulting in runaway greenhouse conditions (Foley 2015; Kump 2018) (Fig. 2).
During the later Paleogene (~33 Ma). Prominent greenhouse intervals spanned the Ediacaran through the early Paleozoic, the middle Paleozoic, and the Mesozoic to early Cenozoic. Interestingly, the Precambrian record is sparse with regard to icehouse intervals. Aside from a few putative glaciogenic deposits in Archean sedimentary sequences, the ~2.3 Ga Huronian glaciations represent the only well-documented icehouses prior to the Cryogenian. In short, there is an ~1.6 billion year interval without any known evidence of icehouse climates. Understanding what processes drive deviations from one steady-state climate to a new one remains a topic of high interest, with ongoing debates focused on whether climatic transitions are controlled by changes in the CO₂ inputs or changes in the efficiency of the weathering sink.

Weathering-driven models for climate change seek out mechanisms that can enhance global weathering efficiency and CO₂ consumption. Weathering rates are dependent on temperature, precipitation, and exposed reactive surface area of the material being weathered. A leading hypothesis postulates that the concentration of continents in low-latitudes (i.e., the tropics) causes intense weathering due to high precipitation and hot and humid climates, which causes cooling and favors icehouse conditions (Marshall et al. 1988). This hypothesis has led to an increased focus on concentrations of mafic crustal rocks in low-latitudes because mafic minerals weather more rapidly, and at lower temperatures, than felsic minerals, thereby enhancing the “weatherability” of the crust. Increasing crustal mafic rocks in the tropics can be accomplished through the eruption of large igneous provinces (LIPs) or by accretion of island-arc terranes in low-latitudes. Cooling during the Cryogenian and Cenozoic has been attributed to low-latitude LIP emplacement (e.g., Goddéris et al. 2003; Kent and Muttoni 2013), whereas tropical arc-terrane accretion might be responsible for discrete cooling events during the Cretaceous and Cenozoic (Jagoutz et al. 2016) and for the end-Ordovician Hainanian icehouse (Swanson-Hysell and Macdonald 2017). Mafic LIPs emplaced on stable cratons may have a large initial reactive surface area, but, without extensive uplift and physical erosion, that surface could be rapidly leached, leaving the greater volume of the unexposed rock blocked from the weathering zone—a process termed “soil-shielding” (e.g., Hartmann et al. 2014). This makes the arc-terrane collisions a more appealing mechanism by which to change weatherability and to drive cooling, because accretionary processes induce uplift, erosion, and exhumation of the bedrock, vastly increasing its reactive surface area and weathering potential. The interaction between mineral supply and reaction kinetics makes orogenic systems preferential sites for enhanced weathering. At present, tectonically active regions are thought to be the orogenic systems preferential sites for enhanced weathering, and exhumation of the bedrock, vastly increasing the weathering due to high precipitation and hot and humid climates, which causes cooling and favors icehouse conditions. The Himalaya would not meet the assumed criteria for a prominent low-latitude weathering system, yet the Himalaya modifies the climate system such that it can play a major role in global weathering.

The relationship between long-term climate transitions and low-latitude emplacement of mafic bodies in deep time is not clear (McKenzie et al. 2016; Mills et al. 2017). While some LIP and arc-terrane emplacement events may have been coincident with cooling events, many were not. Multiple LIPs have erupted in equatorial locations without any notable cooling effects, e.g., during the Cambrian and the Triassic. Similarly, extensive collisional belts existed around equatorial regions throughout the Cambrian, which remained a greenhouse interval (e.g., McKenzie et al. 2014; Cao et al. 2017; Mills et al. 2017). On the other hand, changes of the volcanic CO₂ flux into the surface system appear to be directly associated with major climatic transitions. Multiple studies focusing on paleogeographic volcanic arc distributions have shown that changes in arc length relate to icehouse-greenhouse transitions at various intervals in Earth history (e.g., Lee et al. 2013; Mills et al. 2017). Analysis of detrital zircons in global sedimentary deposits that span the past ~720 million years showed a direct relationship between zircon production—a proxy for regional continental arc magmatism—and all major climatic transitions throughout this interval (McKenzie et al. 2016) (Fig. 2). Continental arc systems are of particular interest because, via decarbonation reactions, they have the ability to liberate carbon from carbonates preserved in the upper plate (Lee et al. 2013; Mason et al. 2017).

While outgassing may generally determine baseline climate states, pCO₂ represents a balance between both sources and sinks. Quantifying outgassing rates is a difficult task in deep time due to the uncertainties in estimating modern CO₂ fluxes and the potential additive input from crustal carbon sources, which may be more complicated for LIPs. Furthermore, the development of continental arcs often involves compression mountain building events that enhance weatherability, thereby dampening the outgassing contribution (Jiang and Lee 2017). As noted above, weathering rates are dependent on multiple variables that are difficult to estimate in Earth’s history. Therefore, our understanding of ancient climatic transitions relies on our ability to interpret the rock record. For example, the lack of a consistent relationship between the sporadic occurrence of low-latitude mafic bodies and global cooling does not mean their occurrences did not influence climate change: their contributions may have depended on baseline conditions during their emplacement.

CLIMATE STEADY STATES, THRESHOLDS, AND “CATACLYSMES”

At some periods during Earth’s history, long-term endogenic processes might have “pre-set” the climate baseline close to a threshold that could have been easily crossed from shorter-termed events, such as LIPs, bolide impacts, or seafloor methane release. The combination of long-term fluctuations in CO₂ emissions and short-term events could have played an important role in biologic evolution. Perturbations of Earth’s carbon cycle can lead to mass extinctions if they exceed either a critical rate at long timescales or a critical size at short timescales (Rothman 2018). The influences of rapid CO₂ fluctuations from LIP events on mass extinctions are already discussed elsewhere in this issue of Elements; thus, we will speculate on the relative importance of changes in the baseline pCO₂ associated with variations in outgassing on carbon cycle perturbations and on Earth system “catastrophes”. 
Most major mass extinctions have occurred during greenhouse climates. This might be due to the fact that the Earth has spent more time in a greenhouse state (Fig. 3). However, a link between some extinctions and environmental conditions has been recognized that involves the carbon cycle. In particular, changes in carbonate saturation state have been postulated as key drivers of extinctions (Knoll and Fischer 2011). The early Paleozoic and the middle Permian through to the end-Triassic encapsulate the highest marine animal extinction rates (Bambach et al. 2004; Alroy et al. 2008) (Fig. 3). The Cambrian “dead interval” of the early Paleozoic is characterized by generally low biodiversity with multiple mass extinction events associated with ocean anoxia and carbon cycle perturbations, as well as an extensive “reef gap” when calcifying animals were of markedly low abundance (e.g., McKenzie et al. 2014 and refs therein) (Figs. 2 and 3). Three major mass extinction events occur around the transition from the Paleozoic to the Mesozoic: the mid-Permian “Guadalupian” (~260 Ma), the end-Permian (~251 Ma), and the end-Triassic (201 Ma) extinctions, all of which were coincident with LIP eruptions and carbon cycle perturbations. These extinctions are also noted for selection against calcifying animals (Clapham and Payne 2011; Knoll and Fischer 2011). Much like the Cambrian, the Mesozoic recorded numerous ocean anoxic events (OAEs) that are believed to have been the result of episodic CO2 perturbations (Jenkyns et al. 2010). The end-Devonian mass extinction also exhibited selection.

![Figure 4](image-url)

**Figure 4.** The Paleozoic–Mesozoic transition. (A) Modeled paleoconcentrations of CO2. (B) Paleoconcentrations of CO2 obtained from proxies. (C) Frequency of detrital “young” zircon ages from Triassic strata. (D) Frequency of detrital “young” zircon ages from Permian strata. Timing of mass extinctions are indicated by vertical red dashed lines. Glacial frequency is shown in blue with the onset of deglaciation from the Late Paleozoic icehouse beginning at ~290 Ma. The zircon data indicate there was a marked increase in outgassing from volcanic activity beginning at ~290 Ma that is coincident with the onset of deglaciation. The proxy and modeled CO2 increase are decoupled by ~50 My from the onset of deglaciation. Late Paleozoic icehouse duration from Montañez and Paullsen (2009); CO2 proxy data from Zeebe (2012); modeled CO2 curve from Royer et al. (2014) and zircon frequencies data from McKenzie et al. (2016).
against calcifying animals (Knoll and Fischer 2011). The Cretaceous–Paleogene extinction—last of the “big 5”—corresponded with both the Deccan (India) LIP and a bolide impact at Chicxulub (Mexico), but lacks notable evidence for marked selectivity against calcifying animals. However, this extinction followed the Jurassic diversification of planktonic calcifying organisms that produced a new deep-ocean carbonate reservoir that could buffer against sustained acidification, thus changing carbon cycle dynamics (e.g., Zeebe 2012).

The collective similarities of environmental conditions and extinction dynamics during the early Paleozoic, mid Paleozoic, and late Permian–Triassic greenhouses imply that background CO₂ fluxes and greenhouse baseline conditions can increase the sensitivity of the surface environment to short-term sizeable CO₂ injections. Whereas the Cambrian corresponded to a protracted interval of widespread volcanism, the Permian–Triassic witnessed a dramatic rise in pCO₂ (Zeebe 2012; Royer et al. 2014) (Figs. 2 and 4). The transition out of the late Paleozoic icehouse was associated with an increase in pCO₂ (Montañez and Poulsen 2008). Although detrital zircon data from Permian and Triassic strata may show low-abundances of “young” zircon dates with ages close to the depositional ages of the strata relative to the total populations (McKenzie et al. 2016) (Fig. 3), closer evaluation of the data shows that the relatively young grains present form a distinct young population that increase in abundance ~290 Ma, which is coincident with the onset of deglaciation (Fig. 4). These young <290 Ma zircons are seen on multiple geographic regions (North America, South America, China, Africa, Southeast Asia, Australia) and represent a rapid, nearly synchronous global increase in the volcanic CO₂ flux at this time (a magmatic “flare up”) that may have caused warming (Fig. 4). This change in surface environment could have amplified the effects of the perturbations caused by LIPs during this time.

There is a final point for consideration. It has been shown that major cooling events, such as the Cryogenian “Snowball Earth” glaciations and the end-Ordovician Hirnantian glaciations, correspond with marked reductions in global magmatism (McKenzie et al. 2016; Mills et al. 2017). The Hirnantian glaciation follows an interval that had a progressive reduction in volcanism and global cooling and that was punctuated with a rapid drop in temperature coincident with the end-Ordovician Hirnantian extinction (Fig. 5). Ordovician cooling may have been driven by

![Figure 5](image-url) Early Paleozoic tectonics, climate, and biodiversity. Note that the reduction in Gondwanan tectonism coincides with a global cooling trend, consistent with the zircon record in FIGURE 3. Taconic arc exhumation had initiated by ~465 Ma. The timing of five mass extinction events (Botomian, Majumian, Steptoean, Sunwaptan, and Hirnantian) are indicated with vertical dashed red lines. Seawater ⁸⁷Sr/⁸⁶Sr relative highs indicate high radiogenic ⁸⁷Sr fluxes from chemical weathering of old continental crust. Carbonate δ¹³C tracks carbon cycle variation and perturbations. Abbreviations on tectonic duration activity: ANT = Antarctica; AUS = Australia; IND = India; AFR = Africa; NCB = North China Block; SAM = South America. Modified from McKenzie et al. (2014). Taconic arc-accretion range from Swanson-Hysell and Macdonald (2017).
increased weathering due to low-latitude arc-terranee collisions of the Taconic orogenic system (Swanson-Hysell et al. 2017). Given a baseline climate state with reduced global outgassing and lower background $p$CO$_2$, the exhumation of a large mafic terrane in the tropics may have been sufficient to have changed global weathering kinetics and to have caused the drop in temperature needed to induce a rapid extinction-linked glaciation. 

In summary, the Earth has experienced many carbon cycle perturbations, although their influences on the climate system and biosphere have been disparate. Whereas $p$CO$_2$ always represents a balance between carbon sources and sinks, changes in global outgassing appear responsible for driving multimillion-year swings in baseline climate state. Extended intervals of high volcanic outgassing may not sustain ocean acidification, but shifts in baseline conditions can influence the carbon cycle and make it more sensitive to perturbation. Effectively, greenhouse intervals may have been more amenable to mass extinctions. Conversely, reduced outgassing may allow temperatures to drop to the low levels that inhibit background weathering rates, where the tropical emplacement of large mafic terranes can change weathering kinetics to initiate short-lived “catastrophic” drops in temperature leading to Snowball Earth events or extinction-driving icehouses. Accordingly, the slow exchanges of carbon between the endogenic and exogenic systems profoundly influence Earth’s climatic state and its biospheric stability.

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Mass extinctions are global-scale environmental crises marked by the loss of numerous species from all habitats. They often coincide with rapid changes in the stable carbon isotope ratios ($^{13}$C/$^{12}$C) recorded in sedimentary carbonate and organic matter, ratios which can indicate substantial inputs to the surface carbon reservoirs and/or changes in the cycling of carbon. Models to explain these changes have provided much fuel for debate on the causes and consequences of mass extinctions. For example, the escape of methane from gas hydrate deposits or the emission of huge volumes of gaseous carbon from large-scale volcanic systems, known as large igneous provinces, may have been responsible for decreases of $^{13}$C/$^{12}$C in sedimentary deposits. In this article, we discuss the challenges in distinguishing between these, and other, alternatives.

**KEYWORDS:** carbon cycle, large igneous provinces, greenhouse gas, climate, Earth system feedback

**MASS EXTINCTIONS**

The fossil record reveals that the evolution of life has been punctuated by several catastrophic events that eliminated species globally (Raup and Sepkoski 1982). After the Cambrian Period (~500 million years ago), five mass extinction events have been identified (colloquially known as “the big five”), but there have been numerous smaller extinction events. Most of these crises coincided with voluminous flood basalt eruptions associated with so-called large igneous provinces (LIPs) (Wignall 2015; Black and Gibson 2019 this issue). Only one, the famous event at the end of the Cretaceous, has been confidently linked to a giant bolide impact (Alvarez et al. 1980). However, not all episodes of giant LIP volcanism coincided with extinction events: for example, major episodes of flood basalt eruption during the Early Cretaceous and the early Paleogene occurred during very low rates of extinction (Figs. 1 and 2) (Wignall 2015). Factors such as the composition of the upper crust through which the LIPs are intruded and whether the basalts were emplaced as subaerial or submarine lavas might explain some of the differences. But the eruption style is not readily correlated with the severity of any biotic disturbance (Svensen et al. 2009; Burgess et al. 2017; Johansson et al. 2018). The role of LIPs in global extinctions is, therefore, enigmatic, but clues to the link between the deep mantle and the biosphere come from perturbations of the biogeochemical carbon cycle as revealed by the sedimentary carbon record and, especially, the changing ratios of constituent stable carbon isotopes. There are many proposed links between LIPs, mass extinctions, and carbon cycle changes, including cooling and acid rain (by SO$_2$ degassing and aerosol formation), greenhouse warming (by CO$_2$ and CH$_4$ degassing), heavy metal pollution, and ozone layer depletion. There are also more intricate scenarios that involve plant die-off, enhanced soil erosion, and elevated weathering, which, in turn, increases the amount of nutrients reaching the oceans and so causes eutrophication, dissolved-oxygen depletion (“marine anoxia”), and turbidity. Many of these changes could have had an impact on the sedimentary carbon isotope record, and it is our challenge to distinguish the different impacts from the different causes on the carbon isotope record.

**UNDERSTANDING THE CARBON CYCLE WITH CARBON ISOTOPE GEOCHEMISTRY**

The isotopes of carbon have the same number of protons but differ in the number of neutrons, and so the mass of the atoms differs. The exact carbon isotope composition of a substance will depend on both kinetic and equilibrium effects (see the introduction of this issue of *Elements* for further details on carbon isotopes). As a reference, stable carbon isotope ratios are, by convention, denoted relative to the Vienna Peedee Belemnite (VPDB). We generally express deviations from this reference value, or when comparing different substances, as “lower” or “higher” (lower means the sample has less $^{13}$C than the standard, or the natural, isotope abundance). But we can also refer to the product in a chemical reaction as being “enriched” (or “depleted”) in $^{13}$C (or $^{12}$C). The carbon isotope values are expressed using the delta ($\delta$) notation in “parts per thousand” (‰), and is derived by the following equation:

$$\delta^{13}C = \left( \frac{(^{13}C/^{12}C)_{\text{sample}} - (^{13}C/^{12}C)_{\text{reference}}}{(^{13}C/^{12}C)_{\text{reference}}} \right) \times 1,000$$

The process, known as isotope fractionation, causes a relative partitioning of the stable isotopes among substances and thereby changes their isotope composition. This is seen in the different pools of carbon on the Earth’s surface. For example, the dissolved inorganic carbon (DIC) in the ocean has higher $\delta^{13}$C values than the organic carbon of plankton in the ocean. The production
of organic matter during photosynthesis is an enzyme-mediated process, which is accompanied by a large carbon isotope fractionation that preferentially selects the light \(^{12}\)C isotope and shifts the material’s \(\delta^{13}\)C to 25‰ lower values on average. In contrast, carbon isotope partitioning during carbonate mineral precipitation causes only a small fractionation \((\delta^{13}\)C values are higher by 1‰–2‰ at Earth’s surface temperatures, based on experimental results) and, therefore, closely approximate the DIC values of the contemporary ocean. These fluxes remove carbon from the ocean–atmosphere system and are balanced, on geological timescales (>100 ky), by carbonate alkalinity \((\text{CO}_3^{2-} \text{ and HCO}_3^-)\), carbon input through continental weathering, and \(\text{CO}_2 \) and \(\text{CH}_4 \) release by metamorphism and via volcanic outgassing. The combined effect of all these fluxes dictates the size and isotope composition of Earth’s surface carbon reservoirs (Fig. 3). On geological timescales, the oceanic DIC pool and atmospheric \(\text{CO}_2 \) behave as one reservoir, because of the continuous exchange between them. This system is known as the long-term biogeochemical carbon cycle, where subtle imbalances in the volcanic and metamorphic carbon input, and the combination of weathering and organic carbon burial, modulate atmospheric \(\text{CO}_2 \) levels and, thus, climate over time. These subtle changes are recorded in the carbonate and organic matter in sedimentary rocks and allow us to study the history of this cycle using \(\delta^{13}\)C records. Table 1 lists some of the frequently used carbon isotope recording mediums.

