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Elements is published six times a year. Individuals are encouraged to join any one of the participating societies to receive Elements. Institutional subscribers to any of the following journals—American Mineralogist, Clay Minerals, Clays and Clay Minerals, Mineralogical Magazine, and The Canadian Mineralogist—also receive one copy of Elements as part of their 2016 subscription. Institutional subscriptions are available for US$165 (US$180 non-US addresses) a year in 2016. Contact the executive editor (jrosso.elements@gmail.com) for information.

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Publications mail agreement no. 400379944

Printed in USA

ISSN 1811-5209 (print)
ISSN 1811-5217 (online)

www.elements.org
www.elementsmagazine.org
www.geoscienceworld.org

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Cover Image: Origin of life: Protocells interacting with organic molecules and minerals in their environment. Nucleotides and an unstructured RNA substrate (magenta); amino acids and peptides (green), an amino acid-nucleotide (alanine adenylate) complex (blue), and pyrite (iron, gray; sulfur, yellow) are shown. Structured ribozymes and a RNA-peptide complex are present within the protocells as well as an iron/sulfur cluster-protein complex. Image Credits: Protocells pictures courtesy of Matthew Chavent (www.matthieuChavent.com/photos/) from Syama Kodali’s lab. Cover image designed and assembled by Fabrice Leclerc. © Fabrice Leclerc
The Mineralogical Society of Great Britain and Ireland (MSGI) is an international society for all those working in the mineral sciences. The society seeks to promote, through various means, the publication and discussion of scientific knowledge in the field of mineralogy, crystallography, and geochemistry, and to disseminate it to the scientific and public communities. The society promotes, through its medals, lectures, and awards, the annual meeting, workshops, and field trips, and support the related disciplines. Membership benefits include the European Journal of Mineralogy, Elements, and a reduced registration fee for the annual meeting.

Society NewS editor: Isabel Abad Martinez (isabel.martinez@uji.es)

Società Italiana di Mineralogia e Petrologia

The Società Italiana di Mineralogia e Petrologia is a professional association founded in 1924 by professionals from the various fields of mineralogy, crystallography, and geochemistry, and to disseminate it to the scientific and public communities. The society promotes, through its medals, lectures, and awards, the annual meeting, workshops, and field trips, and support the related disciplines. Membership benefits include the European Journal of Mineralogy, Elements, and a reduced registration fee for the annual meeting.

Society NewS editor: Catri Corrigan (catri.corrigan@essex.ac.uk)

The Meteoritical Society is an international association founded in 1933 for scientists, collectors, and educators to advance the study of meteorites and other extraterrestrial materials and their parent asteroids, comets, and planets. Members receive our journal, Meteoritics & Planetary Science, reduced rates for Geochemia et Cosmochimica Acta, which we co-sponsor, and a subscription to Elements. We organize annual meetings, workshops, and field trips, and support young planetary scientists worldwide. Through our medals and awards, we recognize excellence in research and education.

Society NewS editor: Ikko Katayama (katayama@hiroshima-u.ac.jp)

The Japan Association of Mineralogical Sciences (JAMS) was established in 2007 by merging the Mineralogical Society of Japan, founded in 1955, and the Japanese Association of Mineralogists, Petrologists, and Economic Geologists, established in 1928. JAMS covers all research fields of mineral sciences, geochemistry, and petrology. Membership benefits include the receiving of the Journal of Mineralogical and Petrological Sciences (JIPS), the Genseki-Kobutsu-Kagaku (GKK) (in Japanese), and Elements. We organize annual meetings, workshops, and field trips, and support young planetary scientists worldwide. Through our medals and awards, we recognize excellence in research and education.

Society NewS editor: Masaaki Yoshida (moya@nakagai.ac.jp)
SOMETHING OLD IS SOMETHING NEW

Dear friends. This final issue of Elements for 2016 marks the end of my term as a Principal Editor.

Looking back, my tenure finishes near to where it began—with a focus on mineral–water interfaces (Elements, “Mineral–Water Interactions,” v9n3, 2013). A recurring theme throughout the current issue is that chemical reactions at mineral surfaces likely had a role in sparking what we now experience as complex living systems. Indeed, mineral–water interfaces may reside at the heart of the ultimate scientific question—“What is the origin of life on Earth?”

We may never fully know the answer. However, advances in our knowledge of crystalline and amorphous solid–water interfaces and the molecular properties of solutions give reasons to be optimistic that we can gain a much deeper understanding.

Why make such a claim? High-resolution imaging techniques, such as in situ TEM, high-energy X-rays, and PEMP are producing an explosion of novel insights into mineral and solution structures and reactions that occur at their interface. Of particular interest is the prevalence of diverse small particles. From molecules to oligomers and nanocrystals, particles are present … well … everywhere. Our colleagues, Jillian Banfield (University of California, Berkeley, USA), Michael Hochella Jr. (Virginia Tech, USA), Lia Addadi (Weizmann Institute of Science, Israel), and many others, have demonstrated the abundance of small particles in every environmental compartment on Earth. Their ubiquity raises the question, touched upon in this issue, of whether the surface energy changes and low-temperature crystal growth. To put this into context, a crowning achievement of the mineralogical and materials disciplines had uncovered a novel idea: diverse materials and minerals can form by particle assembly. It captures the imagination to consider that crystals, including those with faceted habits, can grow by the aggregation and sometimes-oriented assembly of nanoparticles to form synthetic and biological minerals.

But not so fast. We should pause and be humbled by the fact that crystal growth by particle attachment was first proposed during the 18th and 19th centuries. Unbeknownst to much of the world, Russian crystallographers were publishing penciled illustrations of crystal growth by the coalignment of submicron particles into macroscopic crystalline structures (see Ivanov et al. 2014). Moreover, these pioneering Russians understood, at least conceptually, that the surface charge distribution on particle faces must play a role in driving oriented particle–particle interactions.

With the secret life of particles finally being revealed, one might ask, “Are new insights into mineral–water interfaces almost finished?” I would argue, “No!” Right before us, something old is giving rise to something very new. We may expect that we will see these concepts and solution composition and turbidity.

We have now come full circle. With the advent of the high-resolution experimental and theoretical methods mentioned previously, the field of colloid chemistry was transformed seemingly overnight into the nanomaterial and biomolecular disciplines that we know today. At first glance, it would also seem that these disciplines had uncovered a novel idea: diverse materials and minerals can form by particle assembly. It captures the imagination to consider that crystals, including those with faceted habits, can grow by the aggregation and sometimes-oriented assembly of nanoparticles to form synthetic and biological minerals.

But not so fast. We should pause and be humbled by the fact that crystal growth by particle attachment was first proposed during the 18th and 19th centuries. Unbeknownst to much of the world, Russian crystallographers were publishing penciled illustrations of crystal growth by the coalignment of submicron particles into macroscopic crystalline structures (see Ivanov et al. 2014). Moreover, these pioneering Russians understood, at least conceptually, that the surface charge distribution on particle faces must play a role in driving oriented particle–particle interactions.

With the secret life of particles finally being revealed, one might ask, “Are new insights into mineral–water interfaces almost finished?” I would argue, “No!” Right before us, something old is giving rise to something very new. We may be witnessing an advance in our understanding of how the Earth works that will rival the way history now views plate tectonics.

As the molecular details of particle interactions emerge—with solutes, organics, and each other—I expect that we will see these concepts explain some of the long-standing enigmas in the Earth and planetary sciences. The origin of...

Cont'd on page 380
ABOUT THIS ISSUE

How did life arise from inorganic molecules? Did it develop in an early Earth primordial soup or was there an extraterrestrial source? Although the answer to the origin of sentient life has yet to be discovered by scientists, the origins of the genetic blueprints for life (e.g. RNA), the workhorses of life (e.g. proteins), and the protective membranes for life (e.g. lipids) are rapidly being uncovered. But, making the basic building blocks is only the first step. The next steps involve converting those molecules into viable cells. Believe it or not, geoscientists are needed to help uncover the answers to these questions because abiogenesis requires chemical, biological, and geological considerations. We hope the articles in this issue help introduce you to this exciting field of research.

2017 PREVIEW AND FUTURE ISSUES

Our lineup is complete through 2017 (see our preview for 2017 on pages 382 and 383), but there is so much more to cover. If you have ideas for a thematic issue, contact one of our principal editors and submit a proposal for our consideration at our mid-April 2017 editorial meeting. At that time, we will be setting our lineup for the first half of 2019. More information about publishing in Elements can be found at elementsmagazine.org/publish-in-elements/.

EDITORIAL Cont’d from page 379

life? Possibly. You will see connections as you read this issue. The early Earth? Likely. For example, we may finally resolve enigmas of the Proterozoic—that somewhat unusual interval of Earth history characterized by massive deposits of carbonate, sulfate, and iron sediments having textures and compositions that are rarely, if ever, found again in the geological record. And the modern Earth? Definitely. A mechanistic picture of particle-based processes will improve our ability to interpret and manage urgent environmental challenges.

The coming decade promises to be ever more exciting as scientific discovery marches forward. I wish you godspeed in being part of all that lies ahead.

Patricia M. Dove, Principal Editor

In our final issue of 2016, we like to take a moment to extend our appreciation to the guest editors and authors who contributed to the six issues of volume 12. These men and women succeeded at writing compelling articles for Elements’ scientifically diverse audience and in adhering to the journal’s deadlines and guidelines. We also thank our feature editors (Ian Parsons, Penelope King, Michael Wiedenbeck, Cari Corrigan, David Vaughan, and Andrea Koziol) who volunteer their valuable time to produce the Parting Shots, A Life in Science, The Elements Toolkit, CosmoElements, Mineralogy Matters, the Calendar, and People in the News. We also acknowledge the reviewers, our copy-editor Patrick Roycroft, and our graphic artist, who diligently work in the background to bring Elements to life.

In addition, we thank our advertisers for their continued support. In the day and age of digital media, these advertisers have invested in a print publication to reach you! Please take the time to speak with their representatives about their products and services. Those that advertised in 2016 were Analab, Australian Scientific Instruments, Cambridge University Press, CAMECA, Crystal Maker, Elemental Scientific, Excalibur Minerals Corporation, Geological Society of London, Gemological Institute of America (GIA), The Geochemist’s Workbench, International Center for Diffraction Data, International Kimberlite Conference, International Mineralogical Association, IsotopX, National Electrostatics Corporation, Overburden Drilling Management, PanAnalytical, Periodico Mineralogia, ProtoXRD, Rigaku, Savilltex, Selfrag, Society for Geology Applied to Mineral Deposits, TofWerk, and Wiley. Special mention goes to Australian Scientific Instruments, CAMECA, Excalibur Minerals Corporation, The Geochemist’s Workbench, Periodico Mineralogia, ProtoXRD, Savilltex, and Selfrag who advertised in each issue during 2016.

We also want to thank the 17 participating societies who faithfully support this magazine. Without them, Elements wouldn’t exist.

THANKS TRISH!

With this issue, Trish Dove retires as a principal editor of Elements. During her tenure, she was in charge of the following issues: The Mineral-Water Interface (v9n3), Unconventional Hydrocarbons (v10n4), Cosmogenic Nuclides (v10n5), Apatite: A Mineral for All Seasons (v11n3), Geomicrobiology and Microbial Geochemistry (v11n6), and Origins of Life: The Transition from Geochemistry to Biogeochemistry (v12n6). Trish has been a vital part of our editorial team since 2013. Not only did we value her editorial handling of articles, her expertise and experience were invaluable assets during the Executive Editor transition in 2015. Thank you, Trish, for all you have done to help Elements continue to be the most readable and authoritative magazine in mineralogy, petrology, and geochemistry.

Best wishes to everyone for the coming year.

Gordon Brown Jr., Bernard Wood, Friedhelm von Blankenburg, and Jodi Rosso
High-speed Identification and Quantification of Hematite and Magnetite

Iron rust (ferric oxide) has two forms. One is hematite ($\text{Fe}_2\text{O}_3$), called red rust, and the other is magnetite ($\text{Fe}_3\text{O}_4$), called black rust. Ferric oxides exist abundantly in nature; since they have low impact on the human body and ecosystems, and they are cheap, they are used for various applications, such as a corrosion inhibitor, an abrasive agent, a colorant and a catalyst. These ferric oxides have different crystal structures, so they show different X-ray diffraction patterns. Using XRD, one can easily distinguish between these two oxides, and can also perform a quantitative analysis when the sample is a mixture of the two.

Using Rigaku's SmartLab multipurpose diffractometer equipped with a D/teX one-dimensional X-ray detector, even when the source is a 2 kW sealed tube generator, one can perform the identification and quantification of the material in a short time.

Samples blending 10, 20, 30, 40 and 50% of $\text{Fe}_2\text{O}_4$ into $\text{Fe}_3\text{O}_4$ were measured (Fig. 1). Even with data acquisition times as short as 3.5 minutes per measurement, sufficient intensities are obtained. Quantitative analysis results by the Rietveld method show good agreement with the known composition values (Fig. 2).
Volcanoes have played a large role over Earth's history in building the crust, contributing to atmospheric formation, and transferring heat and mass from the interior to the surface. They are also capable of massive disruption of the surface environment and to human civilizations. Volcanoes themselves are the products of crustal-scale systems. But what controls whether a given magma will erupt or stall, and how do processes in one part of the system affect others? Volcano science is advancing rapidly, and improvements in monitoring tools, petrologic tools, and modeling of volcanic processes have greatly improved our understanding of volcanic behavior. This issue brings together contributions exploring volcanic behavior throughout the crustal system.

- **Down the Crater: Where Magmas are Stored and Why They Erupt**
  Keith Putirka (California State University – Fresno, USA)

- **What Does a Magma Reservoir Look Like? The “Crystal’s Eye” View**
  Karl M. Cooper (University of California – Davis, USA)

- **Volatile and Exsolved Vapor in Volcanic Systems**
  Marie Edmonds (University of Cambridge, UK) and Paul J. Wallace (University of Oregon, USA)

- **The Implications of Magna System Models for Forecasting Volcanic Activity**
  R.S.J. Sparks (University of Bristol, UK) and Kathy Cashman (University of Bristol, UK)

- **Global Volcano Monitoring—What Does it Mean When Volcanoes Deform?**
  Juliet Biggs (University of Bristol, UK) & Matt E. Pritchard (Cornell University, USA)

- **Volcanoes: Characteristics, Tipping Points and Those Pesky Unknown Unknowns**
  Colin J.N. Wilson (Victoria University, New Zealand)

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**SULPHIDES**

**Guest Editors:** Kate Kiseeva (University of Oxford, UK) and Marie Edmonds (University of Cambridge, UK)

Despite the bulk silicate Earth only containing 250 parts per million of sulphur, sulphide minerals and liquids have a powerful impact on the behaviour and fractionation of a wide range of elements in the Earth's crust and underlying mantle. According to the V. M. Goldschmidt classification, in the periodic table there are 18 chalcophile elements that have affinity for sulphur and form sulphides. Besides the chalcophile elements, a large number of siderophile elements are also found in nature in association with sulphides. This issue focuses on the broad topics of magmatic and volcanogenic sulphide deposits, the behaviour of sulphides during mantle melting and volcanism, and the mineralogy of sulphides and sedimentary sulphides and their role in the early development of the biosphere.

- **Mineralogy of Sulphides**
  David Vaughan (University of Manchester, UK) and Clare Corkhill (University of Sheffield, UK).

- **Magmatic Sulphide Deposits**
  Stephen Barnes (CSIRO Mineral Resources, Australia), Dave Holwell (University of Leicester, UK) and Margaux Le Vaillant (CSIRO Mineral Resources, Australia).

- **Hydrothermal Sulphide Deposits**

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**ROCK AND MINERAL COATINGS**

**Guest Editors:** Michael Schindler (Laurentian University, Canada) and Ronald Dorn (Arizona State University, USA)

Chemical and/or biological processes can produce coatings on the surfaces of rocks and minerals. These coatings form at the interface between the lithosphere, biosphere, and atmosphere in a diverse range of environments, such as common soils, deserts, volcanic weathering environments, smelter-impacted areas, Antarctica and glaciated environments, and have even been found on Mars. Coatings on rocks and minerals can range from the nano- to the centimeter scale and are information packed on different scales. They provide fascinating records of the biological, geochemical, and environmental conditions present during coating development. Through the study of these coatings, scientists are uncovering important details about climate and environmental changes, temperature variations in the world's oceans, and so much more. This issue will introduce the reader to how these coatings form, how they react with their environment, and a few of the fascinating records that can be deciphered from them.

- **Rock Coatings: The Interface Between Lithosphere, Biosphere and Atmosphere**
  Michael Schindler (Laurentian University, Canada), Ronald Dorn (Arizona State University, USA)

- **The Dynamic Transition Between Weathering Rinds and Rock Coatings**
  Ronald Dorn (Arizona State University, USA), William Mahaney (York University, Canada), David Krinsley (University of Oregon, USA)

- **Life on Rocks**
  Geoff Gadd (University of Dundee, UK)

- **Mineral Surface Coatings in Soils and Sediments: Hosts of Contaminants and Records of Environmental Changes**
  Michael Schindler (Laurentian University, Canada), David Singer (Kent State University, USA)

- **Archaeological Implications of Climatic Change Signal in Rock Coatings**
  David Whitley (ASM Affiliates, USA), Calogero Santoro (Universidad de Tarapacá, Chile), Daniela Valenzuela (Universidad Alberto Hurtado, Chile)

- **Marine Ferromanganese Encrustations: Archives of Changing Oceans**
  Andrea Koschinsky (University Bremen, Germany), James Hein (U.S. Geological Survey, USA)

- **Rock Coatings and their Implications in Astrobiology on Mars: Protection, Preservation, and Practicality**
  Cassandra Marrocho (Niagara University, USA), Barry DiGregorio (University of Buckingham, UK)
Volume 13, Number 4 (August)

MINERAL RESOURCES AND SUSTAINABLE DEVELOPMENT

Guest Editor: Georges Calas (University Pierre and Marie Curie, Paris, France)

Mineral resources are a vital part of any economy, modern or ancient. Since the birth of civilization, man has used these resources for pigments, metals, glasses, ceramics, cements and much more. The media has recently suggested there is a crisis looming over finding mineral resources, including critical metals. Centered on the sustainability of mineral resources, themes addressed in this issue include customer–supplier relationships, exploration, recycling and the circular economy, and environmental post-mining impacts. The broad range of topics embraced by this issue – formation of mineral deposits, minerals engineering, and environmental and societal impacts – will provide readers a better understanding of the large-scale economic, historical and educational aspects of mineral resources.

- Mineral Resources and Sustainable Development
  Georges Calas (University Pierre and Marie Curie, Paris, France)

- Mineral Resources in the Context of Energy Transition and the Circular Economy
  Olivier Vidal (University Grenoble ALPES, France) and Patrice Christmann (BRGM, The French Geological Survey, France)

- Sustainability of Mineral Resources: Mineral Beneficiation and Mining Engineering
  Johan PR De Villiers (University of Pretoria, South Africa) and Frédéric Villieras (Lorraine University, France)

- Critical Metals and Responsible Mining
  Frances Wall (University of Exeter, UK) and Alain Rollat (Solvay, France)

- Improving the Mitigation of the Long-Term Legacy of Post-Mining Activities: New Tools, New Concepts
  Gordon E. Brown Jr. (Stanford University, USA), Michael F. Hochella Jr. (Virginia Tech, USA) and Georges Calas (University Pierre and Marie Curie, France)

- The Education of the Resource Geologists of the Future: Between Observation and Imagination
  Michel Jebraik (University of Quebec at Montreal, Canada) and Jean-Marc Montel (Lorraine University, France)

Volume 13, Number 5 (October)

BORON: LIGHT AND LIVELY

Guest Editor: Edward Grew (University of Maine, USA)

Fifth in the periodic table, boron is a “light” element whose origin has puzzled astronomers because it is not created in stars. It is “lively”, being an essential element for plants, and having medicinal properties, which has stimulated synthesis of organic compounds containing boron. Borates such as colemanite are thought by some to have stabilized ribose, an essential component of ribonucleic acid and critical for the self-assembly of prebiotic organic compounds to constitute life; others have proposed that ribose was stabilized by borate in solution. Boron isotopes provide insight on the processes responsible for the creation of continental crust, and act as a proxy for paleoclimate. Extreme concentrations of boron result in economic evaporitic deposits, and, thus, water-soluble boron minerals, notably borax, have been among the most accessible of useful compounds to humankind, even in antiquity.

- Boron, a Quintessentially Crustal Element.
  Edward S. Grew (University of Maine, USA)

- Boron Behavior During the Evolution of the Early Solar System.
  The First 200 Million Years.
  Charles K. Shearer (University of New Mexico, USA) and Steven B. Simon (University of Chicago, USA)

- The Role of Borate in Prebiotic Organic Geochemistry.
  Yoshihiro Furukawa and Takeshi Kakegawa (Tohoku University, Japan)

- Boron Isotopes in the Exogenic Cycle – Why is Seawater Boron so Isotopically Heavy?
  Martin B. Palmer (National Oceanography Centre, Southampton, UK)

- Advances in the Boron Isotope Paleo-pH Proxy.
  N. Gary Hemming and E. Troy Rasbury (Queens College, UK)

- Origin and Distribution of Evaporitic Borate - The Primary Economic Source of Boron.
  Cahit Helvaci (Dokuz Eylül Universität, Turkey)

- Tripping the Light Fantastic: Organoboron Compounds.
  Penelope J. Brothers (University of Auckland, Australia)

Volume 13, Number 6 (December)

LAYERED INTRUSIONS: NATURAL LABORATORIES FOR MAGMA CHAMBER PROCESSES

Guest Editors: Brian O’Driscoll (University of Manchester, UK) and Jill VanTongeren (Rutgers University, USA)

For more than 50 years, layered mafic-ultramafic intrusions have served as natural laboratories for studying magma chamber processes and magmatic differentiation. Further enhancing our understanding of layered intrusion formation will yield valuable insights into the solidification of magmatic systems, the formation of precious metal deposits, and the timescales over which substantial crust-forming episodes occur. The aims of this issue of Elements are to offer an overview of the state-of-the-art in the petrology of layered intrusions today and a look forward to the future challenges in the field.