**CARBON ISOTOPE CHANGES DURING MASS EXTINCTIONS**

The stratigraphic carbon isotope record is generally stable, but this situation is often different during major extinction intervals when high amplitude (up to 8‰) positive or negative carbon isotope excursions (CIEs) occur. These changes are interpreted as evidence for major perturbations of the long-term biogeochemical carbon cycle, and they provide significant clues as to the nature of ancient crises. These carbon cycle perturbations are thought to be responsible for the rapid and significant climate changes that themselves can cause severe habitat degradation and mass extinction. Here, we focus on the carbon isotope record of the last three mass extinction events (Fig. 2): the Permian–Triassic, the Triassic–Jurassic, and the Cretaceous–Paleogene extinctions. We will first evaluate which sedimentary record(s) (Table 1) most faithfully reflect the functioning of the carbon cycle during these ancient

**Figure 1** Geographic map of flood basalt deposits. Color codes are as follows: Siberian Traps (Russia) = yellow; Central Atlantic Magmatic Province (CAMP) = violet; Deccan Traps (India) = green; other large igneous provinces = dark grey. Land = light grey. Data from Johansson et al. (2018); reconstruction with Gplates (www.gplates.org).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>ISOTOPE RECORDING MEDIUMS, RESPECTIVE CARBON RESERVOIRS RECORDED BY THE MEDIUM, AND THE ADVANTAGES AND DISADVANTAGES OF EACH MEDIUM.</th>
</tr>
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<tbody>
<tr>
<td><strong>Isotope recording medium</strong></td>
<td><strong>Carbon reservoir</strong></td>
</tr>
<tr>
<td>Bulk organic carbon</td>
<td>Dissolved inorganic carbon and atmospheric (\text{CO}_2 )</td>
</tr>
<tr>
<td>(n)-alkanes*</td>
<td>Atmospheric (\text{CO}_2 )</td>
</tr>
<tr>
<td>Bulk carbonate carbon</td>
<td>Dissolved inorganic carbon</td>
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<tr>
<td>Foraminifera shells</td>
<td>Dissolved inorganic carbon</td>
</tr>
</tbody>
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* long-chained \(n\)-alkanes with a predominant odd-over-even chain length are biomarkers assigned to land plant leaf waxes.
Carbonate-rich source rocks from different extinction events, is the variable nature of the size of LIP eruption, from small (<< 0.1 Mkm$^2$) to large (1.8 Mkm$^2$). The size of the orange extinction dots correspond to extinction severity: small (3rd order, meaning generic diversity loss of less than 20%), medium (2nd order, meaning generic diversity loss of between 20% and 35%) and large (1st order, generic diversity loss of more than 35%). LIP data from Johansson et al. (2018) and paleontological data from various sources.

In the following section, we will try to deconvolve those records in terms of cause and consequence, list the mechanism(s) that are most acceptable in the context of current understanding of the respective mass extinction event, and discuss the biological consequences of the proposed mechanisms.

A complicating factor, when comparing $\delta^{13}C$ records from different extinction events, is the variable nature of the sample sources available (Table 1). For example, the widespread occurrence of Permian-to-Triassic limestones from the Tethys realm (which formed in the shelf seas of the vast Tethyan Ocean) has provided many carbonate-derived $\delta^{13}C$ records for the Permian–Triassic (P–Tr) mass extinction. These $\delta^{13}C$ records are obtained from bulk rock samples, which warrants caution because biogenic carbonates consist of clasts, matrix, and secondary calcite precipitates. These components can have different isotopic values, and so variations in their proportions can alter the $\delta^{13}C$ value even when there is no change in the ocean signal. This choice is, however, often unavoidable during mass extinctions due to the elimination of many calcifying organisms (Knoll et al. 2007). Notwithstanding, $\delta^{13}C$ records from different regions in the world often show similar trends, such as seen in P–Tr boundary sediments which show the same, uniform, >100 ky trend of a 4‰–5‰ lowering of $\delta^{13}C$ (e.g., in Iran, the Italian Alps, South China, Tibet, Oman, and Hungary) (Fig. 4). Transient (<100 ky) negative CIEs superimposed on the first-order trend have also been recognized at this time (Cao et al. 2009). However, increased scatter around the mean first-order trend in the post-extinction rock record (Fig. 4) might reflect a shift to a non-skeletal (microbial) carbonate production in the extinction’s aftermath. In addition, the scatter has probably increased due to the incorporation of spatially diverse diagenetic signals produced in unburrowed anoxic sediments (Schroffen et al. 2017). As a result of the low signal-to-noise ratio in bulk rock $\delta^{13}C$ records, the global significance of these secondary CIEs is hard to demonstrate. As an alternative, bulk organic matter from the P–Tr rock record has been used for carbon isotope analysis. However, these organic matter–based $\delta^{13}C$ records are not always able to reproduce the trend in carbonate-based $\delta^{13}C$ records, and $^{13}C$-enriched bulk organics might reflect a turnover in the primary producers from eukaryotic- to prokaryotic-dominated plankton communities (Cao et al. 2009). While bulk organic matter–based $\delta^{13}C$ records can represent an environmental and/or ecological meaningful signal, they are not necessarily related to the long-term carbon cycle. This effect is, above all, controlled by the whole-rock organic material, which is a mixture of organic compounds that can differ in carbon isotopic signature by >10‰ (van de Schootbrugge et al. 2008).

While lithological successions spanning the Triassic–Jurassic (Tr–J) mass extinction are generally devoid of carbonate, carbon isotope records from this time have mostly been derived from bulk organic matter. This is despite the fact that, like the P–Tr carbonate carbon isotope record, some continuous carbonate-bearing successions are available from the Tethyan and Panthalassian regions. However, the direct correlation of carbonate-based stratigraphic $\delta^{13}C$ records with those measured on organic matter is still largely unclear (van de Schootbrugge et al. 2008). Accepting the limitations of bulk organic matter–based $\delta^{13}C$ records, then an apparently variable stratigraphic $\delta^{13}C$ signal could simply reflect varying mixtures of organic compounds with different isotopic values. One solution to this problem is to meticulously separate the bulk organic matter into its individual constituents; another is to produce compound-specific $\delta^{13}C$ records. Thus, by screening the organic matter content of the Tr–J boundary section at Kuhjoch (Austria), Ruhl et al. (2010) showed that carbon isotope fluctuations were largely (but not completely) independent of organic matter compositional changes. One of the most outstanding features of the Tr–J record is an initial, negative CIE of up to 6‰–8‰, seen in many sections, developed over a brief timespan (<100 ky), and recorded in both whole-rock and compound-specific organic material (Ruhl et al. 2010, 2011) (Fig. 5). As the signal is also seen in organic molecules assigned to plant leaf waxes (long-chained n-alkanes with a predominant odd-over-even chain length), it could indicate that the carbon isotope signal records a change in atmospheric CO$_2$ (Ruhl et al. 2011). However, n-alkane extracts can also...
be sourced from different plants with potentially species-specific carbon isotope values (van de Schootbrugge et al. 2008 and references therein). A floral turnover could, therefore, have skewed to plant communities with a particularly $^{13}$C-depleted signature in their leaf waxes. Moreover, changes in water availability can affect physiological processes and these could be expressed as differences in the magnitudes of carbon isotope fractionations, thereby potentially changing the $^{813}$C of the leaf waxes of a single plant species over time.

Notwithstanding the limitations discussed above, compound-specific organic carbon isotope analyses currently represent the most fair report of a carbon cycle perturbation at the Tr–J boundary interval. The initial negative CIE is followed by heavier values and then a long-term trend of up to 4‰ lower $^{13}$C recorded in bulk organic matter (the so-called main CIE) (Fig. 5). However, independent confirmation of this second negative CIE of the Tr–J $^{813}$C record is still largely missing. In this respect, it is important to note that Tr–J sections located in Europe (and also other sites around the world) are marked by pronounced sedimentological, mineralogical, and palaeontological changes over this interval, changes that have been associated with sea-level fluctuations, local extinctions of fauna and flora, and/or modulations of the continental weathering flux (von Hillebrandt et al. 2013). These observations warrant caution when interpreting the main CIE, because organic matter compositional changes could have biased this record (van de Schootbrugge et al. 2008). It therefore would seem that compound-specific $^{813}$C records over broader stratigraphic ranges across the Tr–J boundary interval would be a particularly high-priority target for future studies.

For the Cretaceous–Paleogene (K–Pg) mass extinction, the $^{813}$C changes across this interval are primarily obtained from the carbonate shells of foraminifera. This is in contrast to, for example, the P–Tr event, where it is not possible to construct such high-resolution single-component $^{813}$C records. Foraminifera shells only became major constituents of open marine sediments after the Tr–J extinction event. Foraminifera shells provide many benefits for geochemists. Modern foraminifera precipitate carbonate shells in close equilibrium with marine DIC and are assumed to provide a record of oceanic changes in K–Pg times. In addition, manual selection of individual specimens of foraminifera from sediments allows for screening to eliminate diagenetic alteration, such as recrystallization and crystal overgrowths. Useful, foraminifera also inhabit both seafloor (benthic) and water column (planktic) settings, they can be sourced from different sites around the world, and also other sites around the world, are marked by pronounced sedimentological, mineralogical, and palaeontological changes over this interval, changes that have been associated with sea-level fluctuations, local extinctions of fauna and flora, and/or modulations of the continental weathering flux (von Hillebrandt et al. 2013). These observations warrant caution when interpreting the main CIE, allowing the reconstruction of water column gradients of $^{813}$C values. Nonetheless, it is important to bear in mind that species-specific physiological aspects (e.g., growth rate and photosymbionts) and environmental parameters (e.g., $\text{CO}_2^-$ concentrations) also influence foraminiferal carbonate $^{813}$C.

The K–Pg crisis differs from the previous two mass extinctions in that there is either no, or only a moderate, 0.5‰–1‰ trend to lower or higher $^{813}$C across the event horizon (Zachos et al. 1989; D’Hondt et al. 1998). Prior to the extinction, planktic foraminifera show $^{813}$C values that are up to 2‰ more enriched with $^{13}$C than contemporaneous benthic foraminifera (Fig. 6). This difference disappears at the K–Pg boundary and the two values converge before gradually separating again over the next 300 ky.

**WHAT DO CARBON ISOTOPE CHANGES TELL US ABOUT MASS EXTINCTIONS?**

A plethora of hypotheses have been proposed to explain the P–Tr CIE. Here are three popular ones: 1) a sudden overturn of a stagnant ocean that caused $^{13}$C-depleted deep waters to merge into surface waters where the Tethyan limestones formed (Knoll et al. 1996); 2) a sea-level lowering and exposure of shelf sediments, which then weather to release $^{13}$C-depleted carbon from their stored organic content (Holser and Magaritz 1987); 3) a collapse of primary productivity that caused $^{13}$C-depleted carbon to return to the DIC pool and be incorporated into limestones (Rampino and Caldeira 2005). All of these mechanisms fail to correspond with either geological or modelling evidence. The first hypothesis actually contradicts the oceanic changes observed at the P–Tr boundary, because this event is marked by a replacement of relatively well-ventilated oceans by anoxic oceans (Hotinski et al. 2001) and it is unlikely that such an overturn would produce a >100 ky first-order $^{813}$C trend (Fig. 4). The second does not accord with current evidence of P–Tr sea-level change,
which recognizes a short-term regression followed by a major transgression (Hallam and Wignall 1999). Finally, the third hypothesis is unlikely because multiple lines of evidence suggest that persisting (or increased) primary productivity and consequent oxygen demand is necessary to drive the spread of anoxic water masses during the extinction interval (Meyer et al. 2008).

The LIP Siberian Traps basalts are implicated in the P–Tr extinction and contemporaneous carbon cycle perturbations, and many scenarios have been developed based on this link. Unfortunately, the carbon isotope record is considered to be a poor monitor of eruptions because up to two-thirds of the Siberian Traps lavas may have been erupted before the extinction (Burgess et al. 2017) (Fig. 4). Instead, the main carbon release could have been caused by sill emplacement in the sedimentary basins beneath these flood basalts. This second volcanic phase does overlap in time with the extinction horizon (Fig. 4). Such intrusions would have baked the country rocks, which included both evaporites and organic-rich strata, and caused the escape of large volumes of halocarbons and very $^{13}$C-depleted (down to $-50\%_{oo}$) methane and carbon dioxide (thermogenic gases). Evidence for this process comes from the presence of numerous breccia pipes in the region, which are interpreted to be the product of explosive gas-release events (Svensen et al. 2009). Thus, the P–Tr CIE is now often attributed to both direct (volcanogenic) and indirect (thermogenic) gas emissions from the Siberian Traps, with the latter probably having the greatest influence on the decrease of $\delta^{13}$C values.

The best resolved feature of the $\delta^{13}$C record of the Tr–J boundary beds is the short-lived (<100 ky) initial CIE (Fig. 5), a feature that clearly differs from the long-term P–Tr $\delta^{13}$C trend. The magnitude of the excursion, as recorded in land plants, is extraordinary (up to $8\%_{oo}$) and requires the rapid release of huge volumes of $^{13}$C-depleted carbon into the ocean and atmosphere. The eruption of the flood basalts of the Central Atlantic Magmatic Province (CAMP) was contemporaneous with (or slightly preceding) the initial CIE and, like the Siberian Traps, intrusion of sills into organic-rich strata may have added additional $^{13}$C-depleted carbon into the system (Heimdal et al. 2018). However, such geologically brief negative CIEs are often attributed to the destabilization of methane hydrates (Dickens et al. 1995). Hydrates are ice-like deposits found at shallow depths in sediments beneath cold and/or deep waters. Methane hydrates are very $^{13}$C-depleted ($\delta^{13}$C $\approx -60\%_{oo}$), an effect of biological methane production and recycling during the anaerobic breakdown of organic matter. There are concerns today that modest increases in ocean temperature will cause methane hydrate deposits to destabilize and release large volumes of methane, a potent greenhouse gas, into the atmosphere and so further accelerate the warming trend. Such a positive Earth system feedback would appear as a geologically rapid event in the $\delta^{13}$C record, such as the end-Triassic initial CIE. Methane hydrate destabilization has been proposed for the latest Triassic: it coincided closely with the mass extinction (Ruhl et al. 2011). However, it is puzzling that the emplacement of the CAMP and its thermogenic degassing over ~500 ky did not produce a protracted $\delta^{13}$C trend like that seen during the P–Tr mass extinction.
The convergence of planktic and benthic foraminifera shell δ¹³C records at the K–Pg boundary has been a pivotal observation, which in the 1980s was considered as a signal of complete shutdown of primary productivity (e.g., Zachos et al. 1989) (Fig. 6). This scenario, termed a “Strangelove ocean”, was considered to be consistent with the idea that a bolide impact caused the injection of dust and aerosol in the atmosphere and severely affected global photosynthetic activity (Alvarez et al. 1980). In today’s oceans, DIC shows a carbon isotope gradient with values in surface waters being relatively enriched in δ¹³C than deeper waters, because δ¹³C is taken up by photosynthesizing plankton and incorporated into organic matter. Subsequent remineralization of the organic matter at depth returns the δ¹³C-depleted carbon to the DIC pool and drives the deep water δ¹³C values to more negative values. In an ocean devoid of photosynthesizing plankton, this process does not happen and the surface-to-depth δ¹³C gradient disappears. The Strangelove ocean hypothesis has now largely been dismissed. A modeling study has shown that a certain degree of organic carbon transport to the ocean floor (“export productivity”) must have prevented the ocean’s DIC carbon isotope composition to drift towards δ¹³C values equal to the weathering flux (Kump 1991) (Fig. 3). Also, surviving bottom-dwelling fauna indicates that a food supply to the sea floor must have persisted (Alegret et al. 2012).