- Layered Intrusions: Dynamic Deposits and Petrological Paradises
  Brian O’Driscoll (University of Manchester, UK) and Jill VanTongeren (Rutgers University, USA)

- The Skaergaard Intrusion of East Greenland: A Natural Laboratory for Igneous Petrology?
  Marian B. Holness (University of Cambridge, UK), Troels FD Nielsen (Geological Survey of Denmark), and Christian Tegner (Aarhus University, Denmark)

- Metasomatic Chromitite Seams in the Bushveld and Rum Intrusions
  Edmond A. Mathez (American Museum of Natural History, USA) and Rosamond J. Kinzler (American Museum of Natural History, USA)

- Plagioclase Zonation as an Archive for Magmatic Processes in Layered Intrusions
  Stearns A. Morse (University of Massachusetts Amherst, USA), Jon P. Davidson (Dundee University, UK), and Frank J. Teply III (Oregon State University, USA)

- Quantitative Textural Insights into the Construction and Architecture of Layered Intrusions
  Michael J. Cheadle (University of Wyoming, USA) and Jeffrey S. Gee (SCRIPPS Institution of Oceanography, USA)

- Layered Mafic-Ultramafic Intrusions of Fennoscandia: Mineral Prospectivity in Contrasting Tectonic Settings
  Wolfgang D. Maier (Cardiff University, UK) and Eero Hanski (University of Oulu, Finland)
Symposia

- SY01: Gold through time and space
- SY02: Magmatic sulfide and oxide ore deposits in mafic and ultramafic rocks
- SY03: IOCG-IQA ore systems and their magmatic-hydrothermal continuum: A family reunion?
- SY04: Mineral deposits: theory, experiment and nature - a symposium to recognize the work of A.E. Williams-Jones

Short courses

- SC1: Recent advances in the genesis of mafic and ultramafic ore systems
- SC2: High technology metals (REE, Nb-Ta, Li)
- SC3: Exploration geophysics - new methods, case studies, modeling
- SC4: Linkages amongst iron-oxide alkali-altered systems: From metasomatism to orogenic metamorphism
- SC5: Detecting the alteration footprint around porphyry copper deposits
- SC6: Exploration management and targeting with 3D multidisciplinary models
- SC7: Field portable instrumentation
- SC8: Recent advances in micro-analytical techniques (LA-ICP-MS, CT ... ) applied to ore deposits

Sessions

- S01: Geology, geodynamics and metallogeny of the Rhyacian (2.35 - 2.05 Ga)
- S02: Ore-forming magmatic-hydrothermal processes along active margins
- S03: Exhautive mineral deposits: key controls on the quality (size and/or grade) of deposits and districts
- S04: Uranium deposits: from source to ore
- S05: Iron ore: deposit to global scale processes
- S06: The impact of the supercontinent cycle on ore formation
- S07: Developments of geochronological methods and their application to date ore forming events
- S08: From fertility to footprints: New vectoring tools for mineral exploration
- S09: Geometallurgy: risk reduction through communication, optimization and innovation
- S10: GSC@175: How can government promote exploration success?
- S11: Resources development and perception/acceptability: The role of geosciences
- S12: Gem research: Beautiful windows into earth’s interior
- GS01: General session (posters only)

Field trips

- FT-01: Physical volcanology and metallogenesis of the Ni-Cu-PGE deposits in the Cape Smith Belt, Quebec, Canada
- FT-02: Iron oxide and alkali alteration, skarn and epithermal mineralizing systems of the Grenville Province, Canada
- FT-03: Gold mineralization in the Guyana Shield, Guyana and Suriname, South America
- FT-04: Uranium deposits in the Western Athabasca Basin, Canada
- FT-05: Quebec fortified city: geological and historical heritage
- FT-06: Precious and base metal deposits of the southern Abitibi greenstone belt, Superior Province, Canada
- FT-07: Stratigraphic and metallogenic context of the Sokoman Iron Formation in the Labrador Trough near Schefferville, Quebec-Labrador, Canada
- FT-08: Geologic setting and iron oxide deposits of the mesoproterozic St. Francois Mountains, Southeast Missouri, USA

Important Dates

- **>> January 15, 2017:** Abstract submission opening date
- **>> February 28, 2017:** Deadline for SGA Student grant applications
- **>> April 30, 2017:** Final acceptance
- **>> May 15, 2017:** Deadline for early-bird registration
- **>> August 19, 2017:** Icebreaker cocktail
- **>> August 20, 2017:** Opening ceremony; Student-Industry Event
- **>> August 21, 2017:** Gala Dinner, Chateau Frontenac
- **>> August 23, 2017:** Closing Ceremony

Registration

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Meet the Authors

**Luca Belmonte** was born in the south of Italy and earned his bachelor’s and master’s degrees in engineering from the University “Magna Graecia” of Catanzaro. He then worked at Accenture, before completing his doctoral studies at the University of Genoa (Italy) with Prof. Claudio Nicolini. His PhD work was on radiation damage to protein crystals. Luca joined the National Research Council of Italy, under Dr. Oscar Moran, to work on the characterization of cystic fibrosis transmembrane conductance regulator (CFTR) domains. He is now a postdoctoral fellow at the University of Trento (Italy). His work exploits computational tools to gain insight into the origins of life.

**Punam Dalai** received her master’s degree in chemistry from the Indian Institute of Technology at Roorkee (India) and her PhD from the University of Hohenheim (Germany). Her doctorate focused on the thermal behavior of amino acids in the presence of various inorganic matrices. She then became a post-doctoral researcher at the University of Akron (Ohio, USA) where she is currently working on the potential role of mineral surfaces in the evolution of protocols which could perform proto-metabolism. She is also investigating the effect of metal ions on the stability of lipid biosignatures.

**Hussein Kaddour** is a postdoctoral researcher in the Department of Polymer Science at the University of Akron (USA) where he is exploring the role of minerals in the origins of life. Previously, he was a lecturer and research assistant at the Université de Lorraine in Nancy (France). In 2011, he earned his PhD in molecular biology and biochemistry from the Université Pierre et Marie Curie Paris (France) where he investigated the structure-function relationships of ribozymes. Hussein also earned an MBA in 2012 from Université Panthéon-Assas Paris. Hussein’s research interests include the origin of life, RNA chemistry, RNA therapeutics, and synthetic biology.

**Terence Kee** obtained his BSc (1985) and PhD (1989) degrees in organometallic chemistry at Durham University (UK) and then was awarded a SERC (NATO) postdoctoral fellowship for the Massachusetts Institute of Technology (USA), where he worked with Nobel Laureate Professor Richard Schrock. Kee is a Reader at the University of Leeds (UK), where he has worked since 1990. Kee has been Visiting Professor at the Université de Cergy-Pontoise (France) since 1999 and at the CNRS Centre Biophysique Moléculaire (France) since 2016. He holds affiliate faculty membership in the Department of Astronomy at the University of Florida (USA), received the research award from the Astrobiology Society of Britain in 2008, and has been president of the Astrobiology Society of Britain since 2010.

**Fabrice Leclerc** is a CNRS investigator at the Institute for Integrative Biology of the Cell in University Paris Sud (France). He researches RNA bioinformatics and modeling and has contributed to the field of RNA biology through studying the RNA guide machinery that is responsible for the pseudo-uridylation of RNAs in archaea and on the RNA catalysis in the hammerhead ribozymes derived from viroids. Leclerc has provided reliable 2D and 3D structure-function models on RNA or RNA-protein complexes from archaea, viruses, and viroids.

**Sheref Mansy** completed his PhD on iron–sulfur cluster biosynthesis with Prof. J. A. Cowan at Ohio State University (USA) and a post-doc on protocell studies with J. W. Szostak at Massachusetts General Hospital (USA). After winning an Armenian-Harvard career development award, he setup a laboratory at the University of Trento (Italy). His laboratory builds artificial cells and model prebiotic metallopeptides to gain insight into the boundaries and emergence of life. He is currently an associate professor of biochemistry.

**Marie-Christine Maurel** is a professor of biochemistry at University Pierre and Marie Curie and at the Museum National d’Histoire Naturelle, both in Paris (France). Her research is on the RNA world, including the discovery of the catalytic activity of a nucleoside analog: N6-ribosyl-adenine synthesized under prebiotic conditions. Her laboratory also discovered a co-ribozyme selected in vitro, the adenine-dependent hairpin ribozyme, and she applied, for the first time, baro-biochemistry to ribozymes, in so doing, revealing their extraordinary plasticity.

**Pierre-Alain Monnard** is an associate professor in the Institute of Physics, Chemistry and Pharmacy at the University of Southern Denmark (Odense). He obtained his PhD in Chemistry at the ETH Zurich (Switzerland). After working at the University of California Santa Cruz (USA) and Harvard Medical School (USA), he was appointed Technical Staff Member at Los Alamos National Laboratory (USA) in the Division of Earth and Environmental Sciences. He joined the University of Southern Denmark in 2008. His research is on chemical catalysis in complex chemical systems/networks supported by soft-matter structures and heterogeneous media. He has been involved in the development of chemical systems that model cellular precursors, or protocells, to understand the emergence of life on Earth, with additional applications to modern medicine and synthetic biology (delivery systems and nanoscale bioreactors).

**Nita Sahai** researches the biomolecule–mineral interface and processes that are relevant to the origins of life and to biomineralization. She is currently at the University of Akron (USA); prior to 2011, she was a professor for 11 years at University of Wisconsin-Madison (USA). She is the Ohio Research Scholar in Biomaterials, a Fellow of the Mineralogical Society of America (MSA), MSA Distinguished Lecturer (2013–2014), Romnes Faculty Fellow at University of Wisconsin-Madison (2009), and has received the National Science Foundation (NSF) CAREER award and an NSF Post-Doctoral Fellowship. Nita has been interviewed on radio (US National Public Radio) and appeared on television (US Public Broadcasting Service) to discuss her work on the origins of life.

**Martin A. Schoonen** is Associate Laboratory Director at Brookhaven National Laboratory (USA) and Professor of Geochemistry at Stony Brook University (USA). He joined Stony Brook University in 1989 after receiving a PhD in geochemistry and mineralogy from Pennsylvania State University (USA) and an MS at the University of Utrecht (The Netherlands). He has been interested in mineral surfaces and their reactivities and used experimental and theoretical approaches to explore electron transfer reactions involving metal sulﬁdes.

**Alexander Smirnov** is an associate professor of geology at Lone Star College–Kingwood (USA), having previously worked at Dowling College (USA). He joined Stony Brook University in 1989 after receiving his Diploma in geology from Comenius University (Slovakia) and a PhD in geosciences from Stony Brook University (USA). His PhD and post-doctoral research focused on mineral-mediated nitrogen reduction on the Hadean Earth. More recently, he has become interested in environmental geology, specifically in the effects of dust inhalation on human health.
David Vaughan, Research Professor of Mineralogy at the University of Manchester (UK), has achieved the rare distinction of being elected a Foreign Fellow of the Royal Society of Canada (RSC), that country’s national academy.

David was the founding Director of the University of Manchester’s Williamson Research Centre for Molecular Environmental Science, and is also an Honorary Research Fellow at the Natural History Museum (London, UK). In addition, he has uniquely served as President of the Mineralogical Society of Great Britain and Ireland, President of the Mineralogical Society of America, and President of the European Mineralogical Union. He has also been a Principal Editor of *Elements* magazine (2008–2010).

The Royal Society of Canada was founded in 1882 and recognises scholarly research and artistic excellence, advises governments and organisations, and promotes a culture of knowledge and innovation in Canada and with other national academies around the world. Annually, the RSC elects up to four Foreign Fellows who, at the time of their election, are neither residents nor citizens of Canada and who, by their exceptionally distinguished intellectual accomplishments, have helped promote the object of the RSC in ways that have clear relevance for Canadian society.

The Fellowship citation for David reads as follows: “David Vaughan is the leading international authority on metal sulphide minerals, key materials for the Canadian economy and natural environment. He has pioneered applications of spectroscopic, imaging and computational techniques to study the structure and reactivity of such minerals, and played a major role in establishing the field of molecular environmental science which integrates research on the mineralogical, geochemical and biological systems of the Earth’s surface at the molecular scale.”

WENDY BOHRSON: GEOSCIENCE DIVISION OF THE COUNCIL ON UNDERGRADUATE RESEARCH MENTOR AWARD

Wendy Bohrson, Professor of Geological Sciences at Central Washington University (USA), has been awarded the 2016 Undergraduate Research Mentor Award by the Geoscience Division of the Council on Undergraduate Research (GeoCUR). This annual award recognizes not only exceptional ability in maintaining good student-faculty relations but also in developing innovative approaches to undergraduate-level research.

In his citation in support of Wendy for this award (paraphrased below), Professor Erin Kraal (Kutztown University, USA) wrote:

Wendy Bohrson has engaged undergraduates in research since 1999, by working with individuals and by transforming university culture. Over 25 undergraduates have worked with Bohrson on her research to understand the evolution of magma chambers and young volcanoes. She is described as giving the “most caring, patient, meticulous, and beneficial advising any undergraduate could possibly ask for” balancing her approachability and careful guidance with “vigor, scientific integrity, and work ethic.” This commitment and devotion has brought about deep respect from her students. Bohrson’s undergraduate research students regularly win presentation awards at regional and national meetings and have met success post baccalaureate. Bohrson is a “leader of undergraduate research at the university level.” She was the director of both the Office of Undergraduate Research as well as the National Science Foundation (NSF) funded Science Talent Expansion Program (STEP). She tirelessly worked to transition the STEP mentored research ‘bridging program’ to become a permanent part of the university curriculum. Her colleagues note that even while focusing on administrative duties, Bohrson maintained a vibrant research group, where “a student can succeed and experience research at a level suited to their ability.” She is known as a “role model for productive and transformative faculty-student mentoring relationships.”

Barbara (Barb) Dutrow, the Adolphe G. Guéymard Professor of Geology at Louisiana State University (USA), has received the 2016 Outstanding Educator Award from the American Women in Geosciences, this organization’s premier professional award. The award honors women who are well-established college or university teachers who have played a significant role in the education and support of geoscientists within and beyond the classroom, in advancing the persistence of females and underrepresented minorities in geoscience careers, and in raising the general profile of the geosciences. The award was presented to Barb at the September 2016 Geological Society of America meeting in Denver (Colorado, USA).

Barb was cited for her contributions in all three of the areas of consideration for this longstanding career award (mentoring, instruction and curriculum, and outreach to the broader community). In the area of mentoring, Barb went beyond the traditional responsibilities of a tenured professor at a research institution by skillfully guiding many undergraduates through their first experiences with geological research, as well as mentoring many graduate students and helping them to secure funding for their degrees and research projects. By way of outreach, Barb has created museum exhibits elucidating concepts related to gems and minerals, and she has participated in the annual Tucson Gem and Mineral Show (Arizona, USA), which reaches tens of thousands of people. However, her nomination package was most striking as her contributions to instruction and curriculum. Barb has had a dramatic impact on the teaching of mineralogy across the nation and, one can say, the world, through leading the On the Cutting Edge workshops (run by the US-based National Association of Geoscience Teachers) on pedagogy, publishing research articles on student spatial learning and visualization, sharing numerous teaching activities online through On the Cutting Edge, and coauthoring with Cornelius Klein one of the leading mineralogy textbooks, *The Manual of Mineral Science* (23rd edition), now translated into Portuguese.

2016 DAY MEDALIST: DONALD B. DINGWELL

Donald B. Dingwell (Director of the Department of Earth and Environmental Sciences, Ludwig-Maximilian-University in Munich, Germany) is the 2016 Arthur Louis Day Medallist of the Geological Society of America (GSA). The award text cited how Donald has applied the principles of physics and chemistry to the solution of geologic problems. It is intended to inspire further effort and is, thus, awarded to geoscientists actively pursuing a research career. It is one of the highest honors in geosciences.

The Day Medal recognizes outstanding distinction in the application of physics and chemistry to the solution of geologic problems. It is intended to inspire further effort and is, thus, awarded to geoscientists actively pursuing a research career. It is one of the highest honors in geosciences.

The medal was established in 1948 by Arthur Louis Day, the founding Director of the Geophysical Laboratory of the Carnegie Institution of Washington DC (USA). It has been awarded annually ever since.
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GIA (Gemological Institute of America) invites qualified candidates to apply for the Richard T. Liddicoat Postdoctoral Research Fellowships. One or more fellowships are offered at GIA's Carlsbad, California or New York City locations. The one-to-two year fellowships encourage early career scientists to pursue full-time academic research in mineralogy, geology, physics, materials science and other fields related to gemology – the study of diamonds, colored gemstones, pearls and their treatment. Diamond research activities consider fundamental scientific problems in diamond geology, defect physics and synthesis. Liddicoat Postdoctoral Research Fellows are expected to conduct creative, independent, publishable research and are strongly encouraged to collaborate with GIA scientists as well as outside research institutions and universities. Applicants are encouraged to discuss projects of their own design with potential collaborators and to name them in their research proposal.

The fellowship includes a competitive annual stipend ($60,000+), research funding and travel subsidies for approved offsite research work. Benefits include full health, dental and vision insurance, and the potential reimbursement of relocation expenses. Appointments are for one year and may be extended for a second year based on mutual agreement.

The start date of each fellowship is flexible, but accepted candidates should begin by January 31, 2018. Applicants must have received their Ph.D. in a relevant field by the start date and preferably within the last three years. Effective oral and written English skills and the ability to publish high-level scientific articles are required. Candidates should be willing to travel domestically and internationally as needed.

Applications are due by April 30, 2017 and must include curriculum vitae with a publications list, a three-to-five page research proposal and at least two letters of reference. Incomplete applications will not be considered.

More information about the application process, the Liddicoat Postdoctoral Research Fellowships, GIA's facilities and our current and past research areas are available at GIA.edu/research-careers

GIA was established in 1931 and is the world’s foremost authority on diamonds, colored gemstones and pearls. A public benefit, nonprofit institute with locations in 13 countries, GIA is the leading source of research knowledge, standards and education in gems and jewelry. For more information about GIA, visit GIA.edu
The Transition from Geochemistry to Biogeochemistry

Nita Sahai1, 2, 3 Hussein Kaddour1 and Punam Dalai1

INTRODUCTION

The Earth formed ~4.56 Ga and was initially a hot planet. But oceans, and perhaps even continental crust, may have existed as early as ~4.3–4.4 Ga (Wilde et al. 2001). During this period, Earth was dominated by intense komatiitic volcanism. The first gases released would have been highly reducing and contained H2, CH4 (methane), and NH3 (ammonia). Once the Earth’s core had formed, CO2, N2, and H2O then became the major volcanic outgases that subsequently formed the Earth’s atmosphere, with practically no CH4 and NH3 (Kasting et al. 1993). Earth’s water inventory may have come from volcanic outgassing and/or delivered by comets, meteorites, and micrometeorites. Similarly, organic compounds would have been synthesized within the early atmosphere (endogenously) and delivered from space (exogenously). The ~3.8 Ga greenstones in Isua (Greenland) indicate that permanent oceans existed by that time. Primitive oceans are estimated to have been about twice as salty as modern oceans and were slightly acidic (pH ~5.5) during the Hadean. The date for the emergence of life is still highly debated. The scarcity of rocks from the Hadean Eon and Eoarchean Era, plus problems associated with post depositional alteration, make it difficult to pin down a precise date. A very early date of ~4.1 Ga for the origin of life is based on light carbon isotope signatures from carbon inclusions in zircons of Jack Hills, Western Australia (Bell et al. 2015). Stromatolite-like structures discovered very recently in Isua have been dated to ~3.7 Ga (Nutman et al. 2016), and bacterial microfossil-like structures have been dated at ~3.43 Ga in the Strelly Pool Sandstone Formation, Western Australia (Brazier et al. 2015). Isotopic evidence for methanotrophy and sulfate appear at the much younger ages of ~2.8 Ga to ~2.7 Ga.

Defining Life and the Protocell

The evidence to date suggests that even the most primitive life, at least as preserved in the rock record, was remarkably complex and similar to modern bacteria.

Yet, there must have been some precursor cell-like entities in the pathway from simple inorganic molecules containing C, H, O, N, P, and S to bacterial cells. Discovering this transitional process is at the heart of the origin of life field. In order to simulate this process experimentally, one needs to define the characteristics of a living cell. The search for extraterrestrial life also hinges on defining what exactly life is and what biosignatures one should be looking for. But defining life has proven to be surprisingly difficult. Nevertheless, it is widely accepted that all forms of extant life are characterized by three fundamental features (Fig. 1). First, all cells should possess a lipid bilayer membrane that defines cell boundaries, allows mass- and energy-fluxes across the membrane, facilitates signaling between the cell and its environment, and serves many other essential functions. Second, a universal DNA–RNA-based apparatus acts to transmit genetic information from one generation to the next. This apparatus also has the potential to mutate, thereby allowing evolution by natural selection. Third, all cells need to possess metabolism, which may be described as cycles of enzyme-catalyzed electron-transfer reaction networks to synthesize (anabolize) and to break-down (catabolize) complex molecules (Fig. 2). These processes provide the necessary molecules and energy by which the cell can sustain itself and reproduce. Related to these three characteristic features of life are the corresponding molecular building blocks of life, namely, membrane-building phospholipids, DNA/RNA and proteins, and a variety of critical small molecules such as the adenosine phosphates.

Although it is difficult to define life, it is widely assumed that self-replicating, cell-like entities called protocells possessed all the main characteristics of cells and preceded the Last Universal Common Ancestor (aka “LUCA” – the...
organism from which all living organisms today descend). Today, most prokaryotes live in biofilm communities attached to mineral surfaces, so it is reasonable to assume that the mineral–water interface would have provided a nursery for protocells and that minerals played a role in the synthesis and self-assembly of the earliest protocells. Specific minerals can even be shown to play the role of certain enzymes (Fig. 1).

**Prebiotic Chemistry**

DNA/RNA and proteins are polymers of nucleotide monomers and of amino acids. The production of these genetic molecules involves enzymatically catalyzed polymerization of nucleotide monomers. However, the synthesis of the enzymes (catalytic proteins) and of all proteins requires DNA/RNA. The production of membrane-forming phospholipids is also enzymatically catalyzed. Thus, the origin of life is a prime example of a chicken-and-egg problem, because enzymes are needed to produce DNA/RNA, yet DNA/RNA are needed to produce proteins, including enzymes. Thus, before life originated, what molecules and minerals could have served as prebiotic catalysts for the polymerization of nucleotides and amino acids into DNA/RNA and proteins, respectively?

It is not only the polymerization of nucleotides and amino acids that is problematic. Even the preceding step involving the synthesis of monomers from much simpler starting compounds—such as N₂, CO₂, H₂O, HCN, SO₂ and H₂S, which would have been present in the Hadean and early Archean atmospheres—presents an equally difficult challenge. The difficulties arise from multiple causes. First, carbon is generally in the reduced form in organic compounds, whereas it was the oxidized form of carbon in CO₂ that was most likely the stable form of carbon on early Earth. Achieving sufficient reactant concentrations of reduced carbon to yield products in viable quantities under plausible geological conditions and without enzymes is difficult. Many synthesis reactions, as well as the subsequent polymerization reactions, involve condensation reactions. Another major concern is how to drive such reactions forward in aqueous solutions while preventing the degradation of the organics formed by hydrolysis in these aqueous environments. Even when polymerization has been achieved, selecting functional molecules from the huge combinatorial space of polymers to form self-sustaining and reproducing entities is daunting and is yet to be fully experimentally addressed.