Other possible causes for the isotopic changes at the K–Pg boundary have been presented. One hypothesis is that the extinction saw a change in plankton composition to populations dominated by smaller species that, after death, were less likely to survive to the desert to the sea floor (D’Hondt et al. 1998). In addition, the demise of zooplankton, which produce faecal pellets that facilitate export productivity, implies less δ¹³C-rich organic matter reaching the DIC pool at depth. If this process weakens, then most remineralization will occur near the surface and greatly diminish the surface-to-depth δ¹³C gradient (D’Hondt et al. 1998).

In another twist, Alegret et al. (2012) suggested that a community turnover among foraminifera species, and species-specific δ¹³C signatures, could explain the disappearance of the surface-to-depth δ¹³C gradient altogether. Finally, a purely physicochemical model has recently been proposed by Galbraith et al. (2015), which shows the effect of equilibration timescales on carbon isotope ratios via air–sea exchange, where high atmospheric CO₂ levels weakens the oceanic surface-to-depth δ¹³C gradient. Clearly these are different scenarios to the original Strangelove ocean hypothesis, but the ideas share the notion that there were major changes in plankton populations and/or oceanographic conditions at the K–Pg boundary. There is also a close temporal association between the K–Pg extinction and volcanism, the Deccan Traps LIP (Figs. 2 and 6). Yet, intriguingly, these flood basalts seem to have had little effect on the carbon isotope record. The major difference of this LIP, with respect to the CAMP and the Siberian Traps, might be the lack of extensive intrusive magmatism into organic-rich sedimentary rock. On the other hand, volcanism could have already put ecosystems under stress prior to the Chicxulub (Mexico) bolide impact through volcanogenic CO₂ and SO₂ outgassing and consequent climatic changes. This may have contributed to the mass extinction (Barnet et al. 2017) (Fig. 6).

CONCLUSIONS

The carbon isotope records provide significant insights in the major environmental perturbations associated with mass extinctions, because they help quantify both magnitude and rates of change in the carbon cycle. Brief, high amplitude excursions, such as that seen during the P–Tr mass extinction, are the hallmark of rapid processes, such as the release of vast quantities of methane from hydrates. In contrast, the prolonged decline of δ¹³C values during the P–Tr crisis points to longer-term processes, such as the cumulative effect of the release of thermo-genic gases produced by baking of sediments beneath the Siberian Traps lava pile. The magnitude and duration of the P–Tr trends also eliminates other hypotheses, such as a catastrophic ocean overturn event. The rise of planktic foraminifera in the Jurassic means that, by the time of the
next mass extinction (at the end of the Cretaceous), it is possible to reconstruct the water column surface-to-depth \(^{13}C\) gradient. These data show there were major changes in plankton populations and/or oceanographic conditions during the K-Pg event.

Despite their versatility, carbon isotopes are not a panacea for understanding all aspects of mass extinctions. Most, perhaps all, extinction crises coincide with large-scale volcanism and disturbance to the long-term carbon cycle. But the associated carbon gas emissions might have left little imprint on \(^{13}C\) records. Additionally, failure to account for the limitations inherent to certain isotope recording mediums might lead to erroneous interpretations of carbon isotope excursions. Our evaluation further emphasizes the need for understanding global carbon reservoirs, fluxes, interconnections, and their respective carbon isotope compositions. Aspects such as timing, volumes, location of eruptions, and flux rates from LIP volcanism, likely to be important in extinction scenarios, can only be reliably addressed by including other proxy data, improved dating and computer modeling. As a result, there are several strands in the extinction–volcanism link that are poorly understood. This raises many questions.

Why is the timeline of volcanic outpouring broad relative to the short duration of an extinction pulse? Why are some giant volcanic episodes that have an extensive intrusive component not associated with mass extinctions, such as the Paraná–Etendeka LIP or the North Atlantic Igneous Province, even though others are?

Looking forward, the release of greenhouse gases by intrusive volcanism and through positive feedbacks (as for methane hydrates) provides a tantalizing clue in the search for the smoking gun of ancient extinction events. It also warns of the future effects of more recently emitted fossil carbon into the Earth system.

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The Abraham Gottlob Werner Medal in silver is the highest award of the German Mineralogical Society and honours outstanding contributions to research in mineralogy and closely related fields. The 2019 medal is granted to Donald B. Dingwell, Professor of Mineralogy and Petrology at the Ludwig-Maximilians-Universität (LMU) of Munich (Germany). Don Dingwell has pioneered how to apply the mineralogical sciences to molten and glassy geomaterials. His work on the fundamental nature and properties of silicate melts has laid a foundation for how to better quantify the dynamics and kinetics of magmatic processes. The field of volcanology has benefitted greatly from applying his discoveries in melt physics to eruptive processes. Under his supervision, the fundamental origins of explosive volcanism have been addressed by experimental simulations and by the development of models that can predict the evolution of physical properties of partially molten systems during their ascent to the surface. Thanks to his work, and to the results of his whole research team at LMU, our understanding of how chemical and physical processes interact and so control magmatic and volcanic processes has been substantially improved.

The Beate Mocck Prize is dedicated to supporting mineralogical research by young female scientists, in particular in the fields of petrology and geochemistry. This year, the prize was awarded to two individuals: Ninja Braukmüller (University of Cologne, Germany) and to Laura Otter (Macquarie University, Australia).

For her PhD thesis, Ninja Braukmüller investigated the behaviour of volatiles in chondritic meteorites and the Earth. She has shown that carbonaceous chondrites display a "hockey stick" volatile element depletion pattern. There are indications that Earth exhibits a similar volatile element depletion pattern. With the prize money, Ninja will attend the next Goldschmidt meeting in Honolulu (Hawaii, USA) and combine this with a field trip to Hawaii’s active volcanoes.

Laura Otter’s thesis is entitled “Micro- to Nano-Scale Architecture and Aspects of Skeletal Growth in Marine Calcifiers”. Laura’s work offers new insights into shell architecture, growth dynamics at the submicron scale, and it furthers our understanding of the mechanical properties of different shell ultrastructures. With the prize, she is planning to finance scanning transmission X-ray microscopy experiments at the Advanced Light Source in Berkeley (California, USA). Also, she will present her results in San Francisco (California, USA) at the Fall 2019 meeting of the American Geophysical Union.

The Paul Ramdohr Award is given for the best student contribution at the previous year’s annual meeting of the DMG. The 2018 awardee was Anja Allabar (University of Tübingen, Germany). The DMG honours her excellent presentation “Decompression Induced Phase Separation of Hydrous Vesuvius Melt: Vesicle Nucleation or Spinodal Decomposition?”, which was given at the GeoBonn conference in September 2018. The award was presented to her at the 2019 GeoMünster meeting, held 22–25 September in Münster (Germany).

The 3rd 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 Società Italiana di Mineralogia e Petrolgia 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 • Atomic and thermodynamic modelling • Education and mineralogy • Environmental mineralogy and low T geochemistry • Experimental mineralogy and petrology • Geochemistry, geomicrobiology and biomineralogy • Geochronology • 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
THE CANADIAN MINERALOGIST

Upcoming thematic issue in honor of Professor Elena Sokolova

There will be a thematic issue of *The Canadian Mineralogist* to mark the retirement of Professor Elena Sokolova from the University of Manitoba (Canada). Professor Sokolova is well-known for her crystallographic work on Ti-silicate minerals and on a wide range of other minerals and synthetic analogues.

Call for Papers

The Guest Editor of the Sokolova thematic issue will be Dr. Yulia Uvarova: contact her at CSIRO, PO Box 1130, Bentley WA 6102 Australia; E-mail: Yulia.Uvarova@csiro.au. It is anticipated that the thematic issue will be published in 2020 in either issue 5 or 6. Papers should be submitted before 15 May 2020 for inclusion in this issue. Interested authors are encouraged to contact Dr. Uvarova as soon as possible with an expression of intent.

Latest Release in our Special Publication Series

**Mont Saint-Hilaire: History, Geology and Mineralogy**

Special Publication 14 of *The Canadian Mineralogist*

**Authors:** László Horváth, Robert A. Gault, Elsa Pfenninger-Horváth & Glenn Poirier

**Series Editor:** Robert F. Martin

ISBN 978-0-921294-61-0, SP14, 644 pages, hard cover, 2019

László and Elsa Horváth, a duo of dedicated and dynamic amateur mineralogists, have teamed up with researchers, Robert Gault (a mineralogist) and Glenn Poirier (a geologist) to produce the ultimate book on the legendary Mont Saint-Hilaire deposit of southern Quebec (Canada): *Mont Saint-Hilaire: History, Geology, Mineralogy*. This exceptional book took over 20 years of meticulous preparation. The photography captures the colours of Vásáryely, the symmetry of Escher, the form of Bartók and the intricate patterns of Mandelbrot, all found here, in this miracle of nature. One cannot but marvel at how this single, small quarry contains such mineral diversity. At last count, over 434 mineral species have been found at Mont Saint-Hilaire, representing 9% of all known mineral species. The 66 type minerals first described from this locality represent 1.3% of all known chemical elements included in this mineral mix. Beginning some 124 million years ago, it took several million years and a variety of geological processes to produce this assemblage. Be captivated, learn and, most of all, enjoy!

Order online at www.mineralogicalassociation.ca

MAC AWARDS: CALL FOR NOMINATIONS

**Peacock Medal**

The Peacock Medal is awarded to a scientist who has made outstanding contributions to the mineralogical sciences in Canada. There is no restriction regarding nationality or residency. The medal recognizes the breadth and universality of the awardee’s contributions to mineralogy, applied mineralogy, petrology, crystallography, geochemistry, or the study of mineral deposits.

**Young Scientist Award**

This award is given to a scientist who has made a significant international research contribution during the early part of their scientific career. The scientist will have received his/her PhD not more than 15 years before the award. He or she must be a Canadian working anywhere in the world, or a scientist of any nationality working in Canada. The research areas include mineralogy, crystallography, petrology, geochemistry, mineral deposits, or related fields of study.

**Leonard G. Berry Medal**

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

**Pinch Medal**

The Pinch Medal is awarded every other year since 2001 to recognize major and sustained contributions to the advancement of mineralogy by members of the collector/dealer community. This medal is named for William Wallace Pinch of Rochester (New York, USA) in recognition of his enormous and selfless contributions to mineralogy through the identification of ideal specimens for study and through his generosity in making them available to the academic community. Nominations for the 2020 medals and award are to be submitted to Andrew M. McDonald (Department of Earth Sciences, Laurentian University, Sudbury, ON P3E 2C6, CANADA); E-mail: amcdonald@laurentian.ca

Please submit your nominations by 30 November 2019 for the Pinch Medal and by 31 December 2019 for the others. Check our website, www.mineralogicalassociation.ca, for additional details.

**STUDENT TRAVEL/RESEARCH GRANTS**

Travel and research grants are awarded by the MAC to assist honours undergraduate and graduate students in the mineral sciences. For more information, please see www.mineralogicalassociation.ca. The application deadline for the next awards is 15 January 2020.

**LATEST RELEASE IN OUR 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


Order online at www.mineralogicalassociation.ca
The Call for Sessions, Symposia, Field Trips and Short Courses Proposals is now open!

Once in a decade, the Canadian Society of Petroleum Geologists (CSPG), the Canadian Society of Exploration Geophysicists (CSEG) and the Canadian Well Logging Society (CWLS) partner with the Geological Society of America and the Mineralogical Association of Canada (i.e., GAC–MAC) and the International Association of Hydrogeologists (IAH) to bring together a fully integrated geoscience program. GeoConvention 2020 will be held 11–13 May 2020 in Calgary (Canada) and is your once-in-a-decade opportunity to learn and share knowledge with a wide variety of Earth science professionals. Whether your focus is petroleum, base- or precious metals, geophysics, groundwater, bedrock or seabed mapping, geohazards, uranium, or environmental remediation, GeoConvention 2020 will present the latest developments across a very wide spectrum of the Earth sciences.

GeoConvention 2020 will offer some of the best local and international insights into efficient energy exploration and production, something that is critical to the success of the industry.

If there is a session or workshop or field trip that you would like to host at GeoConvention 2020, we want to hear from you! Please submit your idea via the link below:

https://www.surveygizmo.com/s3/5008912/
Geaconvention-2020-Call-for-Sessions

GeoConvention 2020 Call for Abstracts will Open Mid-September

Keep an eye on the GeoConvention 2020 and MAC websites and their social media accounts to learn when the 2020 Call for Abstracts is live.

More info at: https://www.geoconvention.com/

HOPING TO HEAR BACK FROM YOU WITH YOUR PROPOSALS

2020 SPONSORING SOCIETIES

The Contribution of Mineralogy to Cultural Heritage

The latest book, volume 20, in the EMU Notes in Mineralogy series, has been published: The Contribution of Mineralogy to Cultural Heritage. Paper copies are available for purchase from the Mineralogical Society of Great Britain and Ireland’s website (www.minersoc.org) or from the Mineralogical Society of America’s website (www.minsocam.org). Chapters from the book are available via open access from the Mineralogical Society’s site.

“The competent mineralogist should possess a profound perception of the complexity of natural materials, he/she should have the necessary knowledge of the ancient and recent geological and physicochemical processes acting on them and on the artifacts produced by human activities, and he/she should master most of the methods and techniques useful for investigating our common heritage.

The chapters contributed to this book recognize the important and diverse contributions of mineralogy to the valorization, characterization, interpretation and conservation of cultural heritage. The book focuses on examples of materials and methodological issues rather than technical/analytical details. The authors have attempted to deal with the cultural heritage materials in chronological order of their technological developments, to relate them to past human activities, and to highlight unresolved problems in need of investigation.”

Table of Contents

Chapter 2. “Variations on the silica theme: Classification and provenance from Pliny to current supplies.” By E. Gliozzo.
Chapter 3 “Glass and other vitreous materials through history.” By I. Angelini, B. Gratuze and G. Artioli.
Chapter 5. “Mineralogy of slags: A key approach for our understanding of ancient copper smelting processes.” By D. Bourgarit.
Chapter 12. “Synchrotron radiation infrared microspectroscopy and imaging in the characterization of archaeological materials and cultural heritage artefacts.” By A. Marcelli and G. Cinque.
DISTINGUISHED LECTURERS
The Mineralogical Society of Great Britain and Ireland’s Distinguished Lecturers for 2019–2020 will be:

Caroline Peacock (University of Leeds, UK)
- Talk A: "Mineralogical Controls on Earth’s Climate"
- Talk B: "Mud, Mud, Glorious Mud: How Marine Sediments Help Control the Earth System"

and Sami Mikhail (St. Andrews University, UK)
- Talk A: “Diamonds Illuminate the Nature of Earth’s Deep and Dynamic Carbon Cycle”
- Talk B: “Is Earth’s Atmosphere Growing or Shrinking?”

See the society’s website (https://www.minersoc.org/distinguished-lectures.html) for details of dates and venues for these talks.

METAMORPHIC STUDIES GROUP LAUNCHES THE NEW BARROW AWARD
A new award named after George Barrow (1853–1932), a geologist with the Geological Survey of Great Britain and the first to assign index minerals to zones of progressive metamorphism (now-termed Barrow Zones), has been launched by the Metamorphic Studies Group (MSG).

“The Barrow Award will be awarded annually to a scientist who has made an outstanding contribution to metamorphic studies. Publications, teaching, outreach and other activities leading to the promotion of metamorphic geology, in the broadest sense, will be taken into account in making the award. Nominees do not have to be members of the Mineralogical Society, Fellows of the Geological Society of London or nationals of Great Britain and Ireland. The award is open to a scientist at any stage of their career (early, mid or late).”

Nominations should include a statement on the merits of the candidate, a summary curriculum vitae (CV) and a list of the nominee’s more important contributions. Letters of support may be submitted from up to two additional people.

Nominations will remain on the table for three years. Previous recipients of the award, and members of the MSG Committee (at the time of nomination and adjudication) will not be eligible for the award.

Nominations for the 2020 medal should be sent to the Chair of the Metamorphic Studies Group committee, to arrive not later than 1 December 2019. Submissions should be compiled as a single package in pdf format, to include the nomination statement, CV of the candidate and the optional additional letters of support. The nomination package should be attached to an e-mail with a title which identifies the name of the award and the name of the nominee. The e-mail address to use is metamorphicstudiesgroup@gmail.com.

MINERAL DEPOSITS STUDIES GROUP 2020
The next Mineral Deposits Studies Group (MDSG) meeting will be held from 6–8 January 2020 at the Natural History Museum London (UK). Further details to follow on the MDSG website: www.mdsg.org.uk.

MEMBERSHIP REMINDER
We encourage all you academics 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).

SIR ARTHUR RUSSELL BIOGRAPHY
One of our members, Roy Starkey, is working on a biography of the famous British mineralogist Sir Arthur Russell (1878–1964), a prominent member and former president of the MinSoc.


As part of his research Roy has asked if there are readers of Elements who may have attended Mineralogical Society meetings or events prior to 1964, when Sir Arthur was alive.

Roy is keen to hear from anyone who may have memories or any information to contribute, and especially any photographs of Sir Arthur at mineralogical events, or perhaps of one of the society visits to view his wonderful collection at his home, Swallowfield Park.

Please contact Roy directly if you have anything which may be of interest: Roy’s e-mail is Roy.starkey@gmail.com.

SOCIETY BURSARIES 2019
Student Bursaries (round 2 for 2019) have been awarded to J.O. Edgar (Newcastle University, UK) and C. Pesce (Northumbria University, UK)

To apply for 2020, please note the updated deadlines and periods for which those deadlines apply (https://www.minersoc.org/postgraduate-bursaries.html).

Impact factors: Mineralogical Society of Great Britain and Ireland. The award is open to any stage of career (early, mid or late).


IMPACT FACTORS 2019
The MinSoc’s journals both fared very well in this year’s impact factor announcements. Mineralogical Magazine improved to 2.21; that of Clay Minerals to 1.78. The editorial teams for both journals and our colleagues at Cambridge University Press continue to work hard to maintain and improve these levels.

One of our members, Roy Starkey, is working on a biography of the famous British mineralogist Sir Arthur Russell (1878–1964), a prominent member and former president of the MinSoc.


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To apply for 2020, please note the updated deadlines and periods for which those deadlines apply (https://www.minersoc.org/postgraduate-bursaries.html).

Reports will appear on the society’s website in due course (https://www.minersoc.org/bursary-report.html).

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Recent Content in Mineralogical Magazine [June 2019, v83(3)]

“The 51st Hallimond Lecture: Time’s Arrow, Time’s Cycle: Granulite Metamorphism and Geodynamics”. By Michael Brown, Tim Johnson


“Magnesioleydite and Straßmannite, Two New Uranyl Sulfate Minerals with Sheet Structures from Red Canyon, Utah”. By Anthony R. Kamp, Jakub Plášil, Anatoly V. Kasatkin, Barbara P. Nash, Joe Martý


“Rinkite-(Y), Na₂Ca₄YTi(Si₂O₇)₂OF₃, a Seidozerite-Supergroup TS-Block Mineral from the Darai-Ploiz Alkaline Massif, Tien-Shan Mountains, Tajikistan: Description and Crystal Structure”. By Leonid A. Pautov, Atali A. Agakhanov, Vladimir Yu. Karpenko, Yulia A. Uvarova, Elena Sokolova, Frank C. Hawthorne

“Subaerial Sulfate Mineral Formation Related to Acid Aerosols at the Zhenzhu Spring, Tengchong, China”. By Lianchao Luo, Huaguo Wen, Rongcai Zheng, Ran Liu, Yi Li, Xiaotong Luo, Yaxian You

“Pampaloite, AuSbTe, a New Mineral from Pampalo Gold Mine, Finland”. By Anna Vymazalová, Kari Kojonen, František Laufek, Bo Johansson, Chris J. Stanley, Jakub Plášil, Patricie Halodová

“Middlebackite, a New Cu Oxalate Mineral from Iron Monarch, South Australia: Description and Crystal Structure”. By Peter Elliott


“Mineralogy and Technological Characterization of Two Kaolin Deposits of the Pyroxenoid Mineral Name ‘Marshallsussmanite’ with a Reinstatement of the Name Schizolite, NaCaMnSi₂O₇(OH)³”. By Joel D. Grice, Aaron J. Lussier, Henrik Friis, Ralph Rowe, Glenn G. Poirier, Zina Fihl


Recent Content in Clay Minerals

“Development of Young’s Modulus of Natural Illitic Clay During Heating and Cooling Stage Of Firing”. By T. Hülán, I. Štub a, A. Shishkin, I. Ozolins, Š. Csáki, P. Ba ik, J. Fridrichová

“Thermally Expanded Vermiculite as a Risk-Free and General-Purpose Sorbent for Hazardous Chemical Spillages.” By N. D. Cuong, V.T. Hué, Y.S. Kim

“Mineralogical and Crystal-Chemical Characterization of the Talc Ore Deposit of Minzanzala, Gabon.” By M. Poirier, J. E. Boulingui, F. Martin, M. Mbina Mounguengui, C. Nkoumbou, F. Thomas, M. Cathelineau, J. Yvon

“An Archaeometric Study of Early Copper Age Pottery from a Cave in Romania.” By A. Enea-Giurgiu, C. Ionescu, V. Hoeck, T. t ma , C. Roman

“Surface Chemistry, Rheology and Microstructure of As-Received SHCa-I Hectorite Gels.” By P.I. Au, M.Y. Du, J.S. Liu, Md. Bashirul Haq, Y.K. Leong


“Assessment of Clayey Materials from Santa Maria (Azores, Portugal) for Peloids Preparation.” By A. Cerqueira, C. Costa, D. Terroso, C. Sequeira, F.Rocha

“Determination of Phase Composition of Partially Dehydroxylated Kaolinites by Modeling Their XRD Patterns.” By V. A. Drits, B. A. Sakharov, O. V. Dorzhieva, B. B. Zviagina & H. Lindgreen

Obituary: Dr Enver Murad

SOCIETY RISK REGISTER

Following deliberation by council, the society has created a risk register. This will be considered/edited/updated at each meeting of council going forward. The document will not be posted on the society website but will be made available to any interested member on enquiry.

SOCIETY CODE OF CONDUCT

The society’s new “Code of Conduct for Meetings and Other Events” has been posted on the website at https://www.minersoc.org/code-of-conduct.html.
ROBERTA OBERTI AND LUCA BINDI: NEW ACCADEMIA NAZIONALE DEI LINCEI FELLOWS

Congratulations to the SIMP Fellows Roberta Oberti and Luca Bindi who were elected as new members of the Accademia Nazionale dei Lincei. The official ceremony will take place 8 November 2019 in Rome (Italy) in the presence of the President of the Italian Republic, Sergio Mattarella.

Piergiulio Cappelletti
(SIMP President)

ALEXANDER VON HUMBOLDT RESEARCH AWARDEE: FABRIZIO NESTOLA

Fabrizio Nestola (University of Padova, Italy) received the Alexander von Humboldt Research Award for his outstanding research on the Earth’s interior and his pioneering analytical work on inclusions in superdeep diamonds. His studies combine X-ray diffraction of tiny particles enclosed in diamonds using synchrotron radiation and in-house instruments with highly sensitive detectors. Fabrizio Nestola received the award from Hans-Christian Pape, President of the Alexander von Humboldt Foundation, during a ceremony award held 27 June 2019 in Berlin (Germany) in the presence of the Chancellor of Germany, Angela Merkel, and the Federal President, Franz-Walter Steinmeier.

The award will allow Fabrizio to extend his analytical work to the nano-level by applying transmission electron microscopy, which he will do in collaboration with Dr. Frank Brenker of the Goethe University of Frankfurt (Germany).

INTERNATIONAL NATURAL ZEOLITE ASSOCIATION WEBSITE

On behalf of the officers of the International Natural Zeolite Association (INZA), I wish to inform you that we have a brand new website that you can visit at the following address: https://www.inza.it/. You will find all the information concerning our organization, past meetings, how to join INZA, reading or adding abstracts of new papers in the section “paper showcase”, and news about the next meeting “Zeolite 2022” to be held in the beautiful island of Ischia (Italy).

Alessio Langella, ex officio member Chair of Zeolite ’22

EUROPEAN JOURNAL OF MINERALOGY: OPEN ACCESS

On behalf of the four mineralogical societies who publish the European Journal of Mineralogy, we are pleased to announce that we have signed a contract with Copernicus Publications for a “full open access” publication of our journal. One of the major advantages of this strategy will be to significantly increase the visibility of EJM and to reduce the publication time, primarily because the journal will now be fully on-line. We emphasize that the editorial board and the high standards of manuscript peer-review evaluation will remain exactly the same.

The website for submission of your manuscripts to the journal is already open at the address: https://www.european-journal-of-mineralogy.net/.

Article processing charge (APC): The regular APC will be €75 per printed page (manuscript using Word template) or €70 per printed page (manuscripts using LaTeX). However, SIMP members who are corresponding authors are entitled to a discount of 20% on APC charges.

To facilitate the transition to a fully open-access journal, we will offer an APC that is reduced to €50 per printed page (or €40 for SIMP members) for a period starting 1 January 2020.

As an exceptional offer, all manuscripts submitted before 31 December 2019 will only be charged an APC of €30 per printed page for everyone.

We would like to stress that this is a very competitive and attractive APC strategy for a high-quality journal such as the EJM, which likewise nurtures the ambition of becoming a prime reference journal for mineral sciences.

We are confident that you will continue to support EJM in this new adventure, and we are ready to welcome your best manuscripts!

Warm regards,
The EJM Editorial Committee
**MEREMA 2nd Edition: International School on Mantle Dynamics**

30 March–2 April 2020, Sestri Levante (Italy)

The National Association of Petrologists (GNP) branch of SIMP (Italian Society of Mineralogy and Petrology), in collaboration with the PhD programs of the Universities of Pavia, Ferrara, Genova, Milano, Modena-Reggio Emilia and Torino, is organizing a second International School on Mantle Dynamics (MEREMA 2nd Edition), following on from the successful first MEREMA Winter School of 2017. The second school will be held in Sestri Levante at the wonderful Hotel Vis à Vis (https://www.hotelvisavis.com), situated along the Ligurian coast (Italy), approximately 40 km east of Genova and close to the famous “Cinque Terre”.

The MEREMA 2nd Edition is a European Mineralogical Union (EMU) school aimed at assessing the present state of knowledge on the structure, chemical differentiation and dynamics of the mantle (taken as a whole system), and acquiring information from different disciplines, mainly from petrology and geophysics.

The school is open to graduate and PhD students, post-docs and young researchers in the Earth sciences. The program will include poster sessions to give participants the opportunity to present their research work.

**Major themes of the school are the following:**

- Chemical evolution and dynamics of the Earth’s mantle
- Origin and length scale of chemical and isotopic mantle heterogeneities
- Transfer of heterogeneities from mantle sources to melts

**Lecturers:**

- Prof. Denis Andrault – Observatoire de Physique du Globe de Clermont-Ferrand (France)
- Prof. Guillaume Caro – Centre de Recherches Pétrographiques et Géochimiques (CRPG), Université de Lorraine (France)
- Prof. Cinzia Farnetani – Institut de Physique du Globe de Paris (France)
- Prof. Marguerite Godard – Géosciences Montpellier, CNRS, Université de Montpellier (France)
- Prof. Michel Gregoire – Géosciences Environnement Toulouse (GET-CNRS, CNES, IRS, Université Paul Sabatier), Observatoire Midi-Pyrénées (France)
- Prof. Albrecht W. Hofmann – Max Planck Institut für Chemie, Mainz (Germany)
- Prof. Richard Katz – University of Oxford (United Kingdom)
- Prof. Sarah Lambart – University of Utah (USA)
- Prof. William McDonough – University of Maryland (USA)
- Prof. Yanick Ricard – Université de Lyon, UCBL, ENSL, CNRS, LGL-TPE (France)
- Prof. Barbara Romanowicz – University of California, Berkeley (USA), Collège de France
- Prof. Andreas Stracke – Westfälische Wilhelms Universität, Münster (Germany)

**Organizing and Scientific Committee**

Daniele Castelli (Torino University, Italy), President GNP; Elisabetta Rampone (Genova University, Italy), Vice-President GNP; Costanza Bonadiman (Ferrara University, Italy); Cinzia Farnetani (Institut de Physique du Globe de Paris, France); Patrizia Fumagalli (Milano University, Italy); Albrecht Hofmann (Max Planck Institute, Mainz, Germany); Nadia Malaspina (Milano-Bicocca University, Italy), Secretary GNP; Alessandra Montanini (Parma University, Italy); Maurizio Mazzucchelli (Modena e Reggio Emilia University, Italy); Andreas Stracke (Münster University, Germany); Riccardo Tribuzio (Pavia University, Italy); Alberto Zanetti (Istituto di Geoscienze e Georisorse, Consiglio Nazionale delle Ricerche, Pavia, Italy).

**Registering for the Meeting**

The maximum number of participants is 50. Selection of applicants will be made on the basis of their research topic and CV. After the pre-registration deadline (15 October 2019), selected applicants will receive an e-mail of acceptance in order to proceed with the payment of the registration fee.

Graduate and PhD students, post-docs and young researchers interested in applying for the school should send an e-mail to gnp@unife.it by 15 October 2019 and provide the following information:

- First Name and Family Name
- Institution
- Title and/or brief description of own research to be presented as a poster (max. 300 words)
- PDF version of a CV (max. 1 page of A4)
- Preferred accommodation (double or triple room) and favoured roommate

**Registration fees** will be as follows:

- €345 for a triple room
- €445 for a double room

Participants must be SIMP members for 2020, Membership dues are separate from the registration fee and currently stand at €25 for under 35 years junior members and €50 for regular members.

The registration fee includes full board at the Hotel Vis a Vis, from the overnight of Sunday 29 March 2020 to breakfast on Friday 3 April 2020. The dinner on Sunday March 29 is not included.

Deadline for payment of the registration fee will be 31 December 2019.

Both SIMP membership and school registration fees can be paid on the SIMP website (www.socminpet.it).

Visit the website http://www.socminpet.it/Merema/ for more information about the school program, registration and venue.

For any queries or questions, please contact us at gnp@unife.it or betta@dipteris.unige.it (contact person is Elisabetta Rampone).
Recent advances in compositional data analysis have provided a solution to the Harker diagram problem in which the selected chemical data sum to a constant (e.g., 100%) and the graphical displays make no sense in terms of petrological and mineral stoichiometry. The article employs the Nockolds data set for major element average compositions of igneous plutonic rocks as the basis for a brief tutorial focusing on the Si–Al, Ca–Na and K–Ti relationships in the data. Data pairs are transformed into symmetric coordinates which permit the display of element relationships that are free of the constraints of closure. As a result, Si and Al increase sympathetically from felsic to felsic rocks; Na decreases with increasing Ca from felsic to felsic rocks and in the albite–oligoclase solid solution; and the inverse relationship between K and Ti becomes much clearer due to the reduction of the impact of the remaining parts of the composition. The procedure also permits correlation coefficients to be estimated and that are free from the effects of closure. Computer programming R scripts are provided for the necessary computations and displays, together with the Nockolds data and examples of the use of R functions.

The following abstract is for an article that appeared in issue 182 (March 2019) of the Explore newsletter.

“Application of Fourier Transform Infra-Red Spectroscopy (FTIR) for Mineral Quantification”
John Woods

Fourier transform infra-red spectroscopy is a technique that is used to obtain an infra-red spectrum of absorption or emission for solids, liquids or gases. The absorption excites molecular vibrations and rotations, which have frequencies that are the same as those within the infra-red part of the spectrum. The frequency of the response relates to specific bonds: the greater the response, the higher the concentration. In a manner similar to how X-ray diffraction (XRD) works, it is, possible to both identify and quantify a wide range of compounds. Minerals contain a wide variety of bonds, so the more open their structure, the better the infra-red response. This means that minerals which contain covalent bonds, such as clay minerals, can be both identified and quantified with considerable accuracy. Further to this, the development of new detectors and sampling plates based on attenuated total reflection (ATR) technology means that samples can be presented to the instrument without the need for complex preparation: they simply need to be dry and ground to less than 75 μm. Instrument run time is typically two minutes, and SGS has set up fully quantified methods for the analysis of clay minerals (e.g., illite, chlorite, kaolin, smectite), micas, carbonates (e.g., calcite, dolomite and siderite), feldspars (e.g., plagioclase and K-feldspar), quartz, spodumene, and apatite. The quantification ranges vary between minerals but is usually between 5%–100% with error generally less than 15% (R2 > 90%) even for clay minerals. Although the base methodologies are tolerant of a wide range in matrices, for optimal results it is always preferable to set up matrix matched methods.

The following abstract is for an article that appeared in issue 182 (March 2019) of the Explore newsletter.

“Geochemistry at Exploration ’17”
Hugh de Souza

Exploration ’17 is the most recent in a series of conferences held once every 10 years in Toronto (Canada) that surveys successes in mineral exploration and highlights promising new methods and technologies. Plummeting discovery rates over the last decade have thrown into question the use of conventional exploration techniques, particularly for the discovery of deposits under cover. Paul Agnew, in his geochemistry plenary talk, proposed a detailed geostatistical evaluation of existing data sets augmented by new data from low-detection-limit geochemistry, the use of portable real-time technologies, spectral techniques and an expanded use of mineral chemistry as a fertility and vectoring tool. These approaches were discussed in more detail by specialists in the geochemistry and analytical methods sessions and elsewhere. In the former session, the advantages of molar element ratio lithogeochemical analyses were reviewed, and there was a look forward to where geochemistry needs to advance over the next decade.

The methods session highlighted developments in inductively coupled plasma mass spectrometry technology and their role in gold discoveries in the Yukon (Canada). Low level parts-per-trillion detection of gold in groundwater for the exploration of deeply buried ore bodies and the application of isotopes in mineral exploration to delineate processes may be less used, but technical developments are making their applications easier. Portable analytical technology is developing fast and portable X-ray fluorescence has emerged as a key analytical technology of the last decade. With an aging cohort of geochemists still dominating the profession, new blood is desperately needed to ensure continued progress in exploration geochemistry. For more on the 2017 conference (and previous 1967 to 2007 conferences), visit www.DMEC.ca.