**Geological Processes and Geochemical Environments**

The difficulty of synthesizing monomers from simple starting compounds and subsequently polymerizing them to achieve some type of functionality increases tremendously when attempting to achieve these processes under plausible early Earth geochemical environments and geological processes. For example, some chemical syntheses require very high concentrations of starting compounds and may involve several steps, such as separation and purification. What were the corresponding analogous geological processes? Evaporation, sublimation, rehydration, and others, have all been proposed. But then these processes would need to have occurred in just the right sequence and needed just the right environmental conditions that were used in the experiments (temperature, pressure, pH, etc.). Thus, it is important to consider synthetic scenarios that would be geologically plausible to capture at least a slightly more realistic situation for the origin of life.

Estimating conditions that existed on early Earth relies on the rock record from the Hadean and early Archean. But this is sparse, not least because plate tectonics recycles the crust efficiently. Nonetheless, despite much debate among geoscientists about the ranges of early Earth’s atmospheric composition, there are certain generally accepted conditions. The high partial pressure of CO₂ gas on Hadean Earth would result in an acidic pH (~5–6) for surface waters. Alkaline solutions (pH ~10) would be formed in regions where peridotitic mantle was being serpentinitized. Estimates for inorganic ion concentrations in such scenarios may be obtained based on thermodynamic calculations of atmosphere–water–rock interactions (Schoonen and Smirnoff 2016 this issue).

In addition to organic molecules being synthesized on Earth, organics may also have been delivered from space by meteorites and cosmic dust particles, where the synthesis would have occurred under very different environmental conditions from those on early Earth. Extreme cold temperatures, vacuum-like pressures, and high UV radiation conditions would have been present in space. And, organic molecule synthesis may also be possible under conditions on other planets and their satellites, such as Enceladus and Titan (two moons of Saturn).

**RNA World versus Metabolism-first Theories**

There are several “origin of life hypotheses” currently being researched, and it is worth briefly reviewing them.

Some researchers in the origin of life field believe that the synthesis of DNA is too complex to have occurred without the input of enzymes. The molecule RNA is an information-carrier, and, thus, the discovery that some RNAs can act as enzymes led to a hypothesis that early life was RNA-based (Gilbert 1986). This is the well-known “RNA world” hypothesis (Box 1).

Others have argued that even the synthesis of RNA is difficult and that prebiotic catalytic molecules must have evolved first to create reaction networks for the synthesis of the molecular building blocks. This is called the “metabolism-first” theory. The role of iron sulfide minerals and thioacids in the emergence of the earliest metabolic cycles
before RNA is called the “iron–sulfur world” hypothesis (Wächtershäuser 1990). Another model proposes that the acetyl coenzyme A (acetyl-CoA) pathway linked to a chemiosmotic membrane potential provided the earliest metabolisms (Sousa et al. 2013; Russell et al. 2014; Lane 2015).

The RNA world versus metabolism-first debate has been raging for the past seven decades (Lazcano 2008). However, recent advances suggest that neither hypothesis is exclusively correct. Both RNA and other catalytic molecules may have evolved contemporaneously and, potentially, even cooperatively (Kaddour and Sahai 2014).

In this issue, three main themes are highlighted. First, the critical importance of using geochemically relevant environmental conditions plausible on early Earth for designing experiments that model the emergence and early evolution of life (Schoonen and Smirnov 2016 this issue). Second, the potential role that minerals, dissolved inorganic ions, and ion-clusters (acting as catalysts or as reactants) play in the prebiotic synthesis of the molecular building blocks of life.

This complex process of going from inorganic molecules to protocells will be presented in stages. The reactions of inorganic molecules to form simple organic compounds (such as amino acids, nucleotides, sugars, single chain fatty acids, and small molecules used in metabolism) is covered in Dalai et al. (2016 this issue); Maurel and Leclerc (2016 this issue) and Belmonte and Mansy (2016 this issue) consider the next step, which involves the formation of polymers and complexes of nucleotides and peptides; and Kee and Monnard (2016 this issue) provide a perspective on the importance of encapsulation by a lipid membrane to form a protocell. Third, the need for new ways of thinking about the origin of life problem, possibly by considering that genetic and metabolic molecules evolved cooperatively and synergistically.

In general, addressing these three broad themes is essential to bridging the considerable gap that currently exists in origin of life studies between biochemists/organic chemists on the one hand and geochemists/mineralogists on the other.

GEOCHEMICAL EVOLUTION OF AQUEOUS SOLUTIONS ON EARLY EARTH

Life has been found in almost every environmental niche on Earth. Therefore, is it possible that life could have flourished under early Earth environmental conditions as well. What were the potential aqueous solution compositions and temperatures on early Earth? The weathering of different rock types under Hadean/Archaean atmospheric compositions and the variety of ocean vent chemistries would have controlled the types of aqueous solution chemistries and the suite of secondary minerals that formed in the geological settings of the time. Particular solution chemistries and species of minerals present would have provided different environmental niches for the origin and sustainability of life. Similar conceptual approaches can be envisioned for environments on Mars and other rocky planets. When discussing the origin of life in terrestrial environments, most studies focus on subaerial and subaqueous environments; but subsurface environments and the interface between the two is often not considered. For example, the interface between the open and closed carbonate systems, provided by the hydrologic water

**Box 1** TEN KEY ARGUMENTS FOR THE RNA WORLD HYPOTHESIS.

1. RNA can carry genetic information (e.g. RNA viruses)
2. RNA is a single-stranded, flexible molecule that can adopt tertiary structures
3. RNA is less stable than DNA (therefore, through the evolution rationale, DNA should have come later)
4. Thymine, a nucleobase of DNA, is a methylated uracil, a nucleobase of RNA (methylation is often considered a reaction for preserving biomolecules)
5. An RNA primer is essential for DNA–DNA replication
6. Natural reverse transcriptase is an enzyme that copies RNA into DNA
7. RNA is deeply implicated in peptide bond synthesis (e.g. mRNA, tRNA, rRNA)
8. RNA is deeply implicated in gene regulation (e.g. self-splicing RNA, riboswitches, siRNA)
9. A repertoire of biochemical functions can be achieved by RNA (e.g. aminoacylation, RNA cleavage, RNA ligation).
10. Ribozymes have been discovered to be widespread in all domains of life.

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**FIGURE 2** (A) Metabolism comprises both anabolism (making molecules) and catabolism (breaking up molecules). ADP (adenosine diphosphate); ATP (adenosine triphosphate). Used with permission of © Pearson Education, Inc. from Tortora et al. (2016) Microbiology: An Introduction, 12th Edition, p 110, Fig. 5.1.

(B) Five main molecular building blocks of life. (1) cytidine monophosphate; (2) guanosine monophosphate; (3) amino acid with side chain -R; (4) palmitic acid, a single chain fatty acid (single chain amphiphiles have been proposed to be precursors to phospholipids which form the membranes of modern cells); (5) palmitoyl-oleoylphosphatidy/chole, a phospholipid.
table, is such an environment across which a chemical gradient can be maintained. Schoonen and Smirnov (2016 this issue) address these themes using equilibrium thermodynamics speciation calculations to determine aqueous solution compositions and secondary mineral assemblages under a range of environmental conditions and rock types on early Earth.

**PREBIOTIC SOURCES OF SIMPLE ORGANIC MOLECULES**

Organic compounds had to be present before life began. Simple compounds such as N₂, CO₂, HCN, SO₂, and H₂S must have been polymerized into larger compounds with complex structures and functionality, eventually leading to their self-assembly into a protocell. What were the sources of the starting organic compounds that ultimately yielded protocells, and how could they have accumulated on early Earth? The total inventory of organics would have included both exogenous sources (cosmic dust, comets, meteorites) and endogenous sources. On Earth, organics would have been formed in the atmosphere, in solution, and at the mineral–water interface in subaerial, subaqueous, and subsurface environments.

A fascinating feature of life is its homochiral nature, and homochirality [“handedness” of molecules: laevorotatory, or L, for left-handed symmetry; dextrorotatory, or D, for right-handed symmetry] has often been assumed to be a biosignature. However, amino acids from carbonaceous chondrite meteorites also show an enrichment of L- over D-isomers, even for those amino-acids not utilized by biology. These results suggest that chiral selection may have occurred before life originated and may not be a biosignature. So, by what processes could homochirality have arisen? Dalai et al. (2016 this issue) provide an overview of the natural prebiotic sources of organics, the results of experiments that attempt to simulate exogenous and endogenous organic synthesis, and the potential mechanisms for chiral selection.

**RNA, PEPTIDES, AND MINERALS**

As mentioned above, DNA is considered to be too complex to have been synthesized abiotically, while RNA has proven to be a versatile alternative biomolecule that, since its structural elucidation, has kept on surprising us. Indeed, RNA has characteristics similar to DNA as a genetic molecule. Furthermore, many vital cellular functions, previously thought to be exclusive to proteins, have been found to be achieved by specific types of RNA. For example, ribozymes are small RNA motifs that have catalytic activity; riboswitches are regulatory segments of messenger RNA (mRNA). These discoveries, together with several additional arguments, support the current idea that life may have originated by self-replicating RNA molecules, which preceded the DNA/RNA/protein world (Box 1).

Could minerals have shaped the ancient RNA world? Clays can catalyze the polymerization of nucleotides and amino acids to form RNA oligomers and peptides, respectively. Beyond the RNA world hypothesis, metal sulfides may have played roles such as catalyzing peptide synthesis. Peptide–RNA complexes may have been endowed with special functions, ones that either RNA alone or peptide alone could not have achieved. Maurel and Leclerc (2016 this issue) address the potential role of minerals in the synthesis and self-assembly of RNA and RNA–peptides. These authors also explore the fascinating idea that viroids—short segments of RNA found in nature as plant parasites—are a sort of molecular fossil from a former “RNA world.”

**METAL SULFIDES AND METALLOPEPTIDES IN PROTOMETABOLISM**

Given the very large number of prebiotic organic molecules, as well as the complexes they potentially made with metals and other organics that might have existed on early Earth, it is theoretically possible that a huge number of reaction networks could have formed. However, Morowitz and coworkers (e.g. Smith and Morowitz 2010) have recognized that modern metabolisms utilize a very small number (~300) of metabolites compared to the vast number of molecules possibly formed from random chemical combinations. Morowitz and coworkers have argued that this “sparse metabolism” reflects selection based on chemical kinetics. In this scenario, specific reactions are selected by small-molecule organocatalysts. These are distinct from transition metal–organic complex catalysts (discussed below). Some small-molecule organocatalysts are even capable of enantioselectivity [choosing between L and D molecular forms]. The reductive citric acid cycle was proposed as a core metabolism that could produce all the building blocks of life. A different perspective was offered by Virgo and Ikegami (2013) based on the results of computer algorithms of abstract model reactions. These authors showed that intersecting, branching, autocatalytic reaction networks form easily without the need for an initial catalytic molecule to be present. Virgo and Ikegami (2013) argued that the earliest metabolisms were “maximal” and that the reductive citric acid cycle, or other minimal metabolic systems, were derived by later evolution. Whereas many hypothetical schemes modeling metabolic reactions exist in the literature, experiments that simulate metabolic reactions or that couple more than one reaction into a cycle is a major challenge.

In modern metabolic pathways, the active sites of many enzymes contain organometallic complexes, in particular, iron–sulfur clusters. The metal–sulfur clusters of enzymes are structurally similar to greigite and other sulfide minerals. This similarity in structure has led to suggestions that metabolic pathways developed in the presence of sulfide minerals. The “iron–sulfur world” hypothesis and the acetyl-CoA chemiosmotic potential model propose that metabolic networks developed before RNA. Belmonte and Mamsy (2016 this issue) broaden this concept to explore other metals and peptides in a scenario where various simple catalytic metallopeptide complexes may have predated more complex enzymes. By analyzing modern bacteria, these authors identified that specific peptide sequences that contain aspartic acid (aspartate) are important for binding Mg²⁺, Mn²⁺, Zn²⁺, and Ni²⁺, whereas sequences that contain cysteine (an amino acid that has a –SH side chain) are important for binding Fe²⁺. The identification of such peptide sequences could provide a guiding light for designing experiments to simulate ancient metabolisms.

**TOWARD A PROTOCELL: ASSEMBLING THE COMPONENTS OF LIFE**

A membrane boundary composed of amphiphilic compounds [ones that possess both hydrophilic and lipophilic properties] and that is assembled into a vesicle compartment is one of the key elements of life (Figs. 1 and 2). The membrane defines the cell as a distinct entity, separate from the environment, and plays a critical role in the production and maintenance of the chemiosmotic potential (charge and pH gradients) required to drive cellular reactions. Modern cell membranes consist primarily of phospholipid molecules, but their synthesis is enzymatically catalyzed. So, what was the chemical composition of the protocell boundary? The walls of microscopic pores between mineral grains in rocks or channels in zeolites
have been proposed by some workers to act as the earliest “membranes” but these ideas haven’t been thoroughly tested experimentally. On the other hand, single-chain amphiphilic molecules have been identified in meteorites and synthesized nonenzymatically, so lipid membranes may have self-assembled in the earliest protocols. What are the physicochemical conditions for the stability of either the pore-wall membranes or amphiphile membranes? The term “stability” here refers to membrane formation and its ability to sustain integrity over some relevant period of time (i.e. membranes needed the right balance of leakiness versus impermeability to allow molecules and electrons to pass across the membrane to generate electrochemical gradients long enough for the relevant metabolic reactions). How would the organics encapsulated within either of these types of membranes have evolved into a complex network to give birth to a sustainable protocell? Could minerals have played a role in all these processes? Kee and Monnard (2016 this issue) address these important questions and discuss the critical need of a protocell boundary to form self-sustaining, replicating, cell-like entities.

SYNERGISM AND MUTUALISM IN THE EMERGENCE OF LIFE

Significant advances have been made over the past decade in our understanding of the simple organic molecule–mineral interactions that yield more complex organic molecules (Cleaves et al. 2012). We presently also benefit from a much-improved knowledge of early Earth environments (Sleep et al. 2011). In addition, experiments have shown that specific minerals can play some key roles as “prebiotic enzymes.” For example, montmorillonite can catalyze the formation of RNA polymers (Ferris 2005) and of peptides (Rode 1999); sphalerite (ZnS) can photocatalyze parts of the reverse citric acid cycle (Zhang and Martin 2006). Minerals can also enhance the initial assembly rate of amphiphiles into vesicles, ultimately leading to the formation of a protocell membrane (Hanczyc et al. 2003). The latter finding was recently confirmed in our laboratory and we further showed that the rate-enhancement is dependent on the surface charge of the mineral. Additionally, we found that vesicles were not disrupted by high particle loadings and they can even adsorb intact on a mineral surface (Fig. 3; Sahai et al. 2017). Together, these results suggest that minerals should be given more attention in the context of the emergence of life.

That being said, a careful analysis of the literature raises interesting questions. For instance, in the pioneering work of Prof. James P. Ferris (Rensselaer Polytechnic, New York, USA) and colleagues, only chemically pre-activated monomers were used to react and polymerize into RNA oligomers; even though it is unlikely that such activated nucleotides can be spontaneously generated in prebiotically relevant conditions. Moreover, the yields of these RNA oligomers are rather low, barely enough to be characterized by the most sensitive techniques. Recent efforts have showed that nonenzymatic RNA polymerization can be alternatively achieved by using nonactivated monomers (Spöner et al. 2016). Taken together, these findings have led to the idea that synergism between different catalysts might come into play to enhance the nonenzymatic RNA polymerization of nonactivated nucleotides (Fig. 4) (Kaddour and Sahai 2014).

MULTICOMPONENT SYSTEMS AND PREDICTIVE RELATIONSHIPS

It is obvious that nature cannot be minimized to a single-component system in a clean test tube. The results of experiments aimed at understanding the prebiotic synthesis and self-assembly of organics would be significantly more relevant in a multicomponent system. Thus, in an ideal experiment, the molecular building blocks of life should be present along with the minerals and dissolved inorganic ions known to exist in specific geological environments on early Earth. Recent attempts towards a one-pot reaction approach have been successful in the synthesis of lipid monomers, amino acids, and nucleotides (Patel et al. 2015). It would also be a remarkable achievement to expand this approach to the emergence of a sustainable protocell. In this regard, researchers have been synthesizing chemical systems where nonenzymatic RNA polymerization occurs in model protocells (Szostak 2012). With these significant advances, evaluating the potential complicating effects of inorganic ions, pH, and temperature in a multicomponent system should now be considered as next steps towards integrating chemistry and biology with geology.

Exploring a wider range of environmental conditions are hampered by difficulties in experimental design and...
analytical sensitivity. For example, it can be difficult to analyze reactants and products within model protocell membranes (amphiphile vesicles). This is especially the case in experiments involving mineral suspensions, which tend to aggregate and settle, thereby minimizing interactions with the other components. Furthermore, most reactions are done in batch systems, and geological processes such as wind, rain, and wave action are rarely ever simulated in the experimental design. High-throughput analytical methods are sorely needed to test the huge combinatorial search space that must be explored in more faithfully simulate geological conditions. Careful examination of a wide range of conditions will ultimately allow the development of predictive relationships. For example, the initial rate of vesicle self-assembly at mineral surfaces has been found to be dependent on the isoelectric point (surface-charge) of the mineral and on the degree of aggregation of mineral nanoparticles (Sahai et al. 2017). Such relationships may allow us to predict the plausibility of protocell membrane self-assembly both terrestrially and extraterrestrially.

CLOSING REMARKS

The ultimate challenge in the origin of life field is to understand how complex, functional organic molecules were produced from simple inorganic molecules and how such molecules self-assembled into self-sustaining, self-replicating cell-like entities under plausible environmental conditions on early Earth. This means understanding the transition from geochemistry to biogeochemistry. Traces of environmental conditions on early Earth are preserved in the isotope and element signatures of rare Hadean- and Eoarchean-age minerals and rocks, but the molecular pathways from simple inorganic compounds to cells cannot be retracted with complete fidelity. Nevertheless, chemical pathways that rigorously satisfy scientific rationale can be reasonably inferred based on the results of models and experiments that are hardly ever simulated in the experimental design. We hope that the present issue of Elements illuminates the state-of-the-art in the field, indicates challenging areas for future inquiry, and inspires scientists to adopt interdisciplinary approaches towards uncovering one of the most profound questions in philosophy and science.

ACKNOWLEDGMENTS

The authors are grateful to Dr. Min Gao, Liquid Crystal Institute, Kent State University for the cryo-TEM images and to Dr. Weilong Zhao for coloring the banner image. N. S. and H. K. would like to thank the authors of the invited articles in this issue as well as the reviewers of the manuscripts for their invaluable contributions to this issue. Patricia Dove and Jodi Rosso are thanked for their editorial insights. Nita Sahai gratefully acknowledges financial support from the following grants: NSF EAR Geobiology and Low-Temperature Geochemistry #1251479; the Simons Collaboration on the Origins of Life (SCoL) award #290359 from the Simons Foundation, NY; and “startup” funds from the University of Akron.

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Staging Life in an Early Warm ‘Seltzer’ Ocean

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INTRODUCTION

One of the most challenging geological problems is the composition of the atmosphere, ocean, and solid Earth during the period preceding the origin of life. Lacking a rock record reaching back that far in time, we are left to infer the conditions on the prebiotic Earth by applying what can be gleaned from comparative planetary science, zircons that formed as early as 4.4 Ga, and theoretical approaches. The conditions preceding the origin of life constrain how the proverbial “building blocks of life” might have formed via abiotic reactions. Within this context, there has been interest in evaluating possible mineral-assisted or mineral-catalyzed pathways to make amino acids, to form and polymerize nucleotides, and to form other relevant organic compounds as an alternative to delivering organic molecules by meteorites and asteroids (Schoonen et al. 2004; Cleaves et al. 2012). Formed as weathering products, clays may have provided a mechanism to concentrate, stabilize, and protect biomolecules via intralayer sorption (Lyon et al. 2010). It is important to note that mineral-based reactions may also decompose life’s building blocks—a consideration that has attracted far less attention than their formation (Schoonen et al. 2004).

Before proposing a role for minerals in forming, transforming, concentrating, stabilizing, protecting, or decomposing the building blocks of life, it is necessary to evaluate what type of minerals could have been present on the prebiotic Earth. There may have been a range of environments (e.g., various types of submarine hydrothermal vents, surficial rock exposures, and/or hot springs) during this early period, referred to as the Hadean Eon. At first glance, the problem seems intractable and the parameter space too broad to develop meaningful constraints. However, the analyses of zircons formed during the Hadean, the development of advanced models of the atmosphere during the first billion years after the formation of Earth, and experimental work now provide useful insights and much tighter constraints on the origin of life than hypotheses suggested a few decades ago. This article provides an assessment of the factors that determine the composition of secondary mineral assemblages and associated fluids that may have primed early Earth for the emergence of life, as well as an assessment of the environments most likely to lead to formation of reduced carbon and nitrogen compounds.

CONDITIONS ON THE EARLY EARTH

Earth was too hot for about 2 million years after the Moon-forming event (which took place at ~4.5 Ga) for liquid water to be stable. Once sufficiently cooled, Earth settled into a period of perhaps as long as 20 My to 100 My in which liquid water was present along with a CO2-dominated atmosphere (Zahnle 2006). The partial pressure of CO2 in the atmosphere was initially perhaps as high as 100 atm, subsequently decreasing to levels below 1 atm (Sleep et al. 2001; Zahnle 2006). The rate of CO2 loss would have been governed by the kinetics of water–rock interaction with dissolved CO2 as a reactant.

Elevated CO2 during this period (the early to mid Hadean) may have created favorable conditions for the origin of life. Carbon dioxide is a greenhouse gas and would have contributed to high ocean temperatures, perhaps exceeding 100°C, with atmospheric pressure well in excess of 1 atm, which would suppress boiling. Water–rock reactions would have consumed CO2 over a period estimated to be about 100 My. During the last 20 My of this transition, with 5–25 atm of CO2 remaining, the temperature of the ocean would have been between 60°C and 110°C (Sleep et al. 2001; Zahnle 2006). In essence, this early ocean was a warm carbonated water that reacted with the crust and in
Apart from the presence of elevated CO₂ in the atmosphere, organic compounds that set the stage for the origin of life. A period of time may have produced a significant amount of concentrations of dissolved CO₂ in oceans, this relatively short period of time may have produced a significant amount of organic compounds that set the stage for the origin of life.