The full articles can be viewed at https://www.appliedgeochemists.org/index.php/publications/explore-newsletter.
The Association Internationale pour l’Étude des Argiles (International Association for the Study of Clays) (AIPEA) was founded in 1963 to promote international cooperation in clay research and technology. To date, it has been a relatively informal society. But in June 2019 we received a positive result from our first secret e-ballot to move forward with officially registering AIPEA as a legal society in Spain. Of the 202 votes cast, 174 were in favour of this proposal, 8 opposed, and 20 abstained. Thank you to all who voted.

EUROCLAY 2019 JOINT MEETING WITH CMA AND MCM IN PARIS (FRANCE)

Every four years, the European Clay Groups Association (ECGA) meet at the EUROCLAY conference. The meeting was held 1–5 July 2019 in Paris (France) at the Congress Center of the Pierre and Marie Curie University (part of the Sorbonne University Group in Paris). Two of the national clay groups of AIPEA—the Groupe Français des Argiles (French Clay group) and the Clay Minerals Society (CMS), which is based in North America—jointly organized the meeting together with the Mediterranean Clay Meeting (MCM) series. The conference was a great success, both in terms of the science and the number participants (more than 600), making it the largest EUROCLAY ever. Student participation in EUROCLAY was very high; more than 160 contributions by students were judged by experts in their scientific field. As decided by members of AIPEA and the CMS, the following were the best student poster and best oral presentations (winners and runners-up).

- **Best poster:** Paulina Maziarz (Poland), with co-author Jakub Matusik, for “Effectiveness of As(V) Removal from Wastewaters by Layered Double Hydroxides Impregnated with Fe Oxide”.
- **Best poster runner-up:** Milan Pšenička (Czech Republic), with co-authors Jakub Škoda, and Miroslav Pospíšil for “Sulindac and Mefenamic Acid Intercalated into LDHs Described by a Combination of DFT and Classical MD Simulations”.
- **Best oral presentation:** Mariana Pires Figueiredo (Brazil), with co-authors Alfredo Duarte, Christine Taviot-Gueho, Fabrice Leroux, and Vera Regina Leopoldo Constantino for “Iron-Based layered Double Hydroxides as Drug Carriers: Advantages and Challenges”.
- **Best oral presentation runner-up:** Pierre Picot (France), with co-authors Thibaud Coradin and Antoine Thill for “Methyl-Imogolite: A New Hybrid Nanotube for Water Remediation”.

Chinese Association for the Study of Clays

The 8th National Mineral Science and Engineering Conference of China was held 6–7 August 2018 in Mianyang (Sichuan, China). This conference was organized by Southwest University of Science and Technology (Sichuan, China), and 25% of the contributions came from the clay mineralogy community.

The Second World Forum on Industrial Minerals was held 20–23 October 2018 in Qingyang (Anhui, China). This forum was organized by the Qing Yang Institute for Industrial Minerals; the president of the forum was Prof. Chun Hui Zhou. There was significant international participation.

Tunisian Clay Group

On 28 April 2018, the Tunisian Clay Group (TCG) organized an excursion for students of the Tunis El Manar University to assess and investigate how geomaterials are valorized in the region of Jebel Oust.

Russian Clay Group

Members of the Russian Clay Group participated in a number of field trips and workshops over the last 12 months. These included field trips to the Leningrad region (Russia); participation at the 2nd International Conference for Clays and Ceramics, which was held in Riga (Latvia); attendance at the Workshop on Processing Legacy Radioactive Waste, held 27–31 August 2018 (Moscow, Russia); collaboration with Skoltech (the Russian equivalent to “silicon valley”); participation at the 55th Annual Clay Minerals Society meeting (Illinois, USA). Joint field work was also conducted at the so-termed 10th Khutor bentonite clay deposit in the Republic of Khakassia (Russia).

Reiner Dohrmann, AIPEA President
range to ~120 GPa, corresponding to the pressure at the bottom layer of Earth's mantle (the D^" layer). Using this advanced technique, he determined that the grain growth rate of ε-iron, the dominant phase of Earth's mantle (the D^" layer), is high enough for appreciable grain growth to occur. This result indicates that grain size and stress-insensitive rheology (Harper-Dorn creep) is likely to be the dominant deformation mechanism in the inner core and that a uniform viscosity is to be expected. His research on mantle rheology has shown that periclase is a few orders of magnitude softer than bridgmanite, as inferred from the measurement of silicon diffusion rates in bridgmanite; he has, thus, also discussed the important role of periclase on mantle rheology, viewing the lower mantle as if a two-phase rock. His research group has measured a variety of rheological properties of mantle minerals. Dislocation mobilities in ringwoodite and bridgmanite have been determined, which in turn led Dr. Yamazaki to investigate the viscosity contrast between the transition zone and the lower mantle. He has measured the preferred orientations of the crystal lattices for olivine, stishovite, bridgmanite and a post-perovskite analogue, as caused by deformation, to better interpret seismic observations and to constrain mantle dynamics.

**Manjiro Watanabe Award to Yoshikazu Aoki**

Yoshikazu Aoki was appointed to an academic position at the Faculty of Science in Kyushu University in April 1963 when he was still a master's student at the university. After serving as a technical officer for the former Geological Survey of Japan—the Agency of Industrial Science and Technology, the former Ministry of International Trade and Industry—for five years beginning in September 1966, he returned to Kyushu University as a research assistant at the Faculty of Science in September 1971. He received his Doctor of Science degree in 1978 from Kyushu University with his thesis, “The Morphology of Crystals Grown from Highly Saturated Solution.” Thereafter, he was promoted to assistant professor in 1978 and to professor in 1989. Dr. Aoki taught and guided the students at Kyushu University until his retirement in 2003. During this period, he was engaged in (i) research on descriptive mineralogy, (ii) surveys and research on ore deposits, and (iii) research on crystal growth. His research significantly contributed to the development of mineralogy in Japan, as described below.

(i) Descriptive mineralogy. Dr. Aoki described two new minerals, namely, “taneyalamite” and “nambulite.” He also reported on five minerals newly confirmed to occur in Japan. Among these, his description that taneyalamite, a new mineral of manganese silicate, is a manganese analog of howelite led to him being awarded the Sakurai Medal in 1987. This was a mark of honor for his contributions to our understanding of the metamorphism of manganese iron cherts, particularly under low-temperature and high-pressure conditions.

(ii) Ore deposit research. Dr. Aoki discovered the existence of a globally rare type of beryllium ore deposit comprising beryllium minerals (denalite and phenakite) at Mihara Mine in Hiroshima Prefecture. He then mineralogically and geochemically examined how this ore deposit formed.

(iii) Crystal growth. He theoretically studied the growth form of single crystals and the form of twin crystals to reveal the factors and mechanisms of nucleation and crystal formation. Dr. Aoki not only helped in the development of mineralogy in terms of the abovementioned viewpoints but also contributed significantly to activities that promoted mineral sciences in Japan. For example,
THE THIRD EUROPEAN MINERALOGICAL CONFERENCE

6–10 September 2020 in Cracow [Kraków] (Poland)

The 3rd European Mineralogical Conference (emc2020) will be organized by the Mineralogical Society of Poland on behalf of the following European mineralogical societies: Deutsche Mineralogische Gesellschaft, Mineralogical Society of Great Britain and Ireland, Mineralogical Society of Finland, Österreichische Mineralogische Gesellschaft, Russian Mineralogical Society, Sociedad Española de Mineralogía, Société Française de Minéralogie et de Cristallographie, Società Italiana di Mineralogia e Petrologia, Swiss Society of Mineralogy and Petrology, and the participation of the European Mineralogical Union.

Registration opens 1 March 2020.
Website: https://emc2020.ptmin.eu/. Contact: emc2020@ptmin.eu

The 3rd European Mineralogical Conference has the thematic title “Mineralogy in the Modern World”. As such, the conference will focus on the current and future challenges that face the geosciences (including the planetary and environmental sciences) and how to foster an exchange of new views and research results between scientists from Europe and beyond. The main themes are as follows: advanced analytical techniques; applied mineralogy; archaeometry; atomic and thermodynamic modelling; education and mineralogy; environmental mineralogy and low-T geochemistry; experimental mineralogy and petrology; geobiocochemistry, geomicrobiology and biomineralogy; geochronology; 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 are Tomasz Bajda and Justyna Topolska, both of the AGH University of Science and Technology in Kraków (Poland).

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Original Articles
Crystal chemistry and Raman spectroscopy of momoiite from Japan – Shunsuke ENDO, Mariko NAGASHIMA and Masaki ENAMI
Peak metamorphic temperature of the Nishisonogi unit of the Nagasaki Metamorphic Rocks, western Kyushu, Japan – Yasushi MORI, Miki SHIGENO, Kazuhiro MIYAZAKI and Tadao NISHIYAMA
Crystal structure, large distortion of the Zn tetrahedron, and statistical displacement of water molecules in skorpionite – Tsubasa TOBASE, Akira YOSHIASA, Satoshi JINNOUCHI, Ginga KITAHARA, Hidetomo HONGO, Makoto TOKUDA, Maki OKUBE and Kazumasa SUGIYAMA
Crystal structure change in grossular–Si-free katoite solid solution: Oxygen position splitting in katoite – Atsushi KYONO and Shubhi ARORA
Common occurrence of calcic plagioclase in granitoids from Mt. Kaizuki area, central Japan – Hong MEI, Masaki ENAMI, Motohiro TSUBOI and Yoshihiro ASAHARA

Letter
Raman spectra of tridymite modifications: MC, MX-1, and PO-10 – Masami KANZAKI

Japan Association of Mineralogical Sciences  Cont’d from page 348

he helped develop the modern Japan Association of Mineralogical Sciences when he was the chairman of the previous Mineralogical Society of Japan from June 1996 to October 1998. To honor Dr. Aoki for his achievements, the Japan Association of Mineralogical Sciences awarded him the title of Honorary Member in 2015.
2020 ANNUAL METSOC MEETING INVITATION

You are cordially invited to attend the 83rd Annual Meeting of the Meteoritical Society (MetSoc), which will take place 9–14 August 2020 at the Scottish Event Campus in Glasgow (Scotland). The meeting will be hosted by the University of Glasgow planetary science research group.

Some people may require a visa to visit the United Kingdom. To find out whether you need a visa, and how to apply, see the UK visas and immigration website: https://www.gov.uk/check-uk-visa.

Oral and poster sessions, plenary sessions, and the Barringer Invitational Lecture, will take place within the Loch Suite of the Scottish Event Campus: https://www.sec.co.uk/organise-an-event/event-spaces/loch-suite.

Conference registration and welcome reception begins at 5 PM on Sunday, 9 August 2020, at the Hunterian Museum (https://www.gla.ac.uk/hunterian), which is housed within the historic main building of the University of Glasgow.

On Monday night (10 August 2020), the City of Glasgow will offer you all a warm welcome. The city is providing a free welcome drinks reception for all MetSoc delegates at which will be a representative of the city’s Lord Provost (Mayor) who will personally attend to welcome us. This will be hosted in the Glasgow City Chambers, Glasgow’s finest example of 19th century architecture, located in the heart of George Square in the city centre.

On Wednesday (12 August 2020) excursions will be offered both within the city and that explore the neighbouring countryside, including whisky tasting at one of Scotland’s most scenic distilleries, or a boat trip along Loch Lomond.

The Conference Banquet, with ceilidh (pronounced “kaylee”, Scottish music and dance), will be held on Wednesday night at the magnificent Kelvingrove Art Gallery and Museum, the UK’s most popular museum outside of London. The Kelvingrove is home to internationally important natural history and archaeological collections, as well as artwork by Salvador Dalí, Van Gogh, Whistler, Monet, and Botticelli (https://www.glasgowlife.org.uk/museums/venues/kelvingrove-art-gallery-and-museum).

Several multi-day excursions will be offered, including trips to the Isle of Arran to experience world-class geology, hiking, beer and whisky; trips to Edinburgh and St Andrews, for geology, castles, cathedrals, golf (and probably whisky); and to NW Scotland to see the dramatic Stac Fada and Skye impact members and to have a boat trip to see Loch Coruisk and the Small Isles … and possibly taste some more whisky!

Rooms will be reserved in multiple hotels, having a range of prices. As the Scottish Event Campus is located in the centre of Glasgow there are six hotels within easy walking distance, and many more a stroll away. For hotels a little further away, public transport in Glasgow is generally frequent and reliable, and the Scottish Event Campus has its own train station, bus stops and taxi ranks.

Glasgow is undoubtedly one of Europe’s most dynamic cultural capitals, steeped in culture, rich in history, and alive with excitement. Glasgow was named one of the world’s top ten “must see” cities in 2014 by Fodor’s and the Rough Guide, and is Scotland’s cultural hub, possessing over 20 museums and galleries, most offering free entry. Glasgow is also the envy of many European cities for its amazing and eclectic restaurant and café scene: there are over 3,000 restaurants to choose from across the city, more than 700 bars and cosy pubs, and over 130 music events in the city each week. It is also an easy destination to reach and travel around, with three international airports within an hour’s drive, plus good rail, subway and bus links.

We are looking forward to welcoming you to Glasgow!

Lydia Hallis (email: metsoc2020@glasgow.ac.uk)

INTERNATIONAL MINERALS COLLECTORS ASSOCIATION: BRIAN MASON AWARD

In 1997, Joel Schiff, the first editor of the popular Meteorite magazine, created a travel award in honor of Brian Mason, who was born in New Zealand and spent the majority of his career as a curator at the Smithsonian Institution (USA). The award is given to a student attending the annual meeting of the society who submits an abstract that presents exciting results that are clearly explained and that are of particular interest to readers of Meteorite magazine. The recipient is required to write a popular account of their work for the magazine. Since 2008, the award has been generously funded by the International Meteorite Collectors Association.

This year, the Program Committee for the Sapporo meeting selected Nicola Mari and Jack Piercy to win the Brian Mason Award. Nicola Mari is a graduate student at the University of Glasgow (United Kingdom). His abstract was entitled “Chlorine Abundance in the Shergottite Parental Melt Amphibole and Apatite in Tissint and Zagami” and authors were N. Mari, L.J. Hallis, and M.R. Lee. Jack Piercy is a graduate student at the University of Leicester (United Kingdom). His abstract was entitled “Olivine Alteration in the Shergottite Parental Melt Amphibole and Apatite in Tissint and Zagami” and authors were J.D. Piercy, J.C. Bridges, L.J. Hicks, J.L. MacArthur, R.C. Greenwood, and I.A. Franchi.

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 2020 (January 31 for the Service Award and for the Pellas–Ryder Award). For more information and details on how to submit a nomination for any of these awards, please see the latest Meteoritical Society Newsletter at the society’s website, or e-mail the secretary.

The society gives a number of awards each year. The Leonard Medal honors outstanding contributions to the science of meteoritics and closely allied fields. The Barringer Medal and Award recognizes outstanding work in the field of impact cratering and/or work that has led to a better understanding of impact phenomena. The Nier Prize recognizes outstanding research in meteoritics and closely allied fields by young scientists. The Service Award honors members who have advanced the goals of the Meteoritical Society to promote research and education in meteoritics and planetary science in ways other than by conducting scientific research. The Paul Pellas–Graham Ryder Award is given for the best student paper in planetary science and is awarded jointly by the Meteoritical Society and the Planetary Geology Division of the Geological Society of America. The newest society award, the Elmar Jessberger Award, will be given for the first time in 2020 to a mid-career female scientist in the field of isotope cosmochemistry.
SOCIETY NEWS

2019 ANNUAL MEETING STUDENT TRAVEL AWARDS

On behalf of the Meteoritical Society, we would like to thank the organizations whose generous sponsorships provided student travel grants, postdoc travel grants and travel grants for scientists from countries with limited financial resources. These sponsoring organizations, and the recipients of the travel awards, are listed below.

This year, 45 travel grants were given to students and researchers to attend the annual meeting of the society in Sapporo (Hokkaido, Japan). Student travel grants and travel grants for scientists from countries with limited financial resources are generously sponsored by the Barringer Crater Company, the O. Richard Norton Fund, NASA (Emerging Worlds), the National Institute of Polar Research (NIPR), JAXA, Elsevier, the Meteoritical Society (Travel for International Members Fund and the Endowment Fund), the International Mineral Collectors Association (Brian Mason Award), the Maine Mineral and Gem Museum, the Planetary Studies Foundation, and the Darryl Pitt/Macovich Collection.