Apart from the presence of elevated CO₂ in the atmosphere, a major control on the outcome of any water–rock process is the chemical and mineralogical composition of the rocks involved. There is no Hadean rock record that would allow one to infer what type of rocks might have made up the Earth’s primitive crust. The only relics of the Hadean are zircons that formed 4.4–3.5 Ga (Valley 2006). Zircons are common primary accessory minerals in granitoid rocks and can withstand physical and chemical weathering, allowing them to be deposited and redeposited for billions of years. In essence, zircons are small windows into Hadean conditions. Those found in the Jack Hills of Western Australia suggest that liquid water may have been present on Earth as early as 4.2 Ga. While the zircons are invaluable in helping to constrain Hadean conditions, they are likely derived from small vestiges of rocks formed by partial melting of a Hadean crust that was largely ultramafic to mafic in composition (Taylor and McLennan 2009). Ultramafic and mafic igneous rocks are characterized by their high content of magnesium and iron-rich minerals and relatively low silica content (ultramafic rocks contain less silica than mafic rocks).

On the basis of a higher heat flow during the Hadean, it is a popular notion that most of the earliest crust was komatiitic in composition, komatiites being an igneous rock high in Mg and dominated by olivine (Nishet and Sleep 2001; Meunier et al. 2010). Others have argued that the Hadean crust had a composition similar to mid-ocean ridge basalts (MORB) or tholeiitic basalts (Taylor and McLennan 2009). Peridotite, a mantle material found in ridge basalts (MORB) or tholeiitic basalts (Taylor and McLennan 2009). Peridotite, a mantle material found in modern settings (e.g. the mid-Atlantic off-axis submarine hydrothermal system known as Lost City), may also have been exposed during the Hadean. Rather than choosing one particular rock type, it is prudent to consider all three ultramafic to mafic compositions, as well as a composition that accounts for the small vestiges of continent crust that must have been present to account for the Hadean zircons. The most realistic rock type to represent early vestiges of the continental crust is one of tonalitic composition, with major Na-rich plagioclase and minor quartz and orthoclase (Nutman 2006).

Having settled on a range of rocks to consider and assuming that there was liquid water from 4.2 Ga on, the next step is to decide whether water–rock reactions proceeded under conditions that favor rapid exchange with the atmosphere (hereafter referred to as “open systems”) or conditions that inhibit such exchange (hereafter referred to as “closed systems”). Surficial or shallow environments are expected to have sufficiently rapid gas–water exchange that equilibrium between the fluid and the atmosphere is retained throughout the water–rock interaction. By contrast, in deep environments or in rock-dominated environments (e.g. fluids in cracks) (Fig. 1), the water infiltrating into the rock is in equilibrium with the atmosphere; upon deeper infiltration, however, the fluid evolves out of equilibrium with the atmosphere. In a modern analog, the difference is analogous to modeling reactions in a littoral zone versus reactions in a deep aquifer.

**Figure 1** provides a schematic representation of the settings explored and the variables that must be evaluated when investigating prebiotic early Earth conditions. The purpose of such geochemical calculations is to illustrate the conditions needed to form secondary minerals (clays, zeolites and sulfides) that act as potential catalysts in the synthesis of organic molecules. Besides these minerals, there is an emerging body of literature that shows that metallic alloys form as part of the alteration of ultramafic and mafic rocks (Filippidis 1985; Smirnov et al. 2008). Although small in abundance, these metallic alloys might have played a critical role in the conversion of CO₂ and N₂ on the early Earth into reactive compounds that could be important to the formation of the building blocks of life. The geochemical calculations also constrain the composition of the resulting fluids (Schoonen et al. 2004; Cleaves et al. 2012).

**Figure 1** *(Left)* Schematic of the geological settings and interactions that need to be evaluated in understanding conditions in, above, and below a carbonated ocean on the prebiotic early Earth. Open system is in equilibrium with the atmosphere; closed system is out of equilibrium with the atmosphere. Note gas exchanges between ocean and atmosphere.

**Figure 1** *(Right)* The different variables that need to be evaluated when geochemically modeling early Earth carbonated ocean, rock, and atmospheric interactions. The inputs are the different rock types, CO₂, and temperature (T); the outputs are the different types of secondary mineral assemblages and fluid compositions.
MODELING WATER–ROCK INTERACTION

Building on the decades-long efforts of by various geochemists—Harold Helgeson (deceased) at University of California—Berkeley (USA); Mark Reed at the University of Oregon (USA); Thomas Wolery at the Lawrence Livermore National Laboratory in California (USA); Everett Shock at Washington University and Arizona State University (both USA); Craig Bethke at University of Illinois (USA)—it is now possible to efficiently conduct computer-based water–rock simulations (Bethke 2008). We stress the importance of conducting an ensemble of model calculations so that a range of conditions, such as different rock, gas and solution compositions, can be explored. This is particularly important because the problem being tackled is poorly constrained. For this article, we expand on earlier work in which we explored the interaction of komatiite and tonalite with water in a CO2-rich atmosphere (Schoonen et al. 2004) using Geochemist’s Workbench ® (Bethke 2008).

The emphasis in these water–rock interaction simulations is on the weathering of major rock-forming minerals. The weathering process governs the composition of the water it reacts with and dictates the suite of secondary minerals formed. It should be kept in mind, however, that these calculations do not take into account any kinetic effects that may lead to nonequilibrium assemblages. The potential problem of nonequilibrium assemblages is commonly addressed in thermodynamic calculations by suppressing the formation of minerals that are known not to form during weathering processes. An example is the formation of quartz. Although quartz is predicted to form on the basis of its thermodynamic stability, other forms of silica, such as chalcedony, are often formed instead when basaltic rocks weather.

The key results of several representative simulations are presented in the form of “heat maps,” a visualization tool widely used in biology to display data. Figure 2 shows the results of simulations with four rock types at constant $P_{\text{CO}_2}$ (5 atm) and $T$ (75°C). For each simulation, the secondary mineral composition after 50 g of rock reacted with a liter of water was converted to relative abundances in terms of weight percentage of major classes of secondary minerals. The molar ratio of Ca + Mg over Na + K (recast as a logarithm) and pH are also shown in Figure 2. In Figure 3, the influence of $P_{\text{CO}_2}$ on reactions with one rock type, MORB, is explored, while in Figure 4 the temperature dependence on reactions with MORB is explored at a constant $P_{\text{CO}_2}$ (2 atm).

For the simulations presented here, the reduction of CO2 to methane and other reduced forms of carbon is blocked. This is a reasonable first-order approximation because these reactions do not go forward without a catalyst and are slow even in the presence of a suitable catalyst at the temperatures considered here. Even if the atmosphere contained substantial amounts of molecular hydrogen—perhaps episodically due to meteorite impacts (Zahnle et al. 2010)—CO2 is unlikely to be reduced by hydrogen in open systems without a suitable catalyst and higher temperatures. In closed ultramafic or mafic systems, CO2 reduction to methane is likely (explained below). However, the amount of CO2 in closed systems is limited, and its reduction to methane formation will not materially change the secondary mineral assembly. Hence, as a first approximation, we consider CO2 to be inert, even in closed systems.

The results of the calculations in which the water–rock interaction takes place at 75°C while maintaining equilibrium with CO2 at 5 atm (i.e. open system) show that none of the secondary mineral assemblages contain zeolites or clays. The secondary mineral assemblages are instead dominated by a combination of SiO2 and carbonates. The formation of carbonates effectively locks up most of the divalent cations; only iron is present as a metal sulfide. These modeling results are consistent with experimental work on water–basalt interaction at 10 atm CO2 (Gysi and Stefansson 2012). The secondary mineral assemblage for all starting materials changes considerably if the initial water that had been equilibrated with the CO2-rich atmosphere is not kept in equilibrium with the atmosphere during reaction with the rock. These closed conditions lead to secondary mineral assemblages that have far less carbonates, are essentially devoid of SiO2 and sulfides, and contain abundant clays and/or zeolites. The composition of the resulting fluid also changes depending on whether the system maintains equilibrium with the atmosphere or not. Equilibrium with CO2 throughout the water–rock interaction buffers the pH to values slightly below neutral, while in closed systems the resulting solution is alkaline. Fluids in closed systems tend to be strongly enriched in monovalent cations compared to divalent cations when compared to open systems. In fact, the open system simulation with peridotite suggests that the fluid would be enriched in divalent ions compared to monovalent ions. Solutions dominated by divalent ions may have destabilized primitive membrane vesicles (Monnard et al. 2002) and impeded a critical step toward cellular life (Deamer et al. 2002).
The level of CO₂ concentration in the atmosphere is an important factor in determining the composition of the secondary mineral assemblage in addition to the composition of the crust. As CO₂ falls from 5 atm to 0.1 atm in open systems (Fig. 3), the secondary mineral assemblage begins to include zeolite at the expense of SiO₂ and clays, while the amount of carbonates is also reduced. In closed systems, changes in CO₂ are not as consequential.

A decrease in temperature from 75 °C to 0 °C induces some modest changes in the secondary mineral assemblage. The amount of carbonate in closed systems increases with a decrease in temperature. Perhaps the most important change as temperature decreases in open systems is the switch from fluids that are dominated by Na + K to fluids that are dominated by Ca + Mg (Fig. 4). Given that waters dominated by divalent cations destabilize membrane vesicles (Monnard et al. 2002), the warm conditions during this early stage of Earth history would have been more favorable for the assembly of membrane vesicles.

The major implication illustrated by Figures 2–4 is that water–rock interactions during the warm seltzer stage of the early Earth would have produced a range of fluids with contrasting compositions. The ocean waters would have been slightly acidic as a result of the high carbon dioxide content of the atmosphere, while fluids that infiltrated into ultramafic or mafic rocks would have been alkaline (not withstanding some compositional differences). Mixing of these types of fluids would have set up steep chemical gradients and chemical disequilibrium. Russell and coworkers (Russell et al. 2010) have argued that life arose in these mixing zones as a result of the contrasting chemical composition and the resulting chemical disequilibrium.

**FORMATION OF METALLIC CATALYSTS**

The modeling approach illustrated above allows one to constrain the overall fluid conditions and major secondary mineral assemblages from rock weathering; however, this approach does not address the fate of minor and trace elements incorporated into rock-forming minerals. Some of these minor and trace elements, such as the transition metals, may have played a key role in setting the stage for life. A case in point is the fate of nickel incorporated in olivine, a major mineral component in ultramafic to mafic rocks (e.g. peridotites and basalts). These rocks can contain up to 0.5 wt. % NiO substituted in the structures of olivines and other rock-forming minerals. The forsterite–fayalite–liibenburgite solid solution—commonly referred to as olivine (Mg,Fe,Ni)Si₂O₄—is particularly reactive because the SiO₄ tetrahedra in its structure are not polymerized.

Molecular hydrogen and heat are generated along with metallic secondary minerals when olivine reacts with water, a process referred to as serpentinization (Fig. 5). The molecular hydrogen formation is driven by a reaction between metallic iron and water. Metallic iron itself is a secondary mineral that forms when divalent (ferrous) iron is released from the olivine. The release of heat increases the buoyancy of the resulting solution and triggers an upward movement. The buoyancy can drive solutions out of the rock and into the overlying waters, establishing a circulation pattern independent of tectonic setting. Any nickel contained in the olivine is essentially caught up in this serpentinization process and forms native nickel metal or nickel–iron alloys. The formation of metallic Ni (Ni⁰) and Ni–Fe alloys, especially awaruite (Ni₃Fe to Ni₂Fe), has been well documented both in natural (modern and ancient) and in experimentally simulated serpentinization systems (Filippidis 1985; Mevel 2003). Serpentinization of olivine is not unique as a source of mineral-based hydrogen production: such production has been documented for a number of ferrous-iron-containing minerals, including spinel (Mayhew et al. 2013). In the context of stage X life, metallic nickel and iron, as well as their alloys, are of particular interest because they facilitate the reduction and hydrogenation reactions of both CO₂ and N₂ (Horita and Berndt 1999; Smirnov et al. 2008).

The fate of nickel contained in olivine is further influenced by the availability of hydrogen sulfide. In a system free of hydrogen sulfide, Ni⁰ and awaruite are stable under alkaline to mildly acidic pH conditions, even at temperatures as high as 100°C. In the presence of hydrogen sulfide, nickel–iron alloys are only stable at alkaline pH, and they are replaced by sulfides of varying Ni:Fe:S ratios at low pH. While the presence of sulfur decreases abundances of pure Fe–Ni alloys/metals, sulfides such as heazlewoodite (Ni₃S₂), pentlandite [(Fe,Ni)₉S₈], pyrite (FeS₂) or mackinawite (FeS) can also facilitate the formation of prebiotically useful reduced carbon and nitrogen compounds (Schoonen and Xu 2001; Cody et al. 2004; Singrey et al. 2012; Gordon et al. 2013).

Minerals can participate in the reduction reactions mentioned above either as catalysts or as reactants (Schoonen et al. 1998). A catalyst, by definition, only facili-
tates reactions without net decrease in its mass or reactive surface area. Therefore, even accessory amounts of Ni–Fe metals and alloys, considered negligible on a planetary scale, could have provided globally important amounts of reaction products, such as ammonia and reduced carbon compounds (Smirnov et al. 2008). Conversely, if Ni–Fe metals and alloys participated as reactants, the yields of prebiotically useful products would be proportional to their spatial and temporal availability, and there should then be a strong correlation between prebiotic products and the rates of reactant formation (e.g. via serpentinization) and destruction (e.g. consumed in reactions). While the complexity and local variability in conditions make it challenging to address which of these modes would have been more prevalent on the early Earth, both the metal catalyst and reactant mechanisms have potential for introducing locally, or even globally, significant concentrations of prebiotically relevant compounds.

Overall, the warm seltzer ocean phase of Earth’s history may have been short-lived, but it could have been crucial in setting the stage for the origin of life, aided by a combination of open and closed systems, each with their own suite of major and minor secondary minerals and fluids. During this stage, the Earth may have been endowed with an assortment of organic molecules, primitive vesicles, and perhaps the first metabolic systems thriving on steep chemical gradients at the interfaces between open and closed systems. The reactions that drive the formation of secondary minerals in closed systems and in mafic rock systems still operate today, but the amount of CO₂ dissolved in the infiltrating solutions is significantly lower. Ironically, the closest analogs to the deep past are provided by modern attempts to curb the current buildup of atmospheric CO₂ by injecting this greenhouse gas into basalts, where some of it dissolves into water and reacts (Gysi and Stefánsson 2012).

**ACKNOWLEDGMENTS**

NASA’s Exobiology and Astrobiology program provided more than a decade of funding to Schoonen’s group at Stony Brook University to investigate the role of minerals, particularly sulfides, in shaping the conditions during the Hadean through theoretical and experimental approaches. Many students, including Alexander Smirnov, contributed to this research effort. Collaborations, discussions, and student exchanges with Scott McLennan (Stony Brook University), Daniel Strongin (Temple University), John Peters (University of Montana), Hiroshi Ohmoto and Jim Kasting (Penn State), Tom McCollum (University of Colorado), George Cody (Carnegie), and Nita Sahai (Akron University) helped shape our work and thinking on this topic. Alexander Smirnov would like to thank Francis McCubbin (Johnson Space Center) for providing ongoing petrological perspectives into his work. Schoonen is particularly thankful for the mentorship by Hu Barnes (Penn State) and the interaction with the late Dick Holland, who instilled an interest in the geochemistry of the early Earth. Jan Schoonen, Scott McLennan, two reviewers and Element’s editors are thanked for reviewing an earlier draft of the paper. Work on this paper was supported in part by the RIS³E node of the NASA Solar System Exploration Research Virtual Institute (SSERVI). This is SSERVI publication SERVI-2016-032. Brookhaven National Laboratory is supported by the Department of Energy, Office of Science.
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The onset of life on Earth was preceded by prebiotic chemistry in which complex organic molecules were formed from simpler ones in the presence of energy sources. These prebiotic organics were either synthesized on Earth itself (endogenously) or synthesized extraterrestrially (exogenously) and then delivered to Earth. Organics have been detected in space and have been successfully synthesized under experimental conditions simulating both extraterrestrial environments and early Earth environments. Homochirality and enantiomeric enrichment of organic molecules, which were once considered to be biosignatures, can, in fact, be achieved abiotically. It is important to determine conditions that allow the formation of prebiotic organics and those that preserve them against degradation.

Keywords: prebiotic, hydrothermal, meteorites, cosmic dust, organics, chirality, enantiomeric excess

INTRODUCTION

Life was not formed in one step. Rather, life was formed as a sequence of physico-chemical processes that caused prebiotic chemistry to transition into biology with the emergence of the first cells. Organic monomers may have first formed in a warm “primordial soup,” then polymerized into functional molecules and eventually evolved to more complex life. Important steps in the prebiotic chemical evolution on Earth likely took place during the Hadean and early Archean Eons lasting from the time of Earth’s formation to the end of the late heavy bombardment at ~3.8 Ga. Abiogenic synthesis of organic compounds must have occurred in the atmosphere, in aqueous solutions, and at the mineral–water interface in multiple geological settings (Fig. 1).

It was once believed that organic molecules were synthesized only on Earth. However, spectroscopic investigations of the interstellar medium and the direct analysis of cosmic dust particles, meteorites, asteroids, and comets have revealed that a rich variety of organic compounds exists in space. These organics span a diverse range: from simple molecules, such as hydrogen cyanide (HCN), up to complex macromolecules. These various extraterrestrial sources could have contributed to the total inventory of organics on early Earth, leading to the origin of life (Anders 1989). It has been estimated that ~1,000–10,000 tons of organic matter was delivered annually to Earth 4.2 billion years ago by comets alone. When Carl Sagan famously said in the US television series Cosmos: A Personal Voyage, “We are made of star stuff,” he may have meant not only that it is the pure elements that are made in stars but also that the very organic molecules that are required by life are also produced in space.

Unfortunately, there is practically no geological record of this early chemistry. Thus, it is of special importance to analyze compounds extracted from exogenous sources and also those compounds synthesized in laboratory experiments that attempt to simulate natural terrestrial and extraterrestrial environments. However, experimental conditions must reflect realistic early geological conditions (Sahai et al. 2016 this issue).

In this article, we present a brief discussion on the possible sources of organics on the primordial Earth. Readers are also guided to excellent reviews on the complex organic compounds detected in exogenous sources and synthesized in experiments that simulate endogenous processes (McCollum 2013; Kwok 2016; Sandford et al. 2016).

TERRESTRIAL PREBIOTIC ORGANIC SOURCES

Atmospheric Synthesis

More than seven decades ago, Urey and Miller synthesized organic molecules in an experiment designed to simulate lightning in what had been presumed to be a reducing atmosphere on early Earth. An electrical discharge was passed through a mixture of CH4, H2, and NH3 gases. The resulting organic products detected included glycine, alanine, aspartic acid, and α-aminonobutyric acid (Table 1). More recently, other amino acids, urea, carboxylic acids, amines, and other compounds have also been detected (Cleaves et al. 2008). In experiments where H2S was used along with the other reducing gases, sulfur-containing amino acids and amines were formed (Bada 2013). However, our present understanding is that the Earth’s early atmosphere was not highly reducing but, rather, was redox neutral, with CO2, N2, and H2O as the dominant gases. Under redox-neutral conditions, amino acids can still be generated in the presence of antioxidants (such as ascorbic acid or ferrous iron) (Cleaves et al. 2008) (Table 1).

In the experiments mentioned above, as well as in some experiments discussed below, amino acid synthesis likely follows the Strecker pathway. In this process, aminonitrile
[H$_2$NCH(R)CN] is first formed by a condensation reaction of cyanide, aldehydes, or ketone with ammonium salt, and is then converted to amino acids by hydrolysis and oxidation (McCollum 2013). Unlike amino acids, the synthesis of purines and pyrimidines has not been achieved in experiments simulating atmospheric synthesis.

**Earth Surface Environments**

The synthesis of organic compounds from the simple starting compounds of NH$_3$, H$_2$O, CO$_2$, and HCN typically involves condensation, addition, hydrolysis, and/or redox reactions. Condensation reactions best proceed in the absence of aqueous solutions. Moreover, many of the synthetic reactions require high concentrations of the reactants. Intertidal pools, inland evaporitic playas, flanks of volcanic crater lakes, sedimentary pores in the unsaturated zone of groundwater, and altiplano desert soils offer a range of geological environments that undergo periodic wetting and drying cycles, freeze–thaw cycles, and sublimation, all of which have the potential to facilitate condensation reactions and concentrate compounds.

A wide range of biologically relevant organic compounds have been synthesized by heating NH$_3$, H$_2$O, and HCN in aqueous solutions at temperatures between 30°C to 100°C (Oró 1961). Combining HCN with H$_2$O yields formamide [HC(O)NH$_2$], a molecule that is highly reactive and that can subsequently be reacted to yield most of the precursor compounds required for biologically important molecules, such as amino acids, glycinamides, and even adenine and imidazole. The addition of formaldehyde (CH$_3$O) to the system yields monosaccharides. Using HCN chemistry, nucleotides (i.e. nucleobase + ribose + phosphate), amino acids, and phospholipids can all be synthesized (Sutherland 2016).

Despite these experimental successes in prebiotic synthesis, they are not geochemically realistic. In most cases, high concentrations of reactants are typically required. For example, 1 M phosphate is required for nucleotide synthesis (Sutherland 2016). Oró (1961) used 1–11 M HCN. Amino acids were not detected in studies where more dilute solutions were used (McCollum 2013). Furthermore, although formamide is a versatile compound for prebiotic synthesis, its high reactivity means that it may not survive long enough in natural environments in order to build up to the concentrations used in the experiments. Apart from the problems with high concentrations, in some synthesis reactions, purification and separation steps of the intermediate compounds may be required at different stages of the reaction. The geological environments to accumulate such high reactant concentrations, as well as the correct sequence of physical separation processes, remain to be elucidated.

**Hydrothermal Systems**

High-temperature hydrothermal vents emit fluids at temperatures of ~250–400°C, containing reduced transition metals and high concentrations of dissolved gases CO$_2$ and H$_2$S, all of which results in very acidic pH values of ~2–3. An example is the Rainbow hydrothermal field in the Azores region of the Atlantic Ocean. The vent solutions come in contact with cool, alkaline ocean water, which creates concentration, redox, and thermal gradients that can be exploited for the synthesis of organic compounds and metabolic reactions. Dark-colored metal sulfide minerals and CH$_4$ and H$_2$ are formed at these “black smoker” vents. Interestingly, some iron sulfide minerals, such as greigite, have crystal structures that are similar to the structures of transition metal–sulfide clusters at the active sites of many metabolically related enzymes.

**Figure 1** Five environments for potentially synthesizing prebiotic organic molecules. 1 The atmosphere; 2 Extraterrestrial delivery; 3 and 4 Mineral–water interface and aqueous solutions at Earth’s surface; 5 Hydrothermal vents and subsurface environments. Note that oceans are not shown in the image but would have been present. Modified from Lazcano (2006).

**Table 1** Relative abundances of 14 amino acids compared to glycine synthesized in experiments simulating endogenous synthesis (early Earth’s atmosphere) and identified in natural extraterrestrial sources (carbonaceous chondritic meteorites). The relative abundances reflect the number of moles of each amino acid relative to the number of moles of glycine obtained in each experiment or meteorite. * = < 0.5; ** = 0.5–5; *** = 5–50; and **** = > 50. Values not available given by – sign.

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Simulated Endogenous source</th>
<th>Exogenous source: Meteorites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reducing atmosphere</td>
<td>Redox-neutral atmosphere</td>
</tr>
<tr>
<td>Glycine</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td>Alanine</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td>β-alanine</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>α-amino-n-butyric acid</td>
<td>****</td>
<td></td>
</tr>
<tr>
<td>α-aminoisobutyric acid</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Valine</td>
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</tr>
<tr>
<td>Serine</td>
<td>**</td>
<td>****</td>
</tr>
<tr>
<td>Isovaline</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Norvaline</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>Aspartic acid</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td>Glutamic acid</td>
<td>**</td>
<td>****</td>
</tr>
<tr>
<td>Proline</td>
<td>*</td>
<td>***</td>
</tr>
<tr>
<td>β-amino-n-butyric acid</td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td>β-aminoisobutyric acid</td>
<td>*</td>
<td>**</td>
</tr>
</tbody>
</table>

Adapted from Miller (1987); Zaga et al. (2008); Cleaves et al. (2008)
A fundamentally different kind of oceanic vent system, hosted by ultramafics, gives rise to the so-called “white smokers” (e.g. the Lost City and the Strytan hydrothermal fields of the mid-Atlantic and north of Iceland, respectively). These vent fluids have milder temperatures (60–90°C), alkaline pHs of ~9–11, and precipitate white-colored calcium and magnesium carbonates. The hydrothermal activity in these systems is driven by the chemical reactions between seawater and the mantle peridotite that underlies the oceanic crust. Olivine in peridotite reacts with seawater and dissolved CO₂ to form serpentine, magnetite, and either brucite or magnesite, while releasing dissolved silica and H₂ or CH₄.

Both black and white smokers could provide the ideal environment for supporting the emergence of the earliest metabolisms (methanogenesis, acetogenesis, and methanotrophy) without the need for a preceding RNA world. Amino acid oligomers were detected in experiments simulating black smoker hydrothermal systems (Kawamura et al. 2005). Organics have been detected in both Rainbow and Lost City vent fluids, but the ¹³C isotopic analyses do not preclude a partial biological origin (Konn et al. 2009).

Various aliphatic hydrocarbons, aromatic hydrocarbons, and carboxylic acids have been produced under simulated hydrothermal conditions (McCollum 2013). Organics are formed abiotically by Fischer–Tropsch type (FTT) reactions in which a solid surface catalyzes the reduction of CO or CO₂ by H₂. But, as with the Strecker synthesis of amino acids, the FTT reactions require unrealistically high concentrations (~0.1 M or greater) of reactants, and product yields decrease with increasing carbon chain length.

In other experiments where sulfur is included, the reaction of pyrrhotite (FeS) with H₂S and CO₂ at 25–90°C produces pyrite (FeS₂) and H₂. The H₂ subsequently reduced CO₂ to form alkylthiols and carboxylic acids via a pathway different from the FTT (reviewed in McCollum 2013). In the presence of FeS, pyruvate [H₃CC(O)COO⁻] was formed at a temperature of 250°C and 50–200 MPa pressure from alkylthiols, with formic acid being a source of CO (Cody et al. 2000). This was a milestone achievement because pyruvate is a key intermediate step in the metabolic pathways for the synthesis of many biological macromolecules. Following Cody’s work, Novikov and Copley (2013) reacted pyruvate with H₂S, H₂ and NH₄⁺ with various transition metal sulfides (e.g. pyrite, arsenopyrite, marcasite, sphalerite, and pyrrhotite) at 25–110°C. Interestingly, only a few dominant products were formed with high yields, rather than the myriad of possible compounds, and the dominant compounds are ones widely used in modern metabolic pathways. This result reflects the “sparse metabolism” concept described in Sahai et al. (2016 this issue).

The synthesis of sugars by self-condensation of formaldehyde (known as the formose reaction) requires alkaline conditions and may be catalyzed by calcite and kaolinite. The discovery of white smokers may provide plausible natural alkaline environments by which calcite might facilitate the formose reaction. However, nonselectivity of the formose reaction leads to a mixture of sugars (ketoses, aldoses, and sugar alcohols) with only a small amount of ribose, which is an essential component of nucleic acids. The concentration of formaldehyde required for the experimental system is, again, too high to be geologically plausible. The yield of ribose is increased with the addition of borate, but borate minerals are unlikely to have been abundant on early Earth.

**EXTRATERRESTRIAL PREBIOTIC ORGANIC SOURCES**

Cosmic dust particles range in size from nanometers to 100s of microns and were formed in various regions of space at different times in the history of the Universe. Sources include intergalactic dust, interstellar grains, circumstellar dust, and interplanetary dust particles (dust from asteroids, comets, Kuiper belt objects, and planetary rings). Meteorites and comets are larger bodies from space that sometimes arrive at Earth’s surface. A few of these extraterrestrial sources have been sampled directly: most easily by collection on Earth, but also by spacecraft that have landed on planets of our Solar System and their satellites, and also asteroids and comets and that have either sent data back to Earth or returned samples back to Earth.

**Interstellar Medium (ISM)**

The interstellar medium (ISM) refers to gas clouds in neutral and ionic states, cosmic rays between stars, and cosmic dust. Infrared, microwave, and millimeter-wave spectroscopies have been used to probe space for the spectral signatures of organic molecules. Gas-phase saturated and unsaturated hydrocarbons, alcohols, aldehydes, carboxylic acids, ethers, and N-bearing compounds have all been detected in the ISM. Of particular interest are glycolaldehyde [HOCH₂CH(O)], which is related to sugars, and cyanamide (H₂CN), formamide [HCO(NH₂)] and acetamide [CH₃C(O)NH₂], which are related to peptides. Imidazole, a component of nucleotides, is one of the heterocyclic compounds of C, N and H that has been detected in the ISM (Kwok 2016). Nitriles, which are the precursors of amino acid, have also been detected directly in the ISM using millimeter-wave emission spectroscopy (Kalenskii et al. 2000). There are many spectral lines in the ISM that have yet to be assigned to specific compounds.

It is now generally accepted that gas-phase reactions alone cannot be responsible for the synthesis of such a diverse array of organics, especially for complex molecules. Interstellar grains are nanometer-size grains found in the ISM and are composed of an amorphous silicate or carbon core with outer icy layers of H₂O, CH₄, NH₃, CO, CO₂, CH₃OH, and HCOOH among others (Fig. 2). The surface of the cores is believed to catalyze the reactions of H, O, N and C to form organic molecules (Burke and Brown 2010).

**Figure 2** Synthesis of organic molecules and their precursors in interstellar dust grains can be catalyzed by the surfaces of silicate or refractory carbon phases in the cores of the grains. The products form ice coatings on the cores (including “tholins”). PAHs – polycyclic aromatic hydrocarbons. FROM BURKE AND BROWN (2010).
Interplanetary Dust Particles and Micrometeorites

Interplanetary dust particles (IDPs) are nanometer to ~1–100 μm-size cosmic dust particles, and they can be collected from Earth’s stratosphere by high-flying aircraft. They are usually porous, anhydrous, multicomponent grains of inorganic and organic phases, that were formed in the pre-solar and solar accretionary disk. Comets and asteroids are the sources of IDPs. Tens of thousands of tons of IDPs enter the Earth’s atmosphere annually, and the rate would have been much greater on early Earth (Kwok 2016).

The chemical composition of the IDPs reflects their diverse origins. The inorganic phases of IDPs consist of glassy silicates and grains of chondritic composition. The crystalline phases within the chondritic grains include Mg-olivine, Mg-pyroxene, and feldspathoids, with small quantities of Fe–Ni alloys, sulfides, and calcium–aluminum-rich inclusions. The carbonaceous component of an IDP can be up to 50 wt%, ranging in organic species from simple aliphatic and aromatic compounds to macromolecular polyaromatic hydrocarbons. Many IDPs show only minimal aqueous alteration. Micrometeorites are similar to IDPs except that they are collected from deep ocean sediments and from the Greenland and Antarctica ice sheets.

Meteorites

Meteorites are the surviving fragments of asteroids that reach the Earth’s surface. Among meteorites, the most primitive are the carbonaceous chondrites, which contain ~2 wt% carbon. Organic compounds were first detected by Nagy et al. (1962) in the Orgeuil carbonaceous chondrite, which fell to Earth in 1864. Since then, more than 14,000 organic compounds, including 70 amino acids and other biologically important organic molecules, have been detected (Table 1, Table 2) (Septon 2002; Llorca 2004; Callahan et al. 2011). The major portion (up to 70%) of the organics in meteorites is present as complex insoluble organic matter (Kwok 2016) (Fig. 3). The insoluble organic matter consists of high molecular weight compounds, that contain C, H, N, O, S and P, and is similar to kerogen, which is of biological origin on Earth. Carbon isotopic analysis of these compounds suggest an extraterrestrial origin. The organic matter appears to be preferentially associated with hydrothermally altered minerals in some carbonaceous chondrites and these organics can also undergo reactions during hydrothermal processing.

Asteroids and Comets

Spacecraft have remotely examined some asteroids and comets and landers have sampled their surfaces. Hydrogen cyanide and its polymers have been found on asteroids and comets. For example, infrared spectroscopy of the asteroids 24 Themis and 65 Cybele showed the presence of water ice and red-colored material similar to “tholins.” The latter are complex macromolecular organic compounds formed artificially by ultraviolet radiation of N₂, NH₃ and CH₄. The Stardust spacecraft collected IDPs from the coma of comet 81P/Wild 2 in 2004 and returned the samples to Earth in 2006. Along with various other organics, glycine was detected in these particles. Hydrogen and nitrogen isotopic analyses of these particles indicate an extraterrestrial interstellar or protosolar origin (Kwok 2016; Sandford et al. 2016). The Rosetta spacecraft remotely examined comet 67P/Churumov–Gerasimenko and the Philae lander directly examined this comet’s surface in 2014. Nonvolatile organic compounds, which are probably polycyclic aromatic hydrocarbons, plus sulfides, an Fe–Ni alloy, and an unknown source of P, were identified (Aitweg et al. 2016).

Moon and Other Planets in Our Solar System

Various probes and landers have also been sent to the planets and their satellites in our Solar System. No organics have been detected on the Moon. But CH₄ and H₂O ice are known to exist on Mars. Europa, a satellite of Jupiter, has a water-ice crust and probably a liquid water “mantle.” Among the satellites of Saturn, water ice, methane, propane, and formaldehyde have been detected on Enceladus, whereas Titan has an atmosphere composed mainly of nitrogen, methane, and H₂, plus other organics such as hydrocarbons, HCN, cyanocetylene (HC₃N), CO, CO₂, and liquid hydrocarbon lakes at its poles. The New Horizons spacecraft observed tholin-like dark reddish material in the polar regions of Pluto’s moon Charon.

HOMOCHIRALITY OF LIFE AND ENANTIOMERIC EXCESS OF AMINO ACIDS

Some of the molecular building blocks of life, such as amino acids and sugars, are chiral: that is, they have non-superimposable mirror image structures, known as enantiomers. Chiral molecules have an asymmetric carbon center with four different substituents (Fig. 4). Enantiomers have identical physical and chemical properties except that they interact selectively in chiral environments. Therefore, 50% of each enantiomer (a racemic mixture) is expected in any abiotic chemical reaction.

However, chiral molecules formed biologically show a characteristic preference of one enantiomer over another. For example, sugar residues in nucleotides and polysaccharides are found solely in D-configuration, whereas amino acids are primarily present only in the L-configuration in proteins. The origin of homochirality is one of the key issues in understanding the origin of life. The excess of one enantiomer over another is called an enantiomeric excess. Because homochirality is a characteristic feature of life on Earth, detection of enantiomeric excess in extraterrestrial sources was once considered as a biosignature.
The classes of organic molecules detected in the Murchison carbonaceous chondrite meteorite. The colors in the molecular structures refer to functional groups that are acidic (red), basic (blue), neutral polar (green), and to specifically sulfonic (purple) and phosphonic (orange) acids.

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Structure</th>
<th>Concentration (ppm)</th>
<th>Carbon Chain Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aliphatic hydrocarbons</td>
<td></td>
<td>12-35</td>
<td>C1–C30</td>
</tr>
<tr>
<td>Aromatic hydrocarbons</td>
<td></td>
<td>15–28</td>
<td>C6–C20</td>
</tr>
<tr>
<td>Carboxylic acids</td>
<td></td>
<td>&gt;350</td>
<td>C1–C12</td>
</tr>
<tr>
<td>α-Hydroxy carboxylic acids</td>
<td></td>
<td>15</td>
<td>C2–C8</td>
</tr>
<tr>
<td>Alcohols</td>
<td></td>
<td>11</td>
<td>C1–C4</td>
</tr>
<tr>
<td>Aldehydes</td>
<td></td>
<td>11</td>
<td>C1–C5</td>
</tr>
<tr>
<td>Ketones</td>
<td></td>
<td>16</td>
<td>C1–C5</td>
</tr>
<tr>
<td>Amines</td>
<td></td>
<td>8</td>
<td>C1–C4</td>
</tr>
<tr>
<td>Amino acids</td>
<td></td>
<td>60</td>
<td>C2–C9</td>
</tr>
<tr>
<td>Amides</td>
<td></td>
<td>62</td>
<td>C1–C3</td>
</tr>
<tr>
<td>Sugar-related (sugar alcohols, sugar acids)</td>
<td></td>
<td>60</td>
<td>C3–C6</td>
</tr>
<tr>
<td>Purines and Pyrimidines</td>
<td></td>
<td>2</td>
<td>C4–C5</td>
</tr>
<tr>
<td>Basic N-heterocycles</td>
<td></td>
<td>0.05–0.5</td>
<td>C4–C5</td>
</tr>
<tr>
<td>Sulfonic acids</td>
<td></td>
<td>67</td>
<td>C1–C4</td>
</tr>
<tr>
<td>Phosphonic acids</td>
<td></td>
<td>1.5</td>
<td>C1–C4</td>
</tr>
<tr>
<td>Polymers (macromolecular compounds)</td>
<td>—</td>
<td>&gt;14,300</td>
<td>C&gt;100</td>
</tr>
</tbody>
</table>


Because extraterrestrial organics are assumed to have formed abiotically, it was expected that they would be found in racemic quantities, that is they have equal concentrations of L- and D-isomers. It was tremendously interesting, then, that significant excesses of the D-isomer of sugar-derived compounds (sugar acids and sugar alcohols) (Cooper and Rios 2016) and the L-isomer of a specific subfamily of amino acids (α,α-dialkyl-α-amino acids) and were found in carbonaceous chondrites (Cronin and Pizzarello 1999; Glavin and Dworkin 2009). Isovaline (2-amino-2-methylbutanoic acid), for example, was found to have L-isomeric excesses of 18.5% in the Murchison meteorite, 15.2% in the Orgeuil meteorite, and 6.0% in the Murray meteorite. Thus, enantiomeric enrichment must have occurred abiotically and is not necessarily a biosignature.

If enantiomeric excess is not exclusively a biosignature then the origin of abiological chiral selection must be explained. Many mechanisms might produce enantiomeric excess. In space, the interaction of chiral molecules with circularly polarized light (CPL), which is itself chiral, could introduce enantioselective synthesis up to a few percent. However, the large excesses observed in meteorites cannot be explained solely by an ultraviolet (UV) CPL hypothesis, and additional mechanisms are being investigated.

Minerals such as clays, calcite, and quartz possess chirality and may exhibit stereoselective adsorption for certain amino acids. However, an excess of one chiral form of the mineral over another would be required for an enantiomeric excess to develop. Such an enantiomeric excess of chiral minerals has never been shown.

By whatever means enantiomeric excess began, even a small enrichment could be amplified through subsequent processes such as the preferential sublimation of “conglomerate-forming” crystals. For example, Fletcher et al. (2007) found more than 80% enantiomeric excess of L-leucine in a sublimate compared to a starting value of only 10%.

**FORMING AND SUSTAINING ORGANIC MOLECULES**

The formation of reduced C compounds from CO₂ or CO, and the polymerization of monomers by condensation reactions, are generally thermodynamically unfavorable at ambient temperatures and in the presence of water. Energy must be put into the system to drive the reactions forward. Various energy sources such as UV radiation, cosmic rays, X-rays, hypervelocity impacts, volcanic eruptions with lightning, geothermal heat, and redox gradients were available in the interstellar medium and on the young Earth for the abiotic synthesis of organic molecules. Conversely, under different environmental conditions, many of these same energy sources may serve to degrade organic molecules.

The organics in meteorites survive entry into Earth’s atmosphere because only the outer layers of the meteorite are affected by frictional heating while the interior of a meteorite remains cold. Furthermore, an organic haze in Earth’s early atmosphere might have protected organic molecules from degradation by short-wave UV-radiation, analogous to the role played by ozone in the modern atmosphere.

Oceans may also have protected dissolved organics from UV radiation because the depth of penetration of UV light is ~200 m. On the other hand, the organics would have been diluted and/or hydrolyzed in water. The deleterious effects of dilution and hydrolysis could have been rescued by thermomelanoid, which is an insoluble glycine polymer. When hydrolyzed, thermomelanoid serves as a source of alanine, aspartic acid, and glycine peptides (Fox et al. 2015).
Heating simple organic molecules or their precursors can yield biologically relevant molecules, but may also result in their destruction. Amino acids, for example, may be shielded from thermal degradation by adsorption within the interlayer spaces of clay minerals (Dalai et al. 2016). The thermal and chemical gradients at hydrothermal vents on the Earth’s surface may have played an important role in thermodynamically favorable reactions for organic synthesis. These reactions may have been catalyzed by transition metal–sulfide minerals such as pyrite. However, destructive free radicals are also generated photo catalytically at the surface of these sulfides and at the surfaces of the ultramafic minerals that constitute peridotite and komatitite. The yield of relevant products in abiotic synthesis reactions is often very small. For stable and for reactive molecules, achieving the relevant concentration to form a protocell would have required processes such as adsorption, evaporation, freezing, and sublimation, as well as a continuous flux of reactants. An interesting aspect of prebiotic organic chemistry is the relative scarcity of phosphorous-bearing compounds detected in space. Phosphorus mononitride has been detected in the interstellar medium, low concentrations of glycine. Origins of Life and Evolution of Biospheres. doi:10.1007/s11084-016-9523-0

Fletcher SP, Jagt RBC, Feringa BL (2007) An astrophysically-relevant mechanism for amino acid enantiomer enrichment. Chemical Communications 25: 2578-2580


Kawamura K, Nishi T, Sakiyama T (2005) Enrichment of apatite and merrillite (whitlockite) are found in chondrites and chondritic grains, and schreibersite occurs in iron meteorites. Intriguingly, despite the low abundance of phosphorous, it is unquestionably one of the essential elements for life.

CONCLUDING REMARKS

The organic inventory of early Earth contained contributions from terrestrial and extraterrestrial sources. In order to understand prebiotic organic synthesis processes on Earth, it is important to conduct experiments under conditions that represent plausible early Earth environmental conditions. The identification of nucleic acid monomers and lipids, or their precursors, in extraterrestrial sources, as well as the synthesis of these compounds experimentally, remains as open avenue of research.

ACKNOWLEDGMENTS

Sahai gratefully acknowledges financial support from the following grants: NSF EAR Geobiology and Low-Temperature Geochemistry #1251479; the Simons Collaboration on the Origins of Life (SCoL) award #290359 from the Simons Foundation, NY; and “startup” funds from the University of Akron.

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From Foundation Stones to Life: Concepts and Results

Marie-Christine Maurel1 and Fabrice Leclerc2

INTRODUCTION

Researchers studying the origin of life are trying to determine the path that the building blocks of life took in developing biological functions: from synthesizing the initial building blocks to the emergence (through organization and evolution) of functional biomolecules such as those responsible for genetic replication and metabolism, which are two essential characteristics of life as we know it. In modern organisms, enzymatic proteins are required for the phosphorylation of nucleotide monomers: a chemically activated species required for the condensation of monomers into oligomers (molecules made of a small number of monomer units up to a few dozen), and for the replication of DNA. But such enzymatic proteins are themselves encoded in the genetic system. So, the question of which appeared first on Earth—the genetic information or the metabolism—is a chicken-and-egg dilemma. In the early 1980s, the discovery of ribozymes (short RNA sequences that bear catalytic activity) provided a new perspective on this dilemma and spawned the idea of a genetic world made exclusively of RNA that could have preceded the contemporary DNA/RNA/protein genetic world. However, replicating RNA would have been very difficult prebiotically because each stage in the replication process requires enzymatic catalysis.

When discussing possible prebiotic scenarios for the origin of life, it is widely believed that mineral surfaces played an important role in adsorbing organic molecules and acting as a template to catalyse specific reactions. There are two reasons for this assumption. First, because of the hydrolytic power of water, any organic molecules synthesized would have been subsequently destroyed and the “prebiotic soup” would have been, in fact, a rather diluted thin soup (solution) that contained less than $10^{-4}$ M carbon (Miller 1987). The probability of random collisions between relevant molecules in primitive bio-organic reactions would have been very low in such a dilute aqueous solution. It seems more realistic to assume that relatively high concentrations of organic substances were reached in systems isolated from the ocean: these could include lagoons, moist soil, and both terrestrial and oceanic hydrothermal sites that would be subject to temperature gradients and hydration/dehydration cycles. Molecules would also be brought into close contact with mineral surfaces in such environments.

A second rationale for the role of minerals is that several of them are known to possess catalytic properties: some can generate reactive oxygen species (free radicals) at their surface when irradiated by ultraviolet light. These free radicals could have either catalysed the formation or the destruction of complex organic molecules, depending on the specific reaction. Furthermore, and alternatively, adsorption of organic molecules in the interlayers of minerals, such as clays, could have played a protecting role against decomposition of organic molecules by light. It is important to note that minerals have been identified to form various prebiotic organic molecule polymers, but the relative abundance of these minerals and their extent of occurrence on early Earth is highly questionable.

In this article, we provide an overview of the current knowledge of prebiotic organic molecule polymerization at mineral surfaces under environmental conditions that may have existed on early Earth. The emphasis is on ribonucleic acid (RNA) oligomerization because that will provide the route for the emergence of the genetic code. The four building blocks of RNA (i.e. the nucleotides of RNA) are made of the two purine nitrogenous bases of adenine (A) and guanine (G) and the two pyrimidine nitrogenous bases of cytosine (C) and uracil (U). Despite the massive body of work devoted to research on RNA polymerization, the mechanisms of nucleotide synthesis are still not understood. In the past few years, the “RNA world” paradigm (i.e. RNA as a carrier of genetic information and catalyst

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S}ystems consisting of mineral surfaces, water, salts and organic molecules are considered to be plausible models of early Earth’s prebiotic environments. The probable involvement of clays, highly soluble minerals, sulfides and other minerals at the beginning of life have spurred a number of experimental studies to investigate organic molecule adsorption, polymerization and catalytic reactions of relevance to prebiotic chemistry. This article reviews current ideas in how life originated, summarises experimental results and presents some of the existing challenges that still beset the field of the origins of life.

KEYWORDS: mineral, salts, hydrothermal sites, extremophile, RNA, origins of life
in primitive cells) has been challenged. New ideas have arisen that suggest the existence of a pre-RNA world where amino acids and peptides (compounds consisting of two or more amino acids linked in a chain) may have shaped the RNA world through, for example, the emergence of a simpler genetic system before the transition to modern genetic systems. In addition to RNA polymerization, we also address amino acid oligomerization to form peptides, something that would eventually evolve into enzymes for metabolic activity; the formation of hybrid RNA/amino acid and peptide/RNA nucleotide molecules; and the potential emergence of viroids before peptide enzymes appeared.

MINERALS: FROM CATALYSIS TO METABOLISM

Nucleotide Monomer Synthesis

One of the most challenging problems in the origin of life field is to explain the prebiotic synthesis of RNA nucleotides (monomers) from their basic components (nucleobase, ribose, and phosphate) and explain the respective activations that promote their polymerization under prebiotic conditions in the absence of enzymatic catalysis. But progress has been made to link the pre-RNA world to the RNA world.

Nucleotide Monomer Synthesis

Saladino et al. (2007) showed that the four nucleobases (adenine, guanine, cytosine, and uracil) could be synthesized by heating formamide in the presence of mineral catalysts and ultraviolet (UV) light.

Ricardo et al. (2004) focused on the stabilisation of ribose (the carbohydrate sugar molecule that forms part of the backbone of RNA) by the borate minerals ulexite and colemanite. Akouche et al. (2016) later demonstrated how ribose could adsorb and be stabilized on amorphous silica, protecting the ribose sugar from degradation and significantly increasing the proportion of ribofuranose compared to ribopyranose forms (Georgelin et al. 2015).

Like other building blocks of RNA, the source of ribose might also come from the interaction of cometary ices containing organic residues (H₂O, CH₃OH, NH₃) and space radiation (Meinert et al. 2016).

The occurrence of phosphate (the other piece of the RNA backbone), however, has been less discussed. It is generally admitted, but without any conclusive evidence, that phosphate sources were present on the early Earth. Where this phosphate originated is a crucial question because of the significant role that phosphate has in the structure of nucleic acids, in the coenzymes that are necessary for enzyme function, and in several metabolic processes. Phosphate is seen as the “molecular unit of currency” for energy transfer. Natural phosphides found in several types of rocks may be the origin of the reactive prebiotic phosphorus that was required on the early Earth (Britvin et al. 2015).

Although the three basic components of RNA could have been present in early Earth conditions and could be assembled into nucleotide monomers, the presence of specific peptide precursors (such as diamino-butyric acid) found in meteorites suggests an alternative path for the transition between the pre-RNA world (with unpolymerized nucleobases) to the modern genetic systems (with polymerized nucleobases). In the peptide model, nucleobases are built upon a peptide backbone instead of the phosphate-ribose backbone currently found in RNA. The condensation of nucleobase acetic acids and N-(2-aminoethyl)glycine (AEG), which are compounds identified in the “prebiotic soup” (Miller 1987), leads to the formation of a peptide nucleic acid (PNA) monomer units which could be later polymerized.

Minerals as Catalysts

Identifying the main organic catalysts (e.g. primitive enzymes) that contributed to the emergence of the earliest biochemical pathways is a major challenge to origin-of-life researchers (Maurel and Ninio 1987). Organic chemists have estimated that if two reactants are immobilized in a favourable position, the increase in the reaction rate through entropy effects may be as high as 10⁸. There is little doubt that the primitive enzymes were rigid, template-like structures that could adsorb the reactants, thereby decreasing the entropy factor of the chemical reactions. In such primitive, rigid and poorly specific systems (in terms of stereochemistry, stereoselectivity, etc.), the efficiency of catalysis would have been solely dependent on the orientation and positioning of the reactants. Moreover, catalysis through entropy effects has a major shortcoming: the template-like rigid catalyst cannot be as efficient as most modern enzymes. During evolution, the catalytic efficiency of modern enzymes has been optimized using different strategies to stabilize the transition state of the catalysed reaction while still binding the substrate which would require some minimum flexibility. Nonetheless, even though inefficient, these primitive rigid catalysts (enzymes) could have arisen by chance events. It is logical to consider that mineral particles could behave very similarly to primordial enzymes by adsorbing, and thereby positioning, one reactant molecule with respect to the other. Minerals may also contribute to the condensation of prebiotic molecules and so help in the polymerization of these molecules.

Considering the range of minerals that were present on early Earth, clays are often considered as chemical mini-reactors in prebiotic synthesis. Clays are aluminosilicate minerals with a layered structure in which the plates stack like the pages of a book. Clay minerals carry an excess negative charge in their interlayer sites as well as charges on the edges of the plates. In many clays, water and cations usually occupy the interlayer sites. Organic molecules can also be adsorbed in the interlayer sites or at edges of the clay plates. Clays can play a role as an ion-exchanger. Some clays (e.g. montmorillonite) can swell and expand enormously in the presence of water and then collapse back upon dehydration. This combination of charged surfaces and swelling capability can concentrate organic molecules, creating an environment favourable for the catalysis of reactions between organic molecules and condensation of prebiotic molecules in geological environments that undergo hydration-dehydration cycles. Therefore, clays (such as montmorillonite) have been used in a number of prebiotic chemical studies. For example, hybrid compounds between amino-acid and nucleotide (amino acid–phosphate or hydride monomers) can be condensed in the presence of minerals. When the energy-rich anhydride bond in the monomer (Scheme 1) is hydrolysed, energy is released which enables the subsequent formation of bonds between amino acids, resulting in peptides. Nevertheless, one may question whether the C–O–P bond in the monomer could itself have formed without the presence of some catalyst.

Other experimental studies have focused on the adsorption and reaction of amino acids and nucleotide acids on clays (Paecht-Horowitz 1978; Ferris 2005). For example, the strong adsorption of “activated” nucleotides (phosphorami­date) on montmorillonite is followed by the formation of a nucleotide dimer. Also studied is the regio-specificity (exclusive preference) of the phosphate-ribose linkages in RNA. It was shown that heterogeneous oligocytidylates
were formed by the montmorillonite-catalysed condensation of activated monomers. The oligocytidylates could then serve as templates for the synthesis of the complementary strand of oligoguanylates.

**Synthesis of Long Polymers of Amino Acids and Nucleotides**

Most theories concerning biological organization assume that nucleotide polymers with lengths in the range of 30–100 monomers are sufficient to make a genetic system viable. As stated by Hill et al. (1998): “… long polymers were synthesized on the surface of minerals in a prebiotic process analogous to solid-phase synthesis.” Their experimental study reported elongation and oligomerization of negatively charged amino acids adsorbed on hydroxyapatite and illite, as well as long oligopeptides of beta-glutamic acid on the surface of hydroxyapatite in presence of a condensing agent (carbodiimide) (Hill et al. 1998). Ferris et al. (1996) showed that montmorillonite could induce the formation of nucleotide oligomers up to 55 monomers long and that illite or hydroxyapatite promoted peptide oligomer formation up to 55 amino acids long. In both studies, oligomerization of the nucleotides and amino acids on mineral surfaces was achieved by successive additions (or “feedings”) of fresh monomers of the respective nucleotides and amino acids. Oligonucleotides adsorbed on sodium montmorillonite can elongate from “activated” monomers such as ImpA (adenosine 5’ phosphorimidazolide), while oligopeptides can polymerize from glutamic acid adsorbed on illite or from aspartic acid on hydroxyapatite.

Catalysis by minerals is unique: the type of catalytic specificity brought about by a particular mineral surface cannot be assumed to extend generally to all metabolites. If non-specificity were the case, then we would have to search for multifunctional surfaces, which are highly unlikely to exist. These observations suggest that the complete suite of catalytic mineral surfaces for promoting different types of prebiotic reactions would have to have been available on the primitive Earth. While many studies have reported long oligomerization of nucleotides, Burcar et al. (2013) argued that a single method of identifying oligomers may not produce reliable results.

The next step in investigating the potential roles of minerals might be to consider the possibility of mineral surface-bound replicating systems as precursors to template-directed reactions of nucleotides. This kind of study has not been reported in the literature to date but provides an interesting angle for future investigations. Mathematical modelling suggests that a template-directed ligation mechanism may operate to facilitate this transition where the ratio between ligation and breakage rates should be ≈1 at concentrations <1M (Tkachenko and Maslov 2015). This model opens new perspectives to experimentally explore the formation of long polymers at low nucleotide concentrations.

Protocell-like vesicle self-assembly can be catalysed by many minerals, including clays (Szostak 2012). In a further conjectural step towards a cellular life, a possible clay-related scenario involves RNA molecules, formed by clay-catalysed polymerization, being incorporated within protocell-like vesicle membranes. The switch from a surface-bound to a surface-free RNA-based replicating system could then be possible through the emergence of derived (auto)catalytic RNAs or ribozymes. These proposals provide directions for future research (Szostak 2012).

**Evaporites: The Role of Soluble Minerals and Inorganic Ions in RNA Stability**

Primordial life may have originated in hypersaline conditions because it is likely that primitive oceans on early Earth were highly saline. Salt is also abundant on the planet Mars and on Jupiter’s moon Europa. Extremely halophilic archaea are organisms that require very high salt concentrations for their survival. They occur in salt flats and evaporitic lakes, such as the Dead Sea in the Middle East or the Great Salt Lake (Utah, USA). These halophile organisms compensate for the high osmotic pressure of their environment by accumulating levels of K+ and Cl− close to saturation with respect to sylvite (KCl) in their cytoplasm. And very ancient salt-tolerant micro-organisms have been isolated from brine inclusions in rock salt crystals. Halophiles may not have appeared as the earliest organisms but their proteins have evolved particular features of halo-adaptation, which provide them with a great tolerance to decreased water activity and to temperature variations. This makes them good candidates for biological traces of survival in ancient dry environments.

Hypersaline conditions can stabilize organic molecules and promote polymerization. For example, the structural integrity of transfer RNA (tRNA) can be maintained at high temperatures (e.g. 82°C for 30 h) and high salt concentrations (e.g. 2 M NaCl). The tRNA adopts a specific cloverleaf 2-D structure (Fig. 1A) and an L-shaped 3-D structure...
Polymerization of standard nucleotides to yield RNA-like polymers is possible in the presence of hypersaline (ammonium chloride) hydrothermal conditions (Da Silva et al. 2015). In parallel, further investigations into wet-dry cycles that may promote the condensation of prebiotic monomers are needed to understand more about the polymerization mechanisms at work and the characteristics of the oligomers involved (Mamajanov et al. 2014).

While polymerization and replication of RNA is critical to understanding the origins of the RNA-world hypothesis, it is equally important to investigate the activity and functions of synthesized RNA oligomers. This is a subject that has only recently been considered. To gain further insight into the biochemical properties, the stability of RNA molecules can be studied in vitro at high temperature in the presence of salt using the SELEX (systematic evolution of ligands by exponential enrichment) method. This in vitro selection allows nucleic acid ligands called aptamers [short nucleic acid oligomers (DNA or RNA) with specific 3-D shapes] to evolve and develop new functionalities. The process involves a repetitive in vitro process of sequential selection and amplification steps from a combinatorial library of nucleic acid ligands.

The SELEX method, again in the context of salty environments, has helped isolate RNA molecules that were resistant to high temperatures (80°C for 65 h) and high salt concentration (2 M NaCl). The sequences of the resulting cloned halo-thermophilic RNAs could be grouped in two families (I and II), each of which possesses very different thermal and chemical stabilities and very different secondary structures. The selected RNA molecules illustrate two different pathways leading to thermal resistance, which may be related to early Earth primitive conditions. Members of family I constitute a good means of storing sequence information. Family II members are chemically less stable and less efficient than those of family I, but this disadvantage is compensated for, in part, during the early steps of in vitro selection in which family II were observed to replicate faster during the early cycles of SELEX. Thus, the thermal and chemical stability and the interactions of RNA with transcriptases and polymerases could be clues to help understand the evolutionary rules of RNA molecules in living organisms. Such rules could help demonstrate that what is at stake for RNA molecules, as also for living organisms, is not only “survival” but also efficient “reproduction” (Vergne et al 2006).

Recent Studies on RNA Catalysis in Extreme and/or Hydrothermal Conditions

The discovery of ribozymes at the beginning of the 1980s radically changed the field of studies on the origins of life by revealing the existence of modern RNAs that could have been preceded by a more ancient RNA world (Gilbert 1986). It is well-known today that RNA is responsible for the storage and transfer of genetic information, for the catalysis of some biochemical reactions, and for several regulatory and metabolic roles within the cell. The challenge now is to understand how efficient, functional ribozyme motifs were synthesized in prebiotic conditions. Ribozymes that catalyse the chemical reaction that leads to the cleavage of a phosphodiester bond are stable under high temperature (80°C) (El Murr et al. 2012) and high pressure conditions (250 MPa) (Tobé et al. 2005), and RNA is resistant to high temperatures and to high salt concentrations (4 M NaCl or 4 M KCl). Furthermore, the influence of high pressure (up to 200 MPa) on the reaction rate is fully reversible, meaning that the dynamics of RNA sub-conformations might have been important to catalyse various reactions during the early development of life.

Sulfur and Iron–Sulfur-based Metabolism

Apart from the polymerization and replication of RNA, the emergence of metabolism for life to sustain itself must also be considered. In very broad terms, anabolism (the constructive phase of metabolism) consists of coupled redox reaction chains that supply the energy needed to condense monomers to yield the long polymers that are required for maintaining and replicating the cell. The breakdown of long biomolecules to release energy for maintaining the cell also relies on redox reaction networks that involve dissolved inorganic ions and complexes, ion–organic molecule complexes and mineral surfaces (especially those of sulfur and iron sulfides).

Primitive metabolic mechanisms may have employed thiol amino acids (Maurel and Orgel 2000). Thioacids are prebiotically plausible because they can be obtained inorganically by the hydrolysis of nitriles in the presence of H2S and are very stable at neutral pH. The oxidation of thioacids is very easy in the presence of prebiotic agents such as ferricyanide. Thus, thioacids are realistic prebiotic compounds capable of being active in many terrestrial environments such as the flanks of volcanoes or at oceanic hydrothermal vents.

Several theories also stress the importance of sulfur and iron in prebiotic processes. Wächtershäuser (1988) proposed that, due to the low redox potential of the FeS/FeS2 redox system, simple prebiotic molecules such as CO2 or formaldehyde could have been reduced to more complex organic molecules. Clays or metal sulfurs from hot springs might have assisted in the production of key biochemical molecules, and the iron sulfide reactions might be the link between geochemistry and biochemistry.

The hypothesis proposed by Wächtershäuser (1988) is referred to as the chemoaotrophic theory of the origin of life. It is based on the formation of a mineral surface, such as pyrite (FeS2), that has been derived from iron monosulfide (FeS) and hydrogen sulfide (H2S). Organic molecules containing negative charges are then attracted to the 2-D surface of pyrite. In an acidic geochemical solution, which was likely for early Earth, pyrite has a positive surface charge and can strongly bind anionic carboxylate and phosphate molecules, as well as mercapto-chemical moieties. All these functional groups are essential in current cellular metabolisms. Biomolecules possessing such functional groups might be the molecular ghosts of ancient molecules: the initiators of primeval functions.

According to Wächtershäuser (1988), the first organism was a chemoaotroph. Such an organism uses the formation of pyrite as a source of electrons and of energy. Carbon dioxide from the atmosphere is reduced by hydrogen, resulting in organic molecules such as carbohydrates, sugars and monomers, all of which can then lead to amino acids.
Finally, some metals that are associated with protein function, such as Fe–S proteins, and of nucleic acid function, may be the evolutionary remains of ancient metals present on Earth when we think life originated.

**PRE-RNA WORLD AND GENETIC SYSTEMS**

**Alternative Genetic System (AGS)**

The difficulty in synthesising nucleotide monomers, not to mention the idea that RNA itself is too complex to have been the first genetic molecule, has focused researchers to search for non-standard molecules as earlier replicators and catalysts and on other means of transitioning to standard nucleic acids. This search has given rise to what is known as alternative genetic systems (AGSs), which attempt to model the first Darwinian ancestors, some of which are presumed to have been endowed with replicative properties (Joyce et al. 1987). One such AGS is the idea that peptide nucleic acids (PNAs) might have preceded RNA nucleotides: in PNAs, the phosphoribosyl backbone is substituted by a pseudo-peptide backbone (see Nucleotide Monomer Synthesis section). Interestingly, the PNA skeleton of N-(2-aminoethyl)glycine has recently been discovered in modern cyanobacteria (Banack et al. 2012). These latter authors assumed that this type of PNA skeleton might be the vestige of an ancient AGS made up of peptide-bearing nitrogenous bases. A potential transition to modern genetic systems might have been easy in protocells.

**RNA–Peptide World**

The origin of the genetic code and of controlled protein synthesis by the genome sequence remains one of the most poorly understood stages in the origin of life. Specific interactions may occur between certain amino acids or small peptides and mono- or polynucleotides. Some models suggest that the genetic code results from some specific modes of interaction between RNA and amino acids (Yarus et al. 2009); RNA can fold in such a way as to bind a specific amino acid (Fig. 2A), while proteins can expose cavities to bind a particular nucleotide (Fig. 2B).

**Over the Ages, Could RNA have Existed Alone?**

In order to question the plausibility of the RNA world, one might ask if we know of current molecular “living fossils,” i.e. entities which represent vestiges of the RNA world. For example, at the frontiers of life we know about RNA viruses, viroids and satellite RNAs. Some viroids can behave like catalytic RNAs; hence, they are considered as remnants of the RNA world (Diener 1989).

A viroid is an RNA that is 246 to 475 nucleotides long and that folds to form rod-like structures with nucleotide base pairing (in which A pairs with U, and C pairs with G). Viroids, found in nature as parasites in plant cells, are structurally, functionally and evolutionarily different from viruses. The origin of viroids is completely unknown, as is the origin of viruses. Among the main hypotheses regarding virus origins is the so-called “escape hypothesis” which states that viruses arose from genetic elements moving between cells. A second hypothesis is the “degeneracy (or regressive) hypothesis” which states that viruses are the remnants of cellular organisms. Neither of these two hypotheses can be applied to viroids as explained below.

Viroids themselves adopt a circular form, which makes them very resistant to degradation. Some viroids contain a ribozyme motif that has been termed the hammerhead ribozyme (HHR), which can cleave itself through strand scission. The viroid genome is small, but it can adopt a higher-order organization, something that is a known driving force in the emergence of life and molecular evolution. Such higher-order organization was shown recently to be present in the viroid infecting avocado (ASBVd: Avocado Sunblotch Viroid) that can self-assemble (Leclerc et al. 2016).

The multiplication of viroids requires three catalytic activities for the genome to be replicated: RNA polymerization, RNA cleavage and RNA ligation. RNA polymerization generates multiple concatenated copies of the genome which are then processed by RNA cleavage and ligated to regenerate the circular form of the genome. RNA polymerization and ligation require protein enzymes from the host plant, whereas RNA cleavage can be achieved, for example, by the HHR motif of the ASBVd viroid. The first two activities might have been lost by the viroid ancestors during evolution because they have been discovered in artificially evolved RNA molecules. The molecules are an RNA-polymerase ribozyme (Fig. 3A) and two structurally divergent RNA-ligase ribozymes (Fig. 3C), both of which were revealed by the SELEX method.

**Figure 2** RNA/amino acid and nucleotide/protein interactions as a potential relict of the primordial genetic code. (A) Interaction between a lysine amino acid and a riboswitch. The amino acid is shown using an atomic CPK (Corey–Pauling–Koltun) model and the nucleotides from the RNA riboswitch by a stick model (the RNA chain is shown by a purple ribbon). The charged amino acid interacts simultaneously with several nucleotide residues of the RNA. Hydrogen bond contacts are indicated by dashed lines (PDB ID: 3DOU). (B) Interaction between a nucleotide residue (adenosine) from an RNA chain and a human protein (PUMILIO1). The nucleotide is shown using an atomic CPK model and the surrounding protein residues by a stick model. The nucleotide residue interacts simultaneously with several amino-acid residues (PDB ID: 1MBW)
The widespread distribution of two different families of ribozymes (hammerhead and twister) in all domains of life (bacteria, archaea, and eukarya) supports the hypothesis that ribozymes were present in all cellular organisms, even early on. For a long time, circular RNAs were considered a rare cellular species or exclusive to viruses, viroids or archaea. However, circular RNAs are now recognized to be highly abundant, conserved and occur naturally in eukaryotes (Diener 1989; Lasda and Parker 2014). Finally, the viroids, and the hammerhead viroids in particular, exhibit the highest mutation rates for any biological entity. This is an important property for fast evolution (Gago et al. 2009).

The “viroid-first” hypothesis, whereby it was viroids that first appeared on Earth (albeit in an RNA world continuum), must be further experimentally and phylogenetically investigated. This is but one of many exciting avenues of research waiting to be pursued by those interested in the origin of life itself.

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Figure 3 Structures of artificial and natural ribozymes with the three basic catalytic activities required for viroid replication. (A) RNA-polymerase ribozyme (PDB ID: 3IVK); the 3-D structure corresponds to a class I RNA ligase (first chemical step of RNA polymerization); a fully active RNA-polymerase ribozyme (capable of catalysing the accurate synthesis of an RNA sequence longer than itself) adopts the same 3-D fold. (B) Hammerhead ribozyme (PDB ID: 2OEU) with an RNase-like activity (self-cleaving). (C) RNA ligase ribozyme (PDB ID: 2OIU). The small coloured dots in and around the three structures indicate the presence of tightly bound metal ions and water molecules.
Life as we know it is completely dependent on metal ions. Gradients of metal ions drive metabolism, metal centers often form the active sites of enzymes, and metal-ion coordination is largely responsible for protein and RNA folding. This dependence on metal ions likely reflects the environment from which cellular life emerged. However, long chain biological polymers were not present on prebiotic Earth. Therefore, the chemical reactions leading to Earth’s first cells must have made use of alternative catalysts that were later superseded by RNA and protein. Here, we discuss the similarities between free metal ions, minerals, and biological enzyme catalysts, and how cellular life could have exploited prebiotic metallocomplexes.