Barringer Crater Company
Chaves, Laura, Purdue University (Colombia/United States)
Choi, Jisu, Korea Polar Research Institute (South Korea)
Florin, Guillaume, CRPG-CNRS (Australia/France)
Griffin, Samantha, University of Glasgow (New Zealand/United Kingdom)
McCain, Kaitlyn, UCLA (United States)
Patzek, Markus, University of Münster (Germany)
Plan, Anders, Lund University (Sweden)
Wu, Yunhua, Purple Mountain Observatory (China)
Zhang, Bidong, University of Western Ontario (Canada/Canada)

Elsevier
Ebert, Samuel, Westfälische Wilhelms-Universität Münster (United States/Germany)
Isa, Junko, Université Grenoble Alpes (Japan/France)
Takeouchi, Atsushi, National Institute for Polar Research (Japan)

International Mineral Collectors Association Brian Mason Award
Mari, Nicola, University of Glasgow (Italy/United Kingdom)
Piercy, Jack, University of Leicester (United Kingdom)

Maine Mineral and Gem Museum
Cicero, Fabio, University of Calgary (Italy/Canada)

O. Richard Norton Award
Baeza, Leonardo, Australian National University (Chile/Australia)
Dunham, Emilie, Arizona State University (United States)
Hayashi, Hideyuki, University of Tokyo (Japan)
Ishimaru, Kana, University of Tokyo (Japan)
Krietsch, Daniela, ETH Zürich (Germany/Switzerland)
Wang, Nian, Institute of Geology and Geophysics, Chinese Academy of Sciences (China)
Zhu, Ke, Institut de Physique du Globe de Paris (China/France)

NASA Emerging Worlds
Alpert, Samuel, American Museum of Natural History (United States)
Cato, Michael, University of New Mexico (United States)
DellaGiustina, Daniella, University of Arizona (United States)
Greer, Jennika, University of Chicago (United States)
Ostwald, Amanda, University of Nevada (United States)

Planetary Studies Foundation
Crossley, Samuel, University of Maryland (United States)
Toranzo, Zachary, Arizona State University (United States)

Darryl Pitt/Macovich Collection
Kramer Ruggiu, Lisa, CEREGE (France)

National Institute of Polar Research (NIPR)
Ono, Haruka, University of Tokyo (Japan)
Takaharu, Saito, Nagoya University (Japan)
Will, Patrizia, ETH Zürich (Switzerland)

Japan Aerospace Exploration Agency (JAXA)
Kamibayashi, Michiru, University of Tokyo (Japan)
Lacznik, Dara, Purdue University (United States)
Martinez, Marina, University of New Mexico (Spain/United States)
Takahashi, Miki, Tohoku University (Japan)
Villalon, Krysten, University of Chicago (United States)
Vissier, Robbin, Freie Universität Berlin (Germany)
Wada, Sohei, Hokkaido University (Japan)

The Meteoritical Society Endowment Fund
Daly, Luke, University of Glasgow (United Kingdom)
Yamamoto, Daiki, Japan Exploration Agency (Japan)

The Meteoritical Society TIM Fund
Chennaoui Aoudjehane, Hasnaa, Hassan II University (Morocco)
Kassab, Fazia, University of Sciences and Technology (USTHB) (Algeria)

IN MEMORIAM: LAUREL WILKENING (1944–2019)

Prof. Laurel Wilkening, a meteoriticist, university administrator, and advocate for planetary science and for women’s issues, passed away 4 June 2019 at the age of 74. She was born in Richland (Washington, USA) on 23 November 1944 and grew up in Socorro (New Mexico, USA). Laurel got her bachelor’s degree in chemistry from Reed College (Oregon, USA) followed by her PhD from the University of California at San Diego (USA) in 1970, working with Hans Seuss.

Wilkening began her scientific career studying the first samples returned from the Moon, and compared the exposure record of lunar samples, particularly as revealed by damage tracks from cosmic rays, with that of meteoritic regolith breccias. Later, her interests turned to comets. She edited the 1982 University of Arizona Press volume Comets, and was deeply involved with planning of a U.S. mission to Halley’s Comet that never materialized. After her graduation, she worked and studied at several institutions, including the Tata Institute of Fundamental Research in Mumbai (India), the Max Planck Institute for Cosmochemistry in Mainz (Germany), and the Muséum National d’Histoire Naturelle in Paris (France).

Laurel became a faculty member at the University of Arizona (USA) in 1973 in the newly formed Department of Planetary Sciences. In 1981, she became head of the department and director of the department’s associated Lunar and Planetary Laboratory. Shortly thereafter, she became the Acting Dean of Sciences at the university when that position was created, and then Vice President for Research. From the beginning of her career at Arizona, she was instrumental in advocating for women’s issues, including pay equity, and was a key figure in the establishment of what is now the Department of Gender and Women’s Studies.

In 1988, she became Provost of the University of Washington (USA), the first female to hold that position. In 1993, she became Chancellor of the University of California Irvine (USA), a post from which she retired in 1998.

Throughout her career, Wilkening was a nationally prominent member of the planetary science community. She served as Vice Chair of the Advisory Committee on the Future of the U.S. Space Programs, Chair of the Space Policy Advisory Board, and Vice Chair of the National Commission on Space during the presidencies of Ronald Reagan and George H. W. Bush. Later, she became a member of the Board of Directors of the Planetary Society, serving four years as Vice President of the society. Asteroid 75562 is named Wilkening in her honor. She was elected a Fellow of the Meteoritical Society in 1978.

Prof. Timothy D. Swindle
Director, Lunar and Planetary Laboratory, University of Arizona (see society webpage for full citation)
The Clay Minerals Society

THE PRESIDENT’S CORNER

The EuroClay 2019 meeting was held 1–5 July 2019 at the new Congress Center of the Pierre & Marie Curie University (Sorbonne Université) in the center of Paris (France) and was a great success. It was a joint meeting of the European Clay Groups Association (ECGA) together with the 56th annual meeting of the Clay Minerals Society (CMS) and the 6th Mediterranean Clay Meeting (MCM). It was organized by the French Clay Group (GFA) under the auspices of ECGA and Association Internationale pour l’Étude des Argiles (AIEPA). The co-chairs of the Local Organizing Committee —Maguy Jaber (LAMS-UPMC, Paris), Bruno Lanson (ISTerre, Grenoble), and Erwan Paineau (LPS, Paris-Sud, Orsay)—deserve our heartfelt appreciation.

The International Scientific Committee, representing 24 different countries from all continents of the globe, did a great job in assembling an exciting program that included 24 special sessions. So, with more than 620 registered participants (over 150 of them students), we were able to cover all possible aspects of clay science as arranged around four main themes: (i) crystallography, mineralogy and modelling; (ii) environment and geological processes; (iii) mineral resources, energy, storage; (iv) functionalized clays and archaeology.

As part of the program, recipients of the 2019 CMS awards delivered their plenary lectures:

- **Marilyn and Sturges W. Bailey Distinguished Member Award** lecture “Memoir of an Illitist” was given by Dennis D. Eberl;
- **Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist Award** lecture “How microbes break the cryptic manganese cycle to form manganese oxide” – by Colleen M. Hansel;
- **George W. Brindley Award Lecture** “Crystal structure of defective lamellar minerals and their X-ray identification: Implications for reactivity” – by Bruno Lanson;
- **Pioneer in Clay Science Award Lecture** “Crystalline and osmotic swelling of clay minerals. Recent advances” – by Laurent J. Michot.
- **George Brown Award** recipient of the Mineralogical Society Clay Minerals Group, Toshihiro Kogure, delivered the plenary lecture “Visualization of clays at the atomic scale”.

The Clay Minerals Society is now in full preparation for its 57th annual meeting which will be held 15–19 June 2020 at the Pacific Northwest National Laboratory (Washington, USA). The call for symposia and topical sessions is already open. Please submit your proposals by the 15 October 2019 deadline to the following e-mail address: CMS2020@pnnl.gov.

One last thought to conclude this column. As a new CMS President, I’ve looked more attentively into the long history of the CMS and realized that, among more than 60 of my predecessors, I’m only the fourth one residing outside of the US. Even more interestingly, all of those four were elected during the last decade and all of those four are from Europe. This definitely reflects the obvious trend of the society to becoming more and more international, especially in recent years, with over 50% current non-US members. I’m absolutely sure this trend will continue. However, I also notice that of nearly 60 positions on various CMS Standing Committees only 19 are occupied by non-US members. I believe there is a lot of room for improvement and would like to invite more non-US members to volunteer and to participate more actively in various aspects of CMS activities. We have the following CMS Standing Committees, and vacancies are available in all of them:

- Committee on Finance and Budget
- Committee on Council Nominations
- Committee on Committee Nominations
- Committee on Policy and Administration
- Committee on Program Development
- Committee on Awards
- Committee on Contributions and Membership
- Committee on Student Grants
- Committee on Nomenclature
- Committee on Source Clay Minerals
- Committee on Electronic Communication

The CMS, as with any society, is only strong because of the participation of its members. Therefore, I would really encourage all members to volunteer and serve on the CMS committee of your choice.

Andrey G. Kalinichev (kalinich@subatech.in2p3.fr) President, The Clay Minerals Society

CMS STUDENT AWARDS

In addition to the CMS awards featured in the president’s message, there were a number of student awards that were conferred at the EuroClay 2019 meeting.

The following received **Student Travel Grants** to help them cover the cost of attending EuroClay 2019: Mary Arenberg, Paolo Benavides, Zachery Burton, Nirrit Cohen, Irina Gurova, Ahmad Khan, Lior Levy, Ying Li, Mouafon Mohamed, Agnel Myriam, Xinyi Shen, Zebadiah Teichert, Magdalena Tuchowska, Kh Ashraf Uz Zaman, Dorianna Vinci, Jennifer Willemsen, Giovanni Zanoni, Chaqun Zhuang, Guanzheng Zhuang, and Yael Zvulunov. The student with the highest scoring application was Yael Zvulunov; he was awarded the Blair Jones/Jan Flinn Travel Award.

Six students received **Student Research Grants**: Zachery Burton, Timothy Campbell, Bidemi Fashina, Ying Li, Chia-Wei Lin, and Mohamed Mouafon. These grants offer up to $3,000 to support students’ clay-related research. Mohamed Mouafon, who had the highest scoring Research Grant application, received the Robert J. Reynolds, Jr. Award. The application deadline for next year’s Student Research Grants will be in February 2020. Students whose research has been supported by a CMS Research Grant will be featured in the upcoming issues of the *Elements* CMS news.
The SFMC’s annual general assembly was held 21 June 2019 at the University Pierre et Marie Curie, Sorbonne University, in Paris (France). The day began with a scientific program focusing on the mineralogy of carbonates, followed by the announcement of the 2019 Haüy–Lacroix Awards for outstanding PhD theses, plus a lecture given by one of the award laureates. Ending this special day was an SFMC activity report and some general announcements.

Scientific Day Lectures: The Mineralogy of Carbonates

Four keynote lecturers were invited to speak on aspects of carbonate mineralogy, ranging from the global carbon cycle to biominerals. The scientific program promoted rich discussion and comprised the following lectures:

- “Carbonates and Pressure” (Tahar Hammouda; Université Clermont Auvergne, Laboratoire Magmas et Volcans)
- “Oxidized Carbon in the Deep Mantle” (Eglantine Boulard; Sorbonne Université, Institut de minéralogie, de physique des matériaux et de cosmochimie)
- “Ab Initio Molecular Dynamics Simulations of Molten Carbonates: From Earth’s Mantle to Fuel Cells” (Rodolphe Vuilleumier; Sorbonne Université, École Normale Supérieure)
- “Effects of Ocean Acidification on the Key Processes Regulating the Life of Coral Reefs” (Aline Tribollet; Institut de Recherche pour le Développement, Laboratoire d’océanographie et du climat: expériments et approches numériques)

2019 Haüy–Lacroix Award

Bertrand Devouard, SFMC President, announced that the 2019 Haüy–Lacroix Award goes to Julie Aufort for her PhD thesis on the fossilisation of biogenic apatites, which was supervised by Etienne Balan (Institut de minéralogie, de physique des matériaux et de cosmochimie, Paris Sorbonne University), and to Lionel Vacher for his PhD thesis “Hydration and Early Stage Isotopic Evolution of Carbonaceous Asteroids: Experimental and Isotopic Approaches” (Centre de Recherches Pétrographiques et Géochimiques, CNRS and at the University of Lorraine, Nancy, France), which was supervised by Yves Marrocchi and François Faure.

After receiving her award from Bertrand Devouard, Julie gave a talk with the same title as her PhD. “Fossilisation of Biogenic Apatites: Crystal-Chemical Approach and Geochemical Applications”.

This work aims to understand how the geochemical record is acquired and preserved by studying the isotopic fractionation properties of apatite, the main inorganic constituent of vertebrates’ bones and teeth, and the crystal-chemical transformations that occur during fossilisation. These transformations were probed at the atomic scale using attenuated total reflection Fourier transform infra-red (ATR-FTIR) and solid-state nuclear magnetic resonance spectroscopies, their interpretations being supported by the modelling of ATR-FTIR spectra and density functional theory calculations of theoretical equilibrium isotopic fractionation. The results were then applied to the study of the transformation of fossil bones from the karst environment of Bolt’s Farm cave system (Cradle of Humankind, South Africa) and from the fluvio-lacustrine environments of the Tugen Hills (Gregory Rift, Kenya). The results highlighted the potentiality of fossil bones to record the local physicochemical conditions that exist in fossilisation environments.

Lionel Vacher could not attend the meeting and will receive his award later.

General Assembly Report

Marc Blanchard, SFMC Secretary, summarized the activity of the society over the last year. The 2018 landmark event was the celebration of the 140th anniversary of the SFMC, which took place 8 June 2018 at MINES ParisTech in Paris and which was attended by about 50 participants. The key lectures of the scientific program have been posted on the society’s web site (https://sfmc-fr.org/?page_id=1978&lang=fr). Other 2018 activities included a five-day field trip in the French Massif Central, which was attended by 25 geologists from various countries, SFMC’s support of scientific meetings via student grants, and the attribution of the 2018 Haüy–Lacroix Award to Simon Couzinié (University of Lorraine, Nancy, France). Marc also recalled the society’s contributions to Elements and the European Journal of Mineralogy, which will become an open access journal from 1 January 2020. The SFMC’s publishing activities were also marked by the sale of the book Minerals with a French Connection (2017, Mineralogical Association of Canada, by F. Fontan and R.F. Martin) and by the scanning of the entire content of the Bulletin de Minéralogie (and its former titles) since 1878, now freely available on the Persee portal https://www.persee.fr/. This platform is maintained with the support of the French Ministry for Higher Education and Research and hosts French-language scientific journals in an open-access spirit. Finally, Marc announced that the society is now on Facebook and Wikipedia. Then, on behalf of Christian Chopin, the SFMC Treasurer, Marc presented the 2018 budget, which was approved.

Before closing the general assembly, Hervé Cardon introduced the local organization for International Mineralogical Association meeting, IMA 2022, which will take place in Lyon (France), with support of the SFMC.
**Notes from Chantilly**

- 2019 election results: the new President of MSA is Carol D. Frost, the Vice President is Mark Ghiroso, and Past President is Mickey Gunter. Kimberly Tait is the new Secretary, and Thomas Duffy remains in office as Treasurer. New Councilors are Przemyslaw Dera and Francis McCubbin, joining continuing Councilors Jay J. Ague, Donna L. Whitney, Mark J. Caddick, and Adam C. Simon. The outgoing Councilors are Sarah Carmichael and Sarah C. Penniston-Dorland.

- MSA 2020 membership renewals will start in September with renewal notices sent electronically, followed by several electronic reminders, before a paper copy is sent to those who do not renew online by November.

- Member subscription rates to the print version of the 2020 *American Mineralogist* will increase. The U.S. member print subscription price will be $150 (currently $135), and the foreign member print subscription price will be $165 (currently $145). Institutional U.S. subscription price (paper and electronic) will increase to $1,200 (from $1,150), and foreign institutional subscriptions will be raised to $1,225 (from $1,150). The institutional electronic-only subscription will increase to $1,125 (from $1,050). Included in the institutional subscription will be all current-year (2020) print issues of *American Mineralogist*, *Reviews in Mineralogy and Geochemistry*, *Elements*, as well as access to the electronic version of these publications on the MSA website starting with volume 1, number 1. GeoScienceWorld subscriber prices for *American Mineralogist* and the *Reviews* are $260 and $200, respectively.

- Members and Fellows who are in the senior, honorary, and life categories are sent renewal notices. They need not pay dues but are sent notices as the best way to prompt an update of membership information, particularly mail and e-mail addresses.

- If you subscribe to other journals through MSA, please renew early, as MSA needs to forward your renewal to those publishers before your subscription expires. These journals are *Gems & Gemology*, *Journal of Petrology*, *Mineral News*, *Physics and Chemistry of Minerals*, *Mineralogy and Petrology*, *Rocks & Minerals*, and the *Journal of Gemmology*.

**CONTRIBUTORS AND BENEFACORS**

Many members support MSA by including a contribution with their annual dues and/or by responding to special appeals. Depending on the wishes of the member, the money is deposited with the principal of the MSA Endowment, MSA Outreach, MSA Mineralogy/Petrology, J.B. Thompson, Edward H. Kraus Crystallographic Research, Blos, or General Operating funds. The income of these funds is used to support MSA’s research grants in crystallography, mineralogy, and petrology; publishing of the *American Mineralogist*; the MSA Undergraduate Prizes; the Mineralogical Society of America Award; the Distinguished Public Service Award; the Dana Medal; the Roebling Medal; the website; the lectureship program; and the Centennial Symposium. If you have not done so previously, please consider contributing at the next opportunity. Here, we want to extend our gratitude to the individuals and organizations that have contributed to MSA between 7 January 2018 and 30 June 2019. These contributors are listed on the MSA website and can be found by selecting “Contributions to MSA” on the MSA home page (http://www.minsocam.org/), under “About MSA.”

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**MSA at 100: Looking Forward**

As I compose my final President’s Letter, I ponder the future of our society and discipline. As I look at the smiling faces of three of my former PhD students above, it gives me great hope. There are many like them without grey hair who will carry on with the service, teaching, and research in mineralogy that the grey-haired ones among us did. What I fret about can also be represented in the photo by the word “asbestos”. It is not the fact that asbestos has presented health problems in modern society, but more how we tend not to be involved in some of these problems, because they can be very controversial.

What I have noticed over my career is a trend, especially among us academics, to look for problems more than to solve them. This hit home when I was working with an industrial hygienist for an industrial minerals company, and he said, “No problems, no funding.” This was further reinforced when we went to visit a small industrial minerals mine, and the president of the company did not want to let us in because we were professors. It was not always this way: in “the good old days” we used to work more closely with such industries. Of course, in the USA, federal funding and university expectations play a role in what is “valued”. Regardless, I think we need to work to help industry solve its problems, not to create more for them.

What I had thought less of over my career is how MSA has been the catalyst for many other professional societies and journals. The outcome of this has been to reduce our number of members. This might be good or bad overall for the geosciences, but it is important for us to be aware of. Something I do believe to be bad is how, along the way, we have given much less attention to what are sometimes referred to as “amateur mineralogists”. They really are the heart of MSA, as they are the ones who collect the minerals we study.

Yes, this letter reads more like what one might see on the opinion page of a newspaper. In fact, I have never written one of those, and have only published the wishes of the member, the money is deposited with the principal of the MSA Endowment, MSA Outreach, MSA Mineralogy/Petrology, J.B. Thompson, Edward H. Kraus Crystallographic Research, Blos, or General Operating funds. The income of these funds is used to support MSA’s research grants in crystallography, mineralogy, and petrology; publishing of the *American Mineralogist*; the MSA Undergraduate Prizes; the Mineralogical Society of America Award; the Distinguished Public Service Award; the Dana Medal; the Roebling Medal; the website; the lectureship program; and the Centennial Symposium. If you have not done so previously, please consider contributing at the next opportunity. Here, we want to extend our gratitude to the individuals and organizations that have contributed to MSA between 7 January 2018 and 30 June 2019. These contributors are listed on the MSA website and can be found by selecting “Contributions to MSA” on the MSA home page (http://www.minsocam.org/), under “About MSA.”

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**Mickey Gunter**

2019 MSA President
MSA STUDENT GRANT AWARDEES

Clementine Hamelin, University of Minnesota (USA), received a 2019 Grant for Student Research in Mineralogy and Petrology for her proposal, “Putting QuiG to the Test: A High-Resolution, Microscale Investigation of the Quartz-in-Garnet Barometer in a Progressive Metamorphic Sequence”. Quartz-in-garnet (QuiG) barometry has been used to investigate the prograde history of metamorphic rocks; however, it has not been thoroughly “put to the test” against a suite of well-documented natural samples that formed over a range of $P$–$T$ conditions in the same tectonic event. Ms. Hamelin proposes to test QuiG barometry against a classical, well-studied, prograde metamorphic Barrovian sequence. She will investigate entrapment pressures recorded throughout successive garnet-bearing Barrovian zones, focusing on the crystallographic and compositional microscale relationships between host garnet and quartz inclusions.

The research will test different formulations of the QuiG barometer in the systematic framework of a Barrovian sequence; focus on the microchemical and microstructural relationship between host garnet and quartz inclusions by characterizing spatial variations in inclusion and host geometry, crystallographic orientation of inclusions relative to host, stress-state of quartz inclusions, and microchemical variations in both host and inclusions; calculate the $P$–$T$ conditions predicted from equilibrium thermodynamics and the $P$–$T$ conditions recorded by a combination of Ti-in-quartz thermobarometry and QuiG barometry for each garnet-bearing zone; and assess the different formulations of the QuiG barometer to determine if they are in accordance with $P$–$T$ conditions known from field settings and from thermodynamic equilibrium.

Marie Takach, Oregon State University (USA), also received a 2019 Grant for Student Research in Mineralogy and Petrology for her proposal: “Documenting Magma Mixing Processes and Timescales in Tephra Fall Deposits: El Misti Volcano, Peru”. El Misti is an historically active Andean arc volcano located within 15 km of Arequipa, the second largest city in Peru. Determining why arc volcanoes, such as Misti, sometimes erupt explosively is crucial for hazard mitigation, especially for volcanoes close to populated areas. Magma recharge and subsequent mixing or mingling are well-documented eruption triggers: the youngest plinian Misti eruption (2000 BP, VEI 5) was shown to have been triggered by an injection of andesitic lava into a rhyolitic magma reservoir. Macroscopic evidence for recharge and magma mingling is recorded in several older eruptions (<35 ky) at Misti. Monitoring can sometimes precede recharge events that force magmas to mingle and erupt catastrophically. To test this assertion, she will use geochemical analyses of glasses and minerals to document end-member compositions; assess for the presence and degree of mixing/mingling based on observations of the glass and mineral geochemistry, mineral zoning, and crystal exchange between magmas; test the timeframes between episodes of magma mixing/mingling and eruption by modeling plagioclase trace element diffusion and measuring amphibole reaction rim thicknesses; and quantify the time elapsed between the explosive eruptions that punctuate Misti’s history via Ar–Ar geochronology.

Kathryn Hobart, University of Minnesota (USA), is the recipient of the 2019 Grant for Research in Crystallography funded by the Edward H. Kraus Crystallographic Research Fund for her proposal “Crystallographic Controls on Abiotic and Microbially Mediated Pyrrhotite Dissolution”. Pyrrhotite is the second most abundant sulfide mineral in the Earth’s crust after pyrite and is frequently associated with intrusive ore deposits. The dissolution of sulfide minerals in environmental systems, particularly pyrite and pyrrhotite, results in the production of acidic and sulfate-rich water, which can have negative impacts on downstream water quality and ecosystem health. Most acid rock drainage is associated with pyrite, and its dissolution is well-studied. Comparatively little, however, is known about the abiotic or microbially mediated dissolution of pyrrhotite.

The Duluth Complex, located in Northern Minnesota, is the site of the largest unexplored copper, nickel, and platinum-group ore body in the world, with the metals held as sulfide minerals associated with pyrrhotite. The major environmental concerns are high concentrations of sulfate in surface waters and its toxicity to the wild rice that is central to the religious and cultural practices of the Anishinaabe people native to the Great Lakes region. The limited experimental work on pyrrhotite dissolution make the environmental impact of proposed mining in the Duluth Complex difficult to predict. Any predictions will require a knowledge of three things: (1) an understanding of pyrrhotite dissolution at near-neutral pH; (2) the microbial influences on that dissolution; (3) whether certain crystallographic directions in pyrrhotite dissolve at different rates or are preferred sites by microorganisms. Ms. Hobart’s research is designed to understand the extent of crystallographic controls on both abiotic and microbially mediated pyrrhotite dissolution.

REVIEWS IN MINERALOGY AND GEOCHEMISTRY

VOLUME 85: Reactive Transport in Natural and Engineered Systems

Jennifer Druhan and Christophe Tournassat, editors. i-xv+ 528 pages. ISBN 978-0-9466850-01-0

The chapters in the 2019 volume fall into three categories. The first set emphasize the state of reactive transport simulation capability to address challenging new frontiers, such as multiscale hybrid approaches, fractured and nanoporous media, multiphase systems, and evolving physical structures. The second set focuses on a variety of novel or expanded reactive transport applications in the Earth sciences, such as stable isotope partitioning, microbial catalysis, vadose zone systems, soils, and watersheds. Finally, the third set emphasizes industrial applications of reactive transport modeling in the fields of waste repositories, carbon sequestration, and subsurface resource recovery. In total, this volume serves as a significant update to its predecessor, describing the diversity of applications that reactive principles are now used to quantify and highlighting the key areas of reactive transport software development necessary to continue advancing these fields.

Description and ordering online at www.minsocam.org or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110 USA phone: +1 (703)652-9950 fax: +1 (703) 652-9951 e-mail: business@minsocam.org. Cost is $45 ($33.75 members MSA, GS, CMS).
RENEW YOUR MEMBERSHIP FOR 2020

Geochemical Society (GS) members can renew their membership quickly and securely on the GS website: www.geochemsoc.org. Renew by 31 December 2019 to save $5 off the regular dues and enjoy uninterrupted access to *Elements*, *Geochemical News*, and registration discounts to Goldschmidt2020 in Honolulu (Hawaii, USA) and to other conferences. Members also have access to the online member directory (available by signing into your profile on the website). You can also choose a two-year membership option to save time and money. If you prefer to renew by mail, please visit the website to download a form to send with your payment.

A reduced professional rate of $15 is now available to scientists from countries classified by the World Bank as having low-income or lower-middle-income economies. If dues are paid before 31 December 2019, then the rate is only $10. Visit geochemsoc.org/membership/join to learn more about which countries qualify. Students from qualifying countries may apply for free memberships through the Introductory Student Membership Program.

<table>
<thead>
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<th>Early (by 31 Dec.)</th>
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<td>$15</td>
<td>$20 / $25</td>
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FOLLOW THE GS ON INSTAGRAM

The Geochemical Society is now on Instagram. Please follow us at: thegeochemical_society. We will be sharing images and stories from our members around the world, as well as news about society programs. Send us a message if you have photos to share of your work or travels.

EARLIER DEADLINES FOR GOLDSCHMIDT2020

Mark your calendars for important upcoming deadlines for the 2020 Goldschmidt Conference in Honolulu (Hawaii). Because next year's conference takes place 21–26 June, these dates are earlier than the typical Goldschmidt deadlines.

<table>
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<tr>
<th>Date</th>
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<tr>
<td>18 October 2019</td>
<td>Call for workshop and sessions closes</td>
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<tr>
<td>15 December 2019</td>
<td>Abstract submission opens</td>
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<tr>
<td>31 January 2020</td>
<td>Grant application opens</td>
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<tr>
<td>14 February 2020</td>
<td>Abstract submission deadline</td>
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<tr>
<td>21–26 June 2020</td>
<td>Goldschmidt2020, Honolulu</td>
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HIGHLIGHTS FROM GOLDSCHMIDT 2019

GS President Roberta Rudnick presents the V.M. Goldschmidt Award to Don DePaolo on 19 August.

The society's new program manager, Mattie Burris, answers questions at the GS booth during the conference.

OFFICER ELECTIONS

The annual election of the society’s board of directors will take place in November 2019 and all GS members are encouraged to participate. You will receive an e-mail in early November with instructions for voting. Information about the candidates is available on the GS website—please take a few minutes to review them and to vote.
Q&A WITH REBECCA NEELY, GOLDSCHMIDT2019 NON-ACADEMIC CAREERS PANELLIST

A series of discussion forums were held at Goldschmidt2019 (18–23 August in Barcelona, Spain) to give students and post-docs the opportunity to find out more about pursuing careers outside of academia. We interviewed some of the panellists who took part, and, in this issue of *Elements*, we hear from Rebecca Neely, whose career path took her away from the laboratory and into the world of scientific publishing.

Rebecca Neely, Associate Editor at *Nature Geoscience*

**What does your job involve?** My primary responsibility is assessing manuscripts and managing the peer review and publication of papers, broadly in the field of geochemistry.

**How did you get your job?** It’s probably an oversimplification to say that I saw the position advertised and thought, “Why not?!” Looking back, I spent a lot of time during my PhD unwittingly developing transferable skills: I read (and edited) almost every paper and PhD thesis written by my colleagues and was responsible for a conference abstract volume. These experiences were certainly useful when it came to the job application, but they also made me realise that I consistently prioritised the work of others over my own. Acknowledging my skills, and where I chose to put my efforts, was an important step in deciding to leave research and pursue other opportunities.

**What advice do you have for PhD students who are thinking of leaving academia?** Gosh, there are so many things I could say. But, for me, the most important thing to remember is that you can use your scientific training in an infinite number of ways. From the inside it can appear as though no one ever leaves academia. But we know that’s not true. So, don’t be afraid to ask what other people have gone on to do. Finally, don’t underestimate your skills. Too often our academic resumes are limited to technical expertise and a few conference abstracts or papers, but research is so much more. It’s communication, graphic design, budget planning, risk assessments, quantitative reasoning, international collaboration, and decision making. You have so much to offer. So, take a breath, reach out to people, and remember that you are highly skilled in a number of different ways and people would be lucky to work with you!

**EAG MEMBERSHIP: JOIN OR RENEW NOW!**

With the end of the year approaching, now is a good time to consider joining the European Association of Geochemistry or renewing your membership. New to the EAG? Join from 15 October 2019 onwards to receive a full year’s membership for 2020.

**Membership Benefits**

**Conferences** Member rates to attend the Goldschmidt conference • Member rates to attend conferences and events organised by the Mineralogical Society of Great Britain and Ireland (MinSoc), the International Association of Geochemistry, the International Society for Environmental Biogeochemistry, the Society for Geology Applied to Mineral Deposits, and the European Association of Geoscientists and Engineers.

**Publications** Print issues of *Geochemical Perspectives* • Print and online issues of *Elements* magazine • Reduced subscription rates to *Chemical Geology* and *GeoFluids* • Member rates to purchase print publications from the MinSoc, the Società Geologica Italiana, the Società Italiana di Mineralogia e Petrologia, and the Association Française pour l’Étude du Quaternaire • Member rates to publish open access articles in *Mineralogical Magazine* and *Clay Minerals*.

**Early Career Scientist Support** Sponsorship of students to attend workshops and conferences in Europe • Ambassador Program, providing support for early career scientists based in Europe to attend conferences outside Europe • Sponsorship of member-led workshops and conferences.

**Information and Networking** Job postings and conference calendar • Monthly newsletters • EAG Blog, Twitter, Facebook and YouTube.

**Membership Rates**

<table>
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<tr>
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<td>Professional 1 year: Low and lower-middle income economies</td>
<td>20 Euros</td>
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Institutional membership packages are also available. Visit www.eag.eu.com/membership for more information or contact our business office.

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**Elements**

October 2019
THE 29th V.M. GOLDSCHMIDT CONFERENCE®

Goldschmidt2019 is now behind us. After two years of intense preparation, there is a sense of relief that it all went well and that everyone had a fantastic conference. Yet also a tinge of sadness that it’s all over. However, Goldschmidt2020 will be here soon enough!

Goldschmidt2019 was held 18–23 August 2019 in Barcelona (Spain) in the beautiful Centro de Convenciones Internacional de Barcelona, located near the beach, which many delegates enjoyed (and to which some groups even managed to get pizzas delivered!). Nearly 4,100 delegates participated in the six-day meeting, making Goldschmidt2019 the third largest Goldschmidt conference, after Paris in 2017 and Florence in 2013. Student representation reached 32%, significantly up on the 25% in 2013.

The organization of Goldschmidt2019 was led by the European Association of Geochemistry (EAG) and overseen by the co-chairs of the Organizing and Science Committees; Derek Vance (ETH Zürich) and Helen Williams (University of Cambridge). However, as always, Goldschmidt is a community-run conference involving hundreds of scientists, ranging from committee members to theme chairs, session chairs, workshop panellists, mentors, student helpers and many more. Everyone contributes to the success of the conference, so the EAG warmly thanks everyone for their participation, time and energy.

Delegates travelled from 74 different countries, and the 15 largest delegations came from the following countries:

<table>
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<tr>
<th>Country</th>
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GOLDSCHMIDT2019: THE DATA

Scientists love data, so here are the main numbers for this year’s conference:

- 4,075 delegates, including 32% students (and 79 accompanying persons)
- 14 themes and 121 sessions
- 4,032 abstracts
- 2,395 talks, including 479 flash talks
- 2,208 posters
- 5 plenary speakers (all recorded and available on the conference YouTube channel)
- 17 pre-conference workshops, attended by 444 participants
- 14 lunch-time events for early career scientists, attended by 394 participants
- 4 field trips
- 67 student helpers
- 240 mentees and 154 mentors
- 40 grant recipients
- 5 bloggers who contributed 15 blog articles
- 47 exhibitors and 18 sponsors
- 340 delegates at the Club Night, 560 at the banquet, and over 100 delegates on the walking tours
- 122 childcare bookings
NEW THIS YEAR: THE FLASH TALKS

Goldschmidt2019 introduced a new talk format: the flash talk. This is where delegates could present a snapshot of their research in four minutes, in addition to presenting a poster. There were 479 flash talks presented in the two flash talk theatres, which were located in the exhibition area. Attendance was very high from the first day and the feedback very positive. As a result, the experience will be repeated in the future.

EARLY CAREER PROGRAM: SPECIAL FOCUS ON NON-ACADEMIC CAREERS

This year, the Early Career Program, developed by Sami Mikhail and Arola Moreras Marti, included a special focus on careers outside academia, inviting geochemists who now work, or have worked, in consultancy, scientific publishing or research and development to share their experience about their career paths.