Keywords: prebiotic chemistry, iron–sulfur cluster, protocell, metallopeptide

INTRODUCTION

Darwinian evolution began on Earth approximately 3.5 billion years ago through a process that transformed geochemically driven organic synthesis and metabolic-like reactions into biochemistry. What exactly transpired may never be known because fossil records of protocellular life have yet to be found. Nevertheless, we do know that the principles of physics and chemistry are unchanged between geological and biological settings. In other words, Stanley Miller’s pioneering experimental work in the 1950s helped popularize the idea that the prebiotic components of life on early Earth could be synthesized in laboratory simulations. Since then, several laboratory experiments have shown that, in addition to amino acids, lipids and nucleotides can emerge from model prebiotic reactions. However, the mechanism by which individual monomeric units of amino acids and nucleotides could assemble into polymers similar to modern day proteins and nucleic acids has been investigated to a lesser extent than the formation of the monomers themselves. Nucleotides can polymerize in the absence of catalysts, and minerals can facilitate the polymerization of activated nucleotides (Orgel and Lohrmann 1974) and of amino acids (Kawamura et al. 2011). Furthermore, minerals can catalyze the formation of vesicles (Sahai et al. 2016 this issue), suggesting a scenario where minerals bring together nucleic acids and lipids to form cell-like compartments, although alternative scenarios are also possible.

Of all the biological polymers, RNA is the most versatile (Maurel and Leclerc 2016 this issue; Sahai et al. 2016 this issue). The ability of RNA to function as a genome and to catalyze chemical reactions makes RNA an ideal candidate for driving early evolution. This has led to investigations of RNA-containing model protocells as a way of gaining insight into the emergence of primitive cellular life (Kee and Monnard 2016 this issue). The model protocells can seemingly copy RNA, grow, divide, acquire nutrients, and compete for survival. Investigations of RNA have revealed much about the chemical-physical underpinnings of cellular life, but much remains largely unexplored. For example, it is unclear how model protocells similar to those that have been built in the laboratory could incorporate a supporting metabolism, i.e. chemical reactions that maintain living systems. Also, RNA-catalyzed reactions are not known in the central metabolic reactions of contemporary biology (Keller et al. 2014). Instead, these reactions are mediated by protein enzymes: the digestion of food is mediated by proteins, not RNA. Although synthetic catalytic RNA molecules built in the laboratory are capable of accelerating a wide variety of reactions, catalytic RNAs are typically incapable of mediating the types of metabolic reactions found in biology. Explaining why this is so is important because, without a supporting metabolism, early cellular life would not have persisted for long enough to have evolved. It seems that some form of metabolism would have been needed early on, in part, to cope with the consumption of resources. In contrast, life is found today nearly everywhere on and near the Earth’s surface because organisms carry with them adaptable metabolic machinery to gather dispersed and varied foodstuff.

If RNA molecules did not catalyze all of the necessary chemical reactions, and protein enzymes were not present on prebiotic Earth, then what could have served as a prebiotic catalyst? Perhaps the required chemistry was mediated by minerals. This suggestion is attractive because some protein enzymes of contemporary life coordinate metallocomplexes that are similar to the constituents of minerals. For example, there is strong structural similarity between greigite (Fe₃S₄) and the Fe₃S₄ and Fe₄S₄ clusters found coordinated to several of the protein enzymes necessary to support life (Russell and Martin 2004).

The influence of metal ions on prebiotic chemistry may not have been confined to mineral surfaces. All organisms are heavily dependent on metal ions acquired from the environment. In fact, estimates put the number of metalloproteins somewhere between one-third and one-half of all proteins. The Fe₃S₄ and Fe₄S₄–containing proteins mentioned above are only a small fraction of the large
number of metalloproteins needed to support contemporary life. Protein and RNA folding are largely dependent on metal-ion coordination and much of central metabolism is mediated by metal ions bound to proteins. However, the way metal ions could have been used to catalyze metabolic-like reactions prior to the existence of highly evolved proteins remains unclear.

**CONTEMPORARY METALLOPROTEINS MAY BE A CONSEQUENCE OF PREBIOTIC METAL CATALYSTS**

Some of the chemical reactions prevalent on prebiotic Earth could have laid the foundation for modern metabolism (Morowitz 2004). Modern day protein enzymes facilitate and control chemical reactions that could initially have occurred abiotically. Not only were the same or similar reactions likely present on prebiotic Earth, but the reactions may have been favored over other competing reactions by the presence of prebiotic catalysts (Copley et al. 2007). The identity of the prebiotic catalysts that shaped the emergence of contemporary metabolism may be gleaned from the protein enzymes that coordinate metal ions. This is because metal ions themselves, in the absence of protein or RNA, can function as catalysts—polymer scaffolds are not necessary. For example, free iron ions can catalytically decompose hydrogen peroxide, and several divalent cations alone can catalyze transphosphorylation reactions (Lowenstein 1958). Metal ions can form more complex, inorganic structures in the presence of compatible ligands. Iron–sulfur clusters analogous to those found in the redox active protein ferredoxin readily form in solutions of iron ions, inorganic sulfide, and additional sulfur ligands (Fig. 1). The resulting non–protein coordinated iron–sulfur cluster is catalytically active (McMillan et al. 1979).

Calvin (1959) noted that the ability of free Fe$^{3+}$ to catalyze the degradation of hydrogen peroxide to water and oxygen was increased 1,000-fold when the iron was coordinated to porphyrin. An additional 10$^2$-fold improvement resulted from coordination of the iron porphyrin (heme) to the large protein enzyme catalase (Fig. 2). Although several intermediate steps would have had to transpire for a reaction catalyzed by free ferric ions to be transformed into a protein enzyme–mediated process, this example illustrates how the intrinsic activity of a metal center can be augmented by genetically encoded material. But it may not just be a case of evolution improving upon the innate activity of metal ions. The prevalence of metalloenzymes may reflect a difficulty in evolving metal-independent sequences, at least with the nucleotides and amino acids exploited by life as we know it. For example, in vitro evolution methods used to identify catalytic sequences invariably select for RNAs and proteins with metal-dependent activity, suggesting that sequence space is more sparsely populated with metal-independent folds. In other words, although enzyme-active sites devoid of metal centers can be envisaged (Casareno et al. 1995), evolution is more likely to hit upon a metal-dependent solution.

**A PROTEIN’S METAL CONTENT MAY REFLECT THE ENVIRONMENT FROM WHICH THE PROTEIN EMERGED**

Attempts at determining the relevance of model prebiotic metallocomplexes must take into consideration thermodynamic affinity and availability (concentration), in addition to reactivity. The metal ions most exploited by biology are those that are readily found in the environment at a concentration of at least 1 nM (Egami 1974), perhaps reflecting a difficulty in forming binding sites with greater affinity in the cases of proteins and RNA ligands. The relationship between physiological relevance and availability is apparent when comparing the affinities of different metal ions for a specific metalloenzyme. That is, affinities typically correspond to the available concentration of the metal ion. For example, even if protein enzymes that mediate phosphorylation reactions frequently display increased catalytic activity in vitro with bound Mn$^{2+}$, the affinity for this metal ion is not sufficient to result in coordination under physiological conditions. Instead, the affinity for Mg$^{2+}$, the physiologically relevant metal, matches the availability of the metal ion (Cowan 1998). Once a protein has evolved to coordinate a metal ion, there is usually no selective pressure to increase the affinity.

Experimental evidence suggests that modern metabolism was shaped by free metal-ion catalysts. Keller et al. (2014) showed that the majority of the reactions of two fundamental metabolic pathways for the breakdown of sugar molecules (glycolysis and the pentose phosphate pathway) could be catalyzed by Fe$^{2+}$ at elevated temperatures. Of the 10 steps of modern glycolysis, five Mg$^{2+}$- and one Zn$^{2+}$-dependent enzyme(s) are exploited (Fig. 3). Dissolved iron ions may have played an even larger role than the analysis of contemporary enzymes suggests. Athavale et al. (2012) demonstrated that Mg$^{2+}$-dependent catalytic
RNA activity can be recovered in the absence of Mg$^{2+}$ by the addition of Fe$^{2+}$. This latter finding is telling because under the more reducing conditions of prebiotic Earth, the availability of dissolved iron would have been greater than today due to the increased solubility of Fe$^{2+}$ over Fe$^{3+}$ and, thus, may have been preferentially used for catalysis. If true, then 60% of the steps of an early glycolytic-like pathway could have depended on iron ions. The impact of dissolved iron could have been even greater at an early evolutionary stage because the progenitors of contemporary nicotinamide adenine dinucleotide [NAD(H)]-proteins may have coordinated iron or iron–sulfur clusters in place of the nicotinamide cofactor (Daniel and Danson 1995).

Contemporary organisms make use of two additional pathways to boost the energy yields from the breakdown of sugars, lipids, and proteins. These two pathways are called the citric acid cycle and the electron transport chain. The proteins of the citric acid cycle and electron transport chain are different from the proteins used in glycolysis in at least one aspect. The enzymatic steps of the citric acid cycle and electron transport chain are predominantly mediated by more complicated metallocomplexes, such as iron–sulfur clusters and heme, than those found in glycolysis. It is unclear if this dissimilarity in metallocomplexes for the different metabolic cycles reflects differences in the environment from which the proteins originated. In the absence of sulfide, an iron–sulfur cluster cannot form. Therefore, mononuclear Fe$^{2+}$ coordination could have emerged from such conditions and may have been later substituted with Mg$^{2+}$ when iron ions were less readily available, e.g. as described above for glycolysis. If, however, the environment did contain sulfide, then the formation of a more complex iron–sulfur cluster would have been more favorable. Because Mg$^{2+}$ cannot form an analogous structure, the presence of the iron–sulfur cluster would have persisted, as seen as seen for the proteins of the extant citric acid cycle and the electron transport chain.

The potential effects of free metal ions on metabolic-like reactions is similar to previous theories based on mineral catalysts because the metal components of the minerals are critically important for activity. Although the only nominal metal in montmorillonite is aluminum, several metal-substituted species occur naturally as a consequence of local environments. In fact, only the alkali and alkaline earth metal substitutions of montmorillonite are able to polymerize nucleotides (Ferris 2005). Similarly, sodium substitution in montmorillonite aids in alanine adenylate polymerization (Paecht-Horowitz 1978), and the sodium forms of kaolinite and bentonite are able to polymerize glycine during wetting–drying cycles (Lahav et al. 1978).

That is not to say that minerals are the same as free metal ions in terms of their potential as prebiotic catalysts. In some ways, minerals better mimic the activity of biological enzymes than free metal ions because some minerals can present surfaces that can bind reactants with high affinity.

### Potential Prebiotic Metallopeptide Sequences May Exist in Modern Proteins

The protein enzymes thought to be the most ancient—based on the combined analysis of sequence, structure, and shared metabolism—all depend on metal ion coordination for their activity (Goldman et al. 2012). Furthermore, the structural features and amino acid sequences that coordinate metal ions are often highly conserved. Peptides based on such metal-binding motifs often retain the ability to bind the metal center (Mulholland et al. 1998). Therefore, in a somewhat analogous way to the metalloenzyme pathway example depicted in Figure 2, a path from free metal ion to metalloprotein can be envisioned to pass through intermediate metallopeptide states. In this way, short peptide sequences that confer some type of selective advantage could be gradually built upon to give longer, more active folds. If such a pathway transpired, then it may be possible to identify these early, potentially prebiotic, peptide sequences within the sequences of modern proteins.

Eck and Dayhoff (1966) were the first to consider the possibility that modern metalloproteins could have arisen from repeated sequences of short peptides. These authors noted that a 55-amino acid redox-active protein from the bacterium *Clostridium pasteurianum* likely resulted from a duplication event. Further, it was found that the protein could be broken down into progressively smaller repetitive units, all the way down to a tetrapeptide (a peptide consisting of four amino acids) (Fig. 4). Although the full-length protein coordinates two FeS$_4$ clusters, the tetrapeptide was not assumed to bind a metal ion. Instead, it was proposed that later mutations resulted in properly positioned cysteines for iron–sulfur coordination (Eck and Dayhoff 1966).

Iron–sulfur cluster proteins are believed to be evolutionarily ancient and are fundamental to several physiological processes, including central metabolism and protein and DNA synthesis. Hence, further effort into deciphering the origins of iron–sulfur proteins is important. The three most common iron–sulfur clusters are mononuclear, FeS$_2$, and FeS$_4$ clusters. In all these clusters, each tetrahedral iron is coordinated by a cysteine side-chain and, in the case of FeS$_2$ and FeS$_4$ clusters, the iron is additionally coordinated by inorganic sulfides (Fig. 1). Even without the use of decomposing H$_2$O$_2$ increases from hydrated Fe$^{3+}$ (10$^{-7}$ ml$^{-1}$s$^{-1}$) to heme (10$^{-2}$ ml$^{-1}$s$^{-1}$) to the protein enzyme catalase (10$^{5}$ ml$^{-1}$s$^{-1}$).

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Figure 2: A comparison of three structures surrounding the metal ion for (left) hydrated Fe$^{3+}$, (center) heme, and (right) catalase. Calvin (1959) noted that the catalytic activity of
of complex search algorithms, several iron–sulfur cluster motifs are easily identifiable, much more so than for non–cysteine ligated metal centers. For example, one class of Fe₄S₄ proteins coordinate their cluster, in part, through a Cysteine–X–X–Cysteine–X–X–Cysteine motif, where X is any α-amino acid. These proteins additionally contain a fourth cysteine ligand further away in the primary sequence that is necessary to coordinate the cluster. Similar motifs can be found for specific classes of mononuclear iron and Fe₂S₂ proteins, although iron–sulfur clusters can be coordinated to quite different sequences.

The peptides that gave rise to iron–sulfur proteins may have impacted the evolution of other protein folds, too, because early metallopeptides were probably quite promiscuous in coordinating metal ions. Modern proteins that coordinate metal ions other than Fe²⁺ (e.g. Ni²⁺ and Zn²⁺) with the same ligand, such as happens with the cysteinyl thiolates, are plentiful. A more modern attempt to infer prebiotic metallopeptide sequences was made by van der Gulik et al. (2009) who searched the protein data bank for short sequences that primarily consisted of prebiotic amino acids [in that study, glycine (Gly), alanine (Ala), aspartic acid...].
(Asp), and valine (Val) were designated as prebiotic amino acids and that coordinated at least one metal ion. The search produced two different metal ion-binding motifs of Asp–X–Asp–X–Asp and Asp–X–X–X–X–Asp–X–Asp. These two motifs are associated in biology with the binding of Mg\(^{2+}\), Mn\(^{2+}\), Zn\(^{2+}\), and Ni\(^{2+}\).

Sequence analysis alone is not adequate to determine the prebiotic plausibility of metallopeptides. It is important to synthesize and test short peptide sequences to see if correlations can be drawn with the activity associated with more complex metalloprotein folds. Although still longer than what many would consider to be prebiotically plausible, a sixteen amino acid peptide taken from the sequence of an iron–sulfur protein from bacteria *Peptococcus aerogenes* ferredoxin was found to stably coordinate an iron–sulfur cluster in aqueous solution (Mulholland et al. 1998). More interestingly in terms of prebiotic relevance, the three amino acid peptide glutathione was shown to coordinate an iron–sulfur cluster (Qi et al. 2012). Each glutathione peptide contains one cysteine ligand, and so four glutathiones are needed to coordinate a single iron–sulfur cluster (Fig. 5). The sequence of glutathione is also attractive because glutathione contains a side-chain peptide bond that cannot be formed by the ribosome. If peptides existed before the ribosome, then the peptides would have likely contained a more heterogeneous distribution of backbone connectivity than that observed in modern proteins. Further, duplications of the sequence of glutathione gives a spacing of cysteine ligands similar to modern day ferredoxins (Scintilla et al. 2016). Of course, it is important to recognize that glutathione itself may not have existed on prebiotic Earth.

These insights show that it is important to dig deeper into “sequence space” by synthesizing and testing the iron–sulfur coordinating ability of a series of short peptide sequences so as to better understand the likelihood of an iron–sulfur peptide existing on prebiotic Earth. However, just existing is not enough. Unless metallopeptides can be shown to do something useful, their existence is meaningless. It would seem that identifying such activity should not be difficult: free metal ions themselves can catalyze reactions, and dipeptides bind divalent cations selectively (Belmonte et al. 2016). Non–metal ion coordinating dipeptides have also been shown to catalyze a few reactions, including peptide bond formation (Gorlero et al. 2009). It seems that the time is right to begin investigating how short peptides can enhance the intrinsic activity of metal centers.

**CONCLUSIONS**

Life as we know it depends heavily on metal ions to catalyze metabolic reactions, to transduce signals, and to form concentration gradients used to drive unfavorable reactions. Although most of contemporary metabolism is controlled by biological enzymes, non enzymatic metabolic reactions persist, including those catalyzed by metal ions. Further, at elevated temperatures metal ions themselves can catalyze the majority of the reactions of at least two fundamental metabolic pathways. Therefore, it is possible that of the many potential reaction networks that could
have emerged, modern day metabolism reflects, at least in part, those reactions that were accelerated by metal ions. If peptides capable of coordinating the available metal ions were present on the early Earth then the reactivity of the metal center would have been modified in a sequence-dependent manner. Unfortunately, with the available data, we cannot conclude if a path similar to what has been described herein occurred. It is not even clear how such metabolic-like reactions could have been harnessed by protocellular structures. It is, therefore, important to experimentally explore the metal ion binding ability and catalytic activity of model prebiotic peptides to gain insight into what was and was not possible.

ACKNOWLEDGMENTS
We thank C. Bonfio, S. Scintilla, and O. D. Topolak for helpful comments on this manuscript. We thank the Simons Foundation (290358), the Armenise-Harvard Foundation, and COST Action CM1304 for financial support.

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On the Emergence of a Proto-Metabolism and the Assembly of Early Protocells

Terence P. Kee and Pierre-Alain Monnard

INTRODUCTION

Whether we will ever unravel how living systems originated on Earth is doubtful. Few pieces of direct evidence for early Earth’s environments, geochemistry, and living systems and/or their precursors exist. Although there is no universally accepted definition of life, researchers in the origin of life field have adopted operative definitions to undertake their investigations. In general, these definitions highlight the central role of water, the ubiquity of cells as basic units of all life forms, and the presence of the triad of DNA/RNA/protein in all life processes. Living systems, even seemingly “simple” prokaryotes, are extremely complex with respect to their molecular components, their structure, and their reaction networks and dynamics.

Moreover, using phylogenomic analysis to surmise the characteristics of early cellular life, one must conclude that even the last universal common ancestor (LUCA) was conceptually not very different from contemporary cells. That is, early cells and the likely systems that preceded them (protocells) were the products of a chemical evolutionary process. Thus, one cannot speak of a protocell type, but rather of a lineage of protocell systems that slowly evolved from simple self-assembled molecular systems towards pre-cellular entities capable of self-sustenance and self-replication.

In their simplest embodiment, inferred from many operative definitions, protocells would have been chemical systems characterized by a compartmentalisation system, a reaction network (even as small as a single reaction) that uses energy transduced from its environment, and some form of information system (Sahai et al. 2016 this issue). This protocell vision implies that early systems were dependent on the chemicals available in the environment, which were either products of geochemical processes (endogenous syntheses on Earth) or some type of extraterrestrial processes (exogenous syntheses) (Dalai et al. 2016 this issue). Furthermore, in the complex prebiotic milieu, a way to select the chemicals of interest, such as by adsorption on a surface, might have been essential to permit the formation of simple self-assembled systems and their stabilization. As protocell complexity gradually increased, in terms of molecular composition and functions, protocells would have been dependent on external sources of chemical raw materials for constructing their own molecules. Chemical energy from the environment to power a protocell’s reaction pathways would have remained necessary until internal robust energy harvesting processes, possibly based on proteinaceous catalysis, were constructed. All these phases in the development of protocell systems could, therefore, have been supported by mineral surfaces and small mineral particles. This review will focus on protocells, their composition and properties, their emergence, their functions (including chemical and energy uptake mechanisms), and their putative evolution toward early cells. While exploring these themes, possible contributions/involvement of geochemistry and geo-biochemistry will be highlighted.

PROTOCELL SUBSYSTEMS

A survey of the literature on the design and investigation of protocells highlights significant variety in subject matter and scope, in part due to the rather vague definition of “protocell” and in part due to proposed protocell applications (for medicine, material sciences, and the origin of life). With respect to the origin of life, the expected evolution of protocells (Fig. 1) leads to further multiplication of potentially relevant systems. In their most evolved embodiment, protocells should have been able to independently...
synthesize their chemicals from simpler chemicals by using energy harvested from the environment (Fig. 2). Even so, it is interesting to define putative functions/properties of the protocell subsystems or component parts.

**Compartment**

To achieve their autonomy, an essential protocell characteristic would have been compartmentalization, which is the confinement of molecular assemblies within defined boundaries (Monnard and Walde 2015). This process must have been key to their emergence and how they evolved ever-increasing complexity (in terms of molecular composition and related functions), ultimately leading to the phospholipid-based membranes of contemporary biochemistry.

The protocell compartment could have had various forms, ranging from inorganic structures to amphiphile structures, as well as mixtures thereof under the express condition that its building blocks could self-assemble due to non-covalent interactions (Monnard and Walde 2015). Protocell composition, nevertheless, had to imperatively evolve towards the lipid-based cell boundaries of contemporary biology. Two other prebiotic compartmentalization properties likely played a central role in determining how protocells functioned: first, stability, both spatial and temporal; second, selective permeability of the compartment boundaries for the exchange of small molecules (Monnard and Walde 2015). These two properties must have been carefully balanced, as too stable a system would not have been able to take up new molecular assemblies necessary for its evolution, while too permeable a boundary would have been an impediment to achieving the necessary local concentration gradients that would allow an internalized catalytic system to produce protocell building blocks efficiently.

**Internal Catalytic Network and Information System**

The internal catalytic network, often referred to as “metabolism”, is the set of catalysts/catalytic assemblies that a protocell would have required to process resources into its own building blocks (Ruiz-Mirazo et al. 2014). The research on this protocell component has focused on two types of process: (i) the synthesis of biopolymers, and (ii) the synthesis of other protocellular building blocks, most prominently those forming the compartment. Biopolymer synthesis, in particular of RNA due to the RNA-world hypothesis (Mansy and Belmonte 2016 this issue; Maurel and Leclerc 2016 this issue), is considered central to the origin of life due to its ability to catalyze reactions under mild conditions, as well as encode the information necessary to construct a cell. However, catalysis by other “non-genetically” coded molecules—such as metal-ions/complexes (Mansy and Belmonte 2016 this issue), short peptides (Adamala and Szostak 2013), or small mineral particles (Summers and Rodoni 2015)—must have been involved in driving early catalytic networks.

**Energy Harvesting**

The ability to harvest energy from a primary source (light, heat or chemical energy) and convert it first into chemical bonds and later into chemical energy currencies is a central property of living systems. At first, energy harvesting systems could have been limited to directly converting chemical precursors, present from their environment and activated by abiotic processes, into building blocks or into more complex molecules: that is, performing thermodynamically downhill reactions. The next big evolutionary step would have been the formation of carbon–carbon bonds. Because this bond formation is a two-electron process, it seems likely that this catalytic function would have required some form of chemical gradient. Nevertheless, a simple energy harvesting function would have started an internal catalytic network.

From this short overview of protocell parts, one can directly surmise that protocell development must have been based on a co-emergence and co-evolution of the protocellular parts/functions from an early stage (Caetano-Anollés and Seufferheld 2013; Krishnamurthy 2015). Indeed, only through the interconnection between constituent parts can a functional protocell be realized. Without a compartment, a robust, complex reaction network and information system cannot arise, and energy harvesting will not occur properly. Moreover, the presence of a compartment can promote the functions of the other parts (Monnard and Walde 2015). A compartment cannot be maintained without other protocell parts. These latter parts will not only provide its building blocks, but also define its basic properties (stability and permeability). These observations have resulted in heightened research into the possible significance of chemical systems in the origin of life, field, because the development of complex molecular aggregates seem to be consistent with the emergence of cellular complexity. The study of complex molecular aggregates is now called “system chemistry” (Kauffman 2011; Ruiz-Mirazo et al. 2014). The system chemistry approach focuses not so much on chemical diversity or individual chemical reactions, but rather on the potential interactions between chemical reactions or their convergence.
Cooperativity within chemical aggregates lies at the heart of system chemistry. Moreover, chemical systems can inherently satisfy the concept of evolutionary continuity.

**MOLECULAR COMPOSITION OF PROTOCELL SUBSYSTEMS**

The involvement of the geological environment would have been crucial in determining the chemicals that were available and in providing an energy source. Even though the actual composition of chemicals composing early protocells is still not clearly defined, one can infer, both from the likely chemical make-up of the last universal common ancestor and from the analysis of the composition of extraterrestrial chemical sources, which early Earth chemicals would have been available and which chemicals would have had the necessary properties to allow functional protocells to form.

**Compartment**

A protocell’s original compartment could have formed by mineral formations (Martin and Russell 2003) or by mineral particles (Li et al. 2014), either by concentrating chemicals onto a particular mineral surface or by particle self-assembly, respectively. Among other chemicals, the inventory of carbon compounds in carbonaceous chondrite meteorites has revealed an abundance of fatty acids (molecules with single saturated hydrocarbon chains up to 12 carbons long) but also related chemicals that could serve as chemical precursors for fatty acids (Dalai et al. 2016 this issue).

Models of terrestrial syntheses, such as the Fischer-Tropsch type syntheses, also have the potential to deliver fatty acids, and derivatives, with similar or longer hydrocarbon chain lengths (McCollom et al. 1999). Alkyl phosphates and phosphonates can be synthesized in simple reactions using phosphorus extracted from Fe/Ni-rich meteorites or minerals such as schreibersite (Pasek and Lauretta 2005; Bryant et al. 2013). These fatty acid and phosphate-based molecules are amphiphiles and, thus, can spontaneously self-assemble into structures (see Fig. 3) when in aqueous solutions at reasonable temperatures and pressures. Amphiphile vesicles would offer the best conditions for the development of a complex reaction network because they, like cells, can co-localize or compartmentalize molecules in three different micro-environments: 1) in the hydrophobic core of bilayers; 2) at the surface of bilayers; 3) within their aqueous lumen for hydrophilic solutes.

**Internal Catalytic Network and Information System**

A protocell should be able to harbour within its compartment reactions that produce its own building blocks. From its simplest form, based on encapsulated metal-ions and complexes or even mineral particles, this reaction system would have gradually evolved first into RNA-based and, over time, into protein catalytic networks, i.e. towards metabolic bio-machinery.

Small organic molecules of various compositions can be produced on mineral surfaces (Cody 2004). The minerals in question participate in the synthesis, either by being a supporting matrix (through specific adsorption), or as a reactant (e.g. redox reactions involving FeS), or as a true catalyst (in the Fischer–Tropsch type syntheses). Thus, mineral particles once encapsulated into a protocell compartment could have carried out these syntheses. The current presence of iron sulfide clusters in enzymes clearly supports such a concept (Mansy et al. 2016 this issue).

Mineral surfaces, such as those of clays, could also have promoted the emergence of biopolymers. Biopolymerizations are condensation reactions that are not favoured in an aqueous environment, even at extremely high monomer concentrations. Amino acid and activated nucleotide monomers could have first adsorbed on mineral surfaces, either spontaneously or as the result of a drying process. Both types of monomers could then be successfully, and non-enzymatically, polymerized (Hill et al. 1998; Maurel and Leclerc 2016 this issue). Recently, an indirect support of chemical reactions by mineral surfaces was also demonstrated by Rajamani et al. (2008): in this case, the dehydration/rehydration cycles of nucleotides in the presence of lipids on solid surfaces led to significant polymerization at relatively mild temperatures; the dehydration of the “dried” films even permitted a partial encapsulation of the biopolymeric products.

Thus, mineral surfaces could have jump-started the emergence of the main constituents of the current biochemistry, provided that some form of selective adsorption was possible. Selective adsorption of chiral molecules on chiral mineral surfaces has been demonstrated by Hazen et al. (2010).

**Energy Harvesting**

The uptake of energy and its conversion into bioenergetic currency (as in the respiration) or chemicals (as in photosynthesis) is central to cellular metabolism. However, a significant problem in the field of abiogenesis concerns...
the emergence of a phosphorus-based bioenergetic system or the development of the chemical machinery needed for photosynthesis from primitive machines within putative early Earth environments and without any sophisticated (proteinaceous) catalysis (Serrano et al. 2004).

Heat would have been the simplest energy to convert into chemical energy for early protocell systems, but it comes at a cost. Heat tends to destabilize amphiphile structures (Walde and Monnard 2015). In the case of light energy, simpler systems that are light-active could have functioned as primitive pigments, e.g., polycyclic aromatic hydrocarbons (PAHs; see Fig. 3) (Cape et al. 2011) whose presence in chondrites and within interstellar environments has been confirmed. These molecules spontaneously insert into vesicle bilayers. Other metal complexes, such as ruthenium and related complexes (Walde and Monnard 2015), if present, could be building up reaction units. Moreover, photosensitive minerals, such as the geologically available titanium dioxide (Summer and Rodoni 2015), could also serve as light-conversion units. In the case of redox-active minerals, iron sulphides would have been available. Thus, in principle, primitive energy harvesting units to power the direct transformation of chemical precursors into protocell units are plausible. These photocatalysts would be able to produce amphiphiles or even the ligation between nucleic acid strands (Walde and Monnard 2015), as well as power the formation of energy currency (Summer and Rodoni 2015). Moreover, PAHs do induce vesicle division (i.e., the splitting of a protocell into two protocells), which is an essential step in self-replication (Zhu et al. 2012).

It is important to remember that the chemical inventory was much more complex than the chemical composition of current cells. For instance, the total number of amino acids in meteorites is around 80; but life is based on a mere 20. By contrast, it is also clear that the presence of additional chemicals may have contributed to the emergence of protocells. As an example, the addition of co-surfactants, such as fatty alcohols or even PAHs, to fatty acid structures extends structure robustness in terms of aggregation equilibria, pH, temperature sensitivity, and solute encapsulation (Walde and Monnard 2015). Primitive mixed compartments might have even had an evolutionary advantage compared to pure ones (Budin and Szostak 2012).

**ProtoCell Construction**

The involvement of mineral surfaces would have been crucial in providing a nurturing environment for protocell formation. The formation of protocells, as is still the case for the current cellular membranes and other protein assemblies, would have been driven by molecular self-assembly processes, which are dependent on environmental conditions (pH, ionic strength, temperature) and, most importantly, on the properties of the molecules themselves and their concentrations (Sahai et al. 2016 this issue; Schoonen and Smirnov 2016 this issue).

**Self-Assembly Processes and Protocell Stability**

Besides being potential compartments themselves, minerals could have supported the formation of other types of compartments, such as amphiphile vesicles. Many mineral surfaces promote vesiculation (Hanczyc et al. 2007): in this

**Figure 3** Energy harvesting systems in amphiphile structures. (A) Decanoic acid, a putative prototypical prebiotic amphiphile. Amphiphiles will only self-assemble into bilayered vesicles (gray circle in centre of image) once their concentration in an aqueous medium surpasses a threshold value, often referred as critical vesicle concentration (CVC). Below the CVC, amphiphiles are present as single molecules (“monomers”); above it, vesicles are formed. The vesicles remain in equilibrium with monomers at a concentration equal to the CVC. Note that amphiphile systems can exhibit more complex equilibria. (B) (Inset) Epifluorescence micrograph of vesicle structures visualized with Nile red, a hydrophobic dye. These systems are used in the laboratory to model protocell compartments. Scale bar = 20 µm. (B) Hydrophobic or hydrophobically derivatized photosensitizers inserted in the protocell compartment boundaries: (1) amphiphilic ruthenium tris-bipyridine; (3) amphiphilic [Fe–Fe] cluster; (5) perylene; (6) 2,3(a)-naphthopyrene. Both (5) and (6) are polycyclic aromatic hydrocarbons (PAHs). (C) Hydrophilic solutes or nanoparticles in the aqueous lumen of protocells: (2) ruthenium tris-bipyridine; (4) [Fe–Fe] cluster; (7) (upper) inorganic pyrophosphite, (lower) inorganic pyrophosphate; (8) mineral particles. (D) An electron transfer system across decanoic acid vesicle bilayers. PAHs, such as (5) and (6), in the compartment boundaries can be excited by light and deliver an electron to an acceptor (here ferrocyanide). The PAH radical cation can be regenerated via electron transfer from a sacrificial electron donor, like ethylenediaminetetraacetic acid (EDTA), in the external medium. This results in net transmembrane electron transfer (Cape et al. 2011).
case, a mineral’s surface facilitates bilayer formation by likely promoting ordering of molecules on their surfaces in specific configurations.

The co-localization of protocol subsystems into protocell compartments might have been induced by mineral surfaces. Indeed, clay particles can both promote the synthesis of RNAs (Maurel and Leclerc 2016 this issue) and the vesiculation of amphiphiles (Hanczyc et al. 2007), even when RNA is associated with a clay’s surface. That is, polymers whose uptake by passive diffusion across amphiphile bilayers is limited could have been produced in situ, only requiring the diffusion of monomers, which is usually large. The same idea should apply to short peptides and other molecules of interest.

Titanium oxide particles promote the formation of amphiphile bilayers on their surfaces, a process that has been proposed as a way of linking mineral chemistry to protocell systems, which in turn links a potential source of chemicals and energy with cell-like boundaries (Summers and Rodoni 2015).

**PROTOCELL EVOLUTION**

It is clear that minerals and geochemistry played a paramount role in the emergence of early protocells. The question remains, however, about the processes that led to how protocells escaped from a mineral’s surface and became suspended as an autonomous system in an aqueous medium. Even though it has been suggested that cellular systems can completely mature in the presence of FeS (Martin and Russell 2003), several essential issues make these processes unavoidable: 1) Direct interactions between polymers and surfaces increase as the length of the polymers increase, resulting into an ever-tighter association which could have prevented the polymers from folding and becoming active catalysts; 2) Not all cellular functions, including protocellular ones, can be carried out on a mineral’s surface, especially considering the intertwined nature of cellular pathways; 3) Environmental changes would have required “migration” of protocells towards more auspicious environments; 4) One mineral would not have produced all the potential catalytic sites necessary for protocell construction and function, never mind subsequent evolution. Although the mineral heterogeneity and large inventory might have afforded a larger network of potential catalytic sites, developing a complete protocell system purely using mineral substrates seems most unlikely.

**Prerequisites for Evolution**

To evolve from their simple embodiments towards full-fledged precellular systems, protocells must have the ability to preserve their composition and functions, transmit them to next generations, and acquire novel functions by either taking up novel molecules from the environment or by merging with other protocells. It seems very unlikely that the transmission of protocellular properties to a new generation was directly linked to the heritable information system. The co-localization of protocell subsystems into protocell systems, which in turn links a potential source of chemicals and energy with cell-like boundaries (Summers and Rodoni 2015).

**Compartmentalization**

The evolution of the compartment subsystem was driven by the availability of amphiphiles, that either alone or in association with other molecules (such as PAHs) would have formed more stable vesicular compartments. The emergence of amphiphiles that possessed longer hydrocarbon chains or double hydrocarbon chains would have ensured better compartment integrity and protection for its contents. However, this would come at a price: the reduction of the protocol’s ability to take up molecules from the environment. Nevertheless, a simultaneous advantage of a stronger compartment boundary is that there would be a permeability decrease that would enable chemical gradients across wall boundaries to emerge, thereby initiating some novel energetics that could be exploited.

**Internal Catalytic Network and Information System**

In every phase of their evolution, protocols would have been dependent on environmental chemical fluxes (chemical syntheses, temperature, dehydration/rehydration cycles). However, protocols must have developed reaction networks that covered their chemical needs. To determine whether an RNA-based catalytic network and information system could have co-emerged, the problem needs to be addressed in relation to the compartmentalization of RNA in amphiphile vesicles. The encapsulation of RNAs on their surfaces increase as the length of the polymers whose uptake by passive diffusion across amphiphile bilayers is limited could have been produced in situ, only requiring the diffusion of monomers, which is usually large. The same idea should apply to short peptides and other molecules of interest.

It is more likely that the first compositional information, as in the genetic system now ubiquitous in modern biology, was directly linked to the heritable information system could have co-emerged, the problem needs to be addressed in relation to the compartmentalization of RNA in amphiphile vesicles. The encapsulation of RNAs on their surfaces has yet to be demonstrated. Maybe ribozymes were assembled from smaller RNA fragments (Doudna et al. 2001), which would have been more readily available. Ribozyme assembly, function and replication would have been promoted by other smaller molecules and metal ions, all of which require a suitable medium for the necessary reactions. Thus, the development of robust RNA metabolism seems to require the presence of an aqueous environment.

**Energy Uptake**

Protocells breaking off from their mineral substrates may have been the trigger for the development of more complex energy harvesting units and the advent of activated phosphorus-based energy-currency molecules, which are the drivers of much of the metabolic activity of contemporary biochemistry (Serrano et al. 2004). The formation of energy currency molecules would have been necessary for the development of a robust “metabolism” because of the need to precisely time chemical production, which the protocell would need to survive. Thus, the emergence of phosphorus-based bioenergetics should not be considered solely as a geochemical outcome but as a consequence of environmental conditions and contingent, system-specific properties of protocell compartmentalization.

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The phosphorus bioenergetics can be understood in terms of four interlinked processes: (i) harvesting external energy (light, minerals, etc.); (ii) generating an electron gradient; (iii) pumping of protons across a semi-permeable membrane (driven by the electron gradient); and (iv) capturing of free energy (free energy associated with the charge and concentration gradient dissipated upon return passage of protons through the transmembrane protein complex) within the molecular disequilibrium between inorganic phosphate (Pi) and condensed inorganic phosphates [pyrophosphate
(PPi)], or nucleoside triphosphates [e.g. adenosine triphosphate (ATP)]. Interestingly, these bioenergetic processes require compartmentalization to co-locate chemical systems (e.g. the light harvesting molecular apparatus) and confine the products. The compartmentalization prevents the dissipation of gradients.

For protocols devoid of sophisticated trans-bilayer transport systems, such permeability would have been essential to ensure access to molecules produced abiotically in the environment. Thus, the properties of these compartmentalization systems seem, at first sight, to preclude the formation of molecular gradients. However, comparisons between various solute diffusion rates show that there is a low permeability of charged small polymers (such as nucleic acids), of small anionic solutes with high charge density (such as potassium ferricyanide) (Cape et al 2011), and of pyranine (a fluorescent dye). Thus, molecular gradients of these molecules, or comparable ones, can be retained for periods of time compatible with further use of their stored energy for other chemical reactions (Fig. 3).

CONCLUSIONS AND OUTLOOKS

The involvement of geology and geochemistry in the emergence of life is undisputable, as is that of chemical systems. Each field has contributed greatly in advancing our knowledge of how life might have arisen. But protocol research still lacks an overall strategy by which to solve the cornerstone questions about how protocells originated. To move forward in this field, more collaborations between the researchers are needed.

As our understanding of prebiotic chemistry and geology broadens, it becomes clear that a resolution of the question of how protocells arose will not come from a single field, but rather from a concerted effort at the interface between many fields. The main challenge is the chemical complexity of the system and finding the appropriate research methodology. Current investigations, for example, are trying to implement cellular functions into a geochemical context. This approach is logical because the product of protocol evolution is known—it is the cell. However, the current assumption that protocol to cell evolution is a relatively linear process might yet turn out not to be correct.

ACKNOWLEDGMENTS

The authors thank colleagues in Odense (Denmark) and in Leeds (UK) for fruitful discussions, as well as the members of the COST [European Cooperation in Science and Technology] Action TD 1308 program, “Origins and Evolution of Life on Earth and in the Universe.

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Recent events show that we have before us rocky times of uncertain worldwide leadership, which will change the world in directions that are not healthy for our planet. As geochemists, we have the skills to address major human impact issues like pollution, ocean acidification or climate change and we need to stand together doing so.

My two years as EAG President have passed quickly with a mixture of very stimulating and, at times, highly time-consuming challenges, as well as rewards. This would not have been possible without the steadfast help of Marie-Aude Hulshoff, our business manager; she is the perfect glue that holds us together at the EAG. Thanks, Marie-Aude.

Over the last two years, I am proud to say that we strengthened our already good collaboration with the Geochemical Society (GS). We also expanded our bilateral agreements (MOUs) – that my predecessor Chris Ballentine started – to now include several European and international societies (most recently including the International Association for GeoChemistry and the Society for Geology Applied to Mineral Deposits). These agreements provide our members and our MOU societies members with more benefits and advantages. We also strive to reach geochemists in under-represented regions of the world through our Distinguished Lecture Program in Eastern Europe and EAG–GS Outreach Series in Africa. We support early career geochemists through our Student and Ambassador Programs, and we built a database of PhD/MSc/BSc programs and courses in geochemistry as well as links to available bursaries. We need your help to make this resource even better so please become active and send us your input.

Finally, the initiative and new member benefit that I am particularly proud of is the launch of Geochemical Perspectives Letters (GPL), a new short-length style geochemical journal written, edited and published by, and for, the geochemical community. We launched it in 2015. Together with the continually successful Geochemical Perspectives, the EAG has created a new home for excellent geochemical science publishing.

For me the highlight each year is the Goldschmidt Conference. In 2015, I helped Eric Oelkers and the Cambridge Publications team organize and run the Prague meeting. Seeing its success was a happy moment of change and we need to stand together doing so.

The students received feedback on diverse aspects including pronunciation, speed of delivery, improving slide content and design, emphasizing key points, and creating effective openings, closings and transitions. The presenters appreciated the input from the other students and group leaders, and received a real confidence boost going into their talks later in the week. Those participants not presenting at Goldschmidt 2016 came away with a lot of advice and ideas for planning and practicing talks and felt better prepared to give an oral presentation at their next international conference.

Although already being experienced presenters in their fields, the group leaders themselves got new ideas about how they might improve their own presentations and gained an awareness of some of the difficulties that mixed-language audiences might have in understanding native English speakers, who can sometimes be prone to speaking fast or using unfamiliar, non-technical language.

The workshop is sure to become a regular fixture at future Goldschmidt conferences and it is hoped that it can be expanded to provide specific help for designing posters and opportunities for native English-speaking students who are presenting at an international conference for the first time.

The organizers would like to thank the Local Organizing Committee in Japan, Elsevier for sponsoring the event, the staff and volunteers at JAMSTEC for their help on the day, and the six group leaders, who contributed their time and energy to the workshop’s success. Anybody interested in attending the workshop at Goldschmidt 2017 in Paris should keep an eye out for news and registration details on the conference website: www.goldschmidt.info/2017/
SPEAKING
- Give the audience time to get used to your accent. Speak clearly and slowly, especially at the start.
- Give synonyms for any unfamiliar or non-technical words that the audience may not understand.
- Try to use everyday English to make your talk more personal. Use active rather than passive forms.
- Avoid saying long numbers in full and approximate them when possible (e.g., “about five million years ago”, instead of “four million, eight hundred and ninety-six thousand years ago”).
- Practice any difficult pronunciation with a native English speaker or listen to examples at www.forvo.com.

SLIDES
- Aim for one clear message per slide and a maximum of 12 to 15 words of text.
- Limit the use of bullet-pointed lists—these can become very boring for the audience after a week of presentations!
- Avoid large blocks of text. The audience will attempt to read the text rather than listen to what you have to say.
- Plan to spend about 1-2 minutes on each slide. If you change slides too quickly, the audience won’t have time to digest the information; if you spend too long on a slide, the audience may lose concentration.
- Adapt and simplify graphs, maps and diagrams. Use thick lines and bold text to highlight key information; remove any unnecessary text or detail.
- Make sure your data can be distinguished by people who are colour-blind. Use symbols for data points.

AND OF COURSE…
- Practice, practice, practice! On your own, in front of friends, with colleagues, with your supervisor, in front of the dog, in a lecture hall, in your office, in the shower, on the bus...

EAG MEMBERSHIP: JOIN OR RENEW

Professionals €25/year or €100/5 years
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EAG endeavours to offer a comprehensive set of membership benefits, including:
- Reduced rates at Goldschmidt conferences
- Print and online issues of Elements, Geochemical Perspectives, Geochemical Perspectives Letters
- Reduced subscription rates to Chemical Geology and Geofluids
- Student sponsorship
- Ambassador Program supporting Early Career Scientists
- Sponsorship of member led workshops and conferences in Europe
- Member rates for print publications of the Mineralogical Society of Great Britain and Ireland (MinSoc), Società Geologica Italiana (SGI), Società Italiana di Mineralogia e Petrologia (SIMP)and Association Française pour l’Étude du Quaternaire (AFEQ), as well as member rates for events organised by the International Society for Environmental Biogeochemistry (ISEB), the International Association for GeoChemistry (IAGC), and the Society for Geology Applied to Mineral Deposits (SGA).

Join/Renew before 1 January to make sure you receive all publications for 2017. Find testimonies from EAG members on the EAG Blog (blog.eag.eu.com) about why they joined our society.

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PARIS | 2017

Abstract deadline: 1 April
In 2001, he was nominated as a Fellow of the Mineralogical Society of Italian) on geochemical prospecting and environmental geochemistry. He has published 240 papers (most of them in international peer-reviewed journals), and written 7 text books (in Italian) on geochemical prospecting and environmental geochemistry. He has been on advanced, low-impact geochemical exploration techniques that leave minimal environment impact and are, therefore, suitable for northern regions.

Davies has received several distinguished fellowships and research awards, including the prestigious Alexander von Humboldt Fellowship of Germany and the 2014 Nigerian Mining and Geosciences Society Shell Petroleum Award