In addition to these, workshops were held on oral presentation skills, science communication, best practices in academic publishing, interactive teaching methods, confidence and public speaking, and the difficult topic of love and careers in academia (or how to manage career paths when a couple consists of two academics). Some of those workshops have been video recorded and you can watch them on the conference YouTube channel.

Each day, a small group of students also had the opportunity to share lunch with the plenary speaker and ask all their questions in an informal setting. The plenary speakers themselves enjoyed the experience. Finally, the pop-up talks were presented mid-week.

All in all, this made for a very comprehensive program for our early career delegates, and we are delighted to notice an increasing representation of the new generation.

A MORE INCLUSIVE GOLDSCHMIDT: AMIGO

The AMIGo initiative was started in 2018, following the efforts made by the Geochemical Society to implement a code of appropriate conduct for the conference. All participants had to abide by this code, and the EAG Council and GS Board members, as well as society staff, received special training and served as points of contact for any delegate who had questions or who experienced harassment during the conference. Those points of contact were easily identified through their yellow badge.

FAMILIES AT THE CONFERENCE

This year, special efforts were made towards offering subsidized childcare at €10 per half day (or €100 for the entire week). We are very happy to report that the childcare facility was fully booked throughout the week. The children themselves interacted very well together and had a lot of fun, and, most importantly, the parents were extremely satisfied with the level of care, which brought them peace of mind while they in turn attended the conference. We are very grateful to Noah’s Ark Childcare for their fantastic work.

PHOTOS, VIDEOS, BLOGS AND MORE

Links to conference websites, videos, photos, program volumes or abstracts can be accessed from the Goldschmidt Archive at goldschmidt.info/conferencesView.

All the blog posts written during Goldschmidt2019 are available on the EAG Blog (blog.eag.eu.com). These include interviews with Bethany Ehlmann (plenary speaker), Katharina Marquardt (EMU medallist), and the non-academic careers forum panellists of Anne Trinquier, Katja Amstätter, Rebecca Neely and Lewis Collins.

The European Association of Geochemistry and the Geochemical Society now look forward to welcoming you 21–26 June to Honolulu (Hawaii, USA) in 2020 and then 4–9 July to Lyon (France) in 2021.
EXPLORING THE MOON IN THE 21ST CENTURY

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INTRODUCTION

In 2019, we are celebrating the 50th anniversary of NASA’s momentous Apollo expeditions to the Moon. The samples brought back by the astronauts, and the fieldwork those astronauts performed on the lunar surface, cemented the Moon’s status as the cornerstone of the solar system. It is not an exaggeration to say that the Apollo expeditions transformed our understanding of our solar system, and, in fact, most of the discoveries made in planetary science since the 1960s can trace directly, or indirectly, from the scientific results of those Apollo expeditions.

Although some erroneously proclaim that the Moon is “Been there, done that”, nothing could be further from the truth. After a long hiatus, beginning in the first years of the 21st century, there has been a resurgence of interest in the Moon, including the Kaguya mission by the Japanese Aerospace Exploration Agency (JAXA); the Chandrayaan-1 mission by the Indian Space Research Organizations (ISRO); four Chinese missions:- 2 orbiters (Chang’E-1 and -2) and two landed missions with rovers (Chang’E-3 and -4); as well as four NASA missions: the Lunar Reconnaissance Orbiter (LRO), the Lunar Crater Remote Observation Sensing Satellite (LCROSS), the Lunar Atmosphere and Dust Environment Explorer (LADEE), and the Gravity Recovery and Interior Laboratory (GRAIL). Taken collectively, the results from these missions have shown that the Moon is a far more interesting, and far more valuable, destination for future exploration than was perceived even during the Apollo era. Results from recent lunar missions have only increased the interest in a vigorous program of lunar exploration and utilization.

The 50th anniversary of Apollo 11 presents the perfect opportunity to take a look to the future. The Moon now presents an entirely new paradigm for planetary exploration through incremental, affordable investments in cislunar (i.e., between Earth and Moon) infrastructure. But how do we do that?

ROADMAP TO THE FUTURE

The Lunar Exploration Analysis Group (LEAG), the community group started in 2004 that organizes and leads the large and diverse lunar exploration community, has developed the Lunar Exploration Roadmap (LER) (LEAG 2016). Featuring inputs from engineers, planetary scientists, commercial entities, and policymakers, the roadmap presents a cohesive strategy to make concrete advances along the following three themes:

1. Science  Use the Moon for scientific research by addressing fundamental questions about the Moon, our solar system, and the Universe around us. Like the four terrestrial planets (Mercury, Earth, Venus, Mars), the Moon has a crust, a mantle, and a core and is, therefore, one of the most accessible destinations to cohesively address questions about early evolution of planetary interiors. The Moon retains a record of the formation, evolution, and impact history of Earth and the inner solar system, as well as an otherwise inaccessible record of the Sun’s evolution and history. Finally, this is another area where the Apollo expeditions represent a strength: there are five decades worth of planetary science hypotheses that lunar geological fieldwork will address. The lunar surface could also provide a unique and stable long-term platform for astronomy. In particular, manned radio observatories or optical interferometers on the far side of the Moon could produce dramatic advances in astrophysics. The LER prioritizes science concepts and goals from the 2007 National Research Council Scientific Context for the Exploration of the Moon report (NRC 2007), which were subsequently affirmed and amplified by the LEAG’s “Advancing Science of the Moon” report (LEAG 2017).

2. Sustainability  Use the Moon to learn how to live and work productively off-planet, for increasing periods, to enable extended off-planet human settlement. The Moon has abundant material and energy resources that can be used to decrease the costs and dramatically increase the capabilities of future solar system exploration. Lunar resources, in particular, offer an enduring opportunity for commercial investment and bringing cislunar space fully into Earth’s economic sphere of influence while building international partnerships. Commerce is a key aspect of ensuring the sustainability of future space activity. Public-private partnerships, growing from initial government-funded lunar resource extractions and utilizations, will provide the capabilities required for any future sustained human space operations.

3. Feed Forward  Use the Moon to prepare for future missions to other destinations. The Moon is the only viable deep-space test-bed for testing technologies, systems, and operations to enable cost-effective human operations beyond low-Earth orbit. The Moon’s combination of radiation, hard vacuum, and low-gravity provides a unique laboratory to study the physiological, biological, and biomedical aspects of long-duration operation on planetary surfaces. Irrespective of the innumerable ways in which lunar exploration is required for the success of future voyages to Mars and beyond, establishing a lunar outpost will establish the comprehensive workforce and industrial base required to successfully make voyages to Mars, dwarf planet Ceres, and beyond.

A VISION FOR LUNAR EXPLORATION IN 2050

Successfully implementing the LER will result in a variety of benefits for the United States of America, and the world. While predicting events three decades hence is fraught with uncertainty, the LER offers a path for a dramatically altered landscape for planetary science and exploration by the year 2050. The Moon’s attainability offers intriguing possibilities where lunar surface operations are commonplace, with at least several hundred people living and working on the Moon full-time. Examples of the kinds of activities we foresee include:

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Transformational Planetary Science  Geology is a field science, and can best be done by humans, mapping and solving complex field problems to answer fundamental questions. By the 2050s, we anticipate that in-person fieldwork would be undertaken by academic institutions (in a similar way that NASA and the NSF support activities in Antarctica) yielding profound benefits for our understanding of the solar system. A lunar outpost, for example, could enable lengthy expeditions to geology field sites across the lunar surface using both humans and human-tended robots, depending on the science question to be addressed.

Enduring Commercial Growth  Fueled by access to lunar resources, large-scale operations on the surface of the Moon and in cislunar space are commonplace and have expanded Earth’s economic reach and dramatically increased the human presence in cislunar space. From refueling assets in geosynchronous space to tourism to space-based solar-power, commercial activities in cislunar space are routine and profitable.

A New Paradigm  Cislunar infrastructure, powered by lunar resources, promises a dramatic increase in NASA’s capability, specifically in planetary science. Missions could be assembled at Lagrange point 2 and supplied using lunar resources, so dramatically lessening current mass constraints prior to routine departures to Mars and other destinations. As another example, return samples requiring complete isolation from Earth’s biosphere from other destinations (such as Mars, or outer planet moons) could be received and examined at completely isolated facilities on the lunar surface.

FOLLOWING THE LUNAR EXPLORATION ROADMAP

There are near-term steps that must be undertaken to ensure that the breathtaking potential of lunar exploration is realized. The Lunar Exploration Analysis Group has developed a roadmap implementation strategy for the 2020s (LEAG 2011) designed from the outset to advance science and have viable on-ramps for commercial activity with objectives clearly traceable to the strategic knowledge gaps (Shearer et al. 2016).

Phase 1 – Prospect for Resources

Build upon the results of recent lunar missions to define whether the resources are actually viable reserves. Such prospecting needs to be a campaign (i.e., visiting several resource-rich locations) and should define the composition, form, and extent of the resources; characterize the environment in which the resources are found; define the accessibility of the resource; quantify the geotechnical properties of the regolith in which the resources reside; establish the capability of autonomously traversing several tens of kilometers to sample and to determine the lateral and vertical resource distribution on meter scales; identify resource-rich areas for targeting future missions; and establish capabilities such as automated cryogenic sample return and curation to facilitate the assay of potential resources.

Phase 2 – Demonstrate the use of Local Resources

Based on the results of Phase 1, the next step would be to carry out an end-to-end demonstration of resource extraction and utilization. This would address important science questions and validate key technologies, including feedstock acquisition and handling, resource storage, resource production system longevity, and dust mitigation strategies.

Phase 3 – Lunar Resource Production

Based upon the results of Phase 2, lunar resources could be utilized to enable increasingly complex operations on the lunar surface, including life-support for human outposts and propellant for reusable landers, all as part of a sustainable human-tended facility on the surface (Spudis and Lavoie 2011).

THE NEXT STEPS ON THE MOON

The Moon represents the fundamental underpinnings for understanding solar system processes and history. The Moon is also the critical enabling asset for any human exploration activity that the world may undertake in space, now and in the future. By the 2050s, creating the capabilities inherent in executing the Lunar Exploration Roadmap will enable us to go anywhere, and do things heretofore only imagined, throughout the solar system.

Building cislunar infrastructure does not require technologies wildly outside our experience base. Rather, it is facilitated with evolved versions of currently existing technologies, such as microwave power transmission, laser communications, solar power, nuclear fission power, regenerative life support, propellant transfer and storage, and telerobotics. In terms of new investments, the demonstration and flight qualification of presently well-conceptualized (but unflown) technologies for cislunar resource extraction and utilization would provide a capability required for any future sustained human space operations. At the time of writing, through Project Artemis, NASA is taking some of the first steps towards a sustainable human presence at the South Pole of the Moon (Fig. 1). With its easy access to benign illumination conditions (Mazarico et al. 2011; Speyerer et al. 2016) and proximity to potentially economic volatile reserves (Li et al. 2018), the South Pole of the Moon is the place where we will convert space from a wilderness, visited only briefly and tentatively, to a sustainable frontier of human activity where we answer fundamental scientific questions, grow a cislunar economy, and pave the way to journeys beyond.

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JOINT POLISH-GERMAN CRYSTALLOGRAPHIC MEETING 2020

JPGCM-2020

ABSTRACT DEADLINE: 1 NOVEMBER 2019

23–27 FEBRUARY 2020
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Submission and registration: www.dgk-conference.de
October 2–5  The Venera-D Landing Sites and Cloud Habitability Workshop, Moscow, Russia. Web page: www.hou.usra.edu/meetings/venerad2019/


October 7–11  DMG Short Course: In Situ Analysis of Isotopes and Trace Elements by Femtosecond Laser Ablation ICP-MS, Hannover, Germany. Contact Stefan Weyer (s.weyer@minerologie.uni-hannover.de)

October 9–11  Geologica Carpathica 70, Smolenice, Slovakia. Web page: geo.skav.si/event/gc-70/


February 11–13  The Impact of Lunar Dust on Human Exploration, Houston, TX, USA. Web page: www.hou.usra.edu/meetings/lundardust2020/

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 18–21  3rd International Planetary Caves Conference, San Antonio, TX, USA. Web page: www.hou.usra.edu/meetings/3rdcaves2020/


March 2–8  36th International Geological Congress, Delhi, India. Web page: www.36igc.org


March 16–20  Chapman Conference on Distributed Volcanism and Distributed Volcanic Hazards, Flagstaff, AZ, USA. Web page: www2.agu.org/en/chapmans-Distributed-Volcanism


June 14–19  Asteroids, Comets, Meteors Conference, Flagstaff, AZ, USA. Web page: www.hou.usra.edu/meetings/acm2020/


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

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

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/eers/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: meteoriticalsociety.org/?page_id=18


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

October 4–8  Materials Science & Technology 2020, combined with ACS 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/


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

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

November 14–17  Asteroid, Comets, Meteors Conference, Flagstaff, AZ, USA. Web page: www.hou.usra.edu/meetings/acm2020/


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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CT03 Expanding the Frontiers of Achnide Materials Science Through Experiment and Theory
CT04 Tailored Interphases for High Strength and Functional Composites—Advances in Experiments, Simulations and AI-Based Design
CT05 Defects, Order and Disorder in Structural and Functional Fluorite-Related Compounds
CT06 Local and Global Fluctuations in Plasticity
CT07 Micro-Assembly Technologies and Heterogeneous Integration—Fundamentals to Applications
CT08 Crystallization via Nonclassical Pathways in Synthetic, Biogenic and Geologic Environments

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EL04 Materials for Nonlinear and Nonreciprocal Photonics
EL05 Scalable Photonic Material Platforms—Applications and Manufacturing Advances
EL06 Photonic Materials for Information Processing and Computing
EL07 Fundamental Mechanisms and Materials Discovery for Brain-Inpired Computing—Theory and Experiment
EL08 Neuromorphic Materials and Devices for Brain-inspired Computing and Artificial Intelligence
EL09 Phase-Change Materials for Electronic and Photonic Nonvolatile Memory and Neuro-Inspired Computing
EL10 Electroactive Ceramics for Information Technologies and Flexible Electronics
EL11 Lead-Free Ferroelectrics and Their Emerging Applications
EL12 Ferroic Materials and Heterostructures for Electronics and Data Storage
EL13 Processing, Microstructure and Multifunctioning of Organic Semiconductors
EL14 New Materials Design for Organic Semiconductors Through Multimodel Characterization and Computational Techniques
EL15 Ultra-Wide Bandgap Materials, Devices and Systems

ENERGY, STORAGE AND CONVERSION
EN01 Next Steps for Perovskite Photovoltaics and Beyond
EN02 Caloric Materials for Sustainable Cooling Applications
EN03 Solar-Energy Conversion for Sustainable Water-Energy-Environmental Nexus
EN04 Dual-Ion Batteries as an Emerging Technology for Sustainable Energy Storage—Anion Storage Materials and Full Dual-Ion Battery Devices
EN05 Low-Cost Aqueous Rechargeable Battery Technologies
EN06 Rational Designed Hierarchical Nanoarchitectures for Photocatalytic System
EN07 Next-Generation Electrical Energy Storage—Beyond Intercalation-Type Lithium Ion
EN08 Multivalent-Based Electrochemical Energy Storage
EN09 Flow-Based Open Electrochemical Systems
EN10 Emerging Inorganic Semiconductors for Solar-Energy Conversion
EN11 Materials, Modeling and Technoeconomic Impacts for Large-Scale Hydrogen and Energy Applications
EN12 Materials for Safe and Sustainable Electrochemical Energy Storage

NANOSCALE AND QUANTUM MATERIALS
NM01 Nanodiamonds—Synthesis, Properties and Applications
NM02 Colloidal Nanoparticles—From Synthesis to Applications
NM03 Nanomanipulation of Materials
NM04 Nanosafety
NM05 1D Carbon Electronics—From Synthesis to Applications
NM06 Theory and Characterization of 2D Materials—Bridging Atomic Structure and Device Performance
NM07 Two-Dimensional Quantum Materials Out of Equilibrium
NM08 2D Atomic and Molecular Sheets—Electronic and Photonic Properties and Device Applications
NM09 Layered van der Waals Heterostructures—Synthesis, Physical Phenomena and Devices
NM10 Synthesis, Properties and Applications of 2D MXenes
NM11 Topological and Quantum Phenomena in Oxides and Oxide Heterostructures
NM12 Synthesis and Control of Dirac or Topological Materials

SOFT MATERIALS AND BIOMATERIALS
SM01 Organ-on-a-Chip—Toward Personalized Precision Medicine
SM02 Progress in Open-Space Microfluidics—From Nanoscience, Manufacturing to Biomedicine
SM03 Flexible, Stretchable Biointegrated Materials, Devices and Related Mechanics
SM04 Fundamental Materials, Devices and Fabrication Innovations for Biointegrated and Bioinspired Electronics
SM05 Engineered Functional Multicellular Circuits, Devices and Systems
SM06 Soft Organic and Hybrid Materials for Biointerfacing—Materials, Processes and Applications
SM07 Bioinspired Synthesis and Manufacturing of Materials
SM08 Emerging Strategies and Applications in Drug Delivery
SM09 Advances in 3D Printing for Medical Applications

Meeting Chairs
Qing Cao, University of Illinois at Urbana-Champaign
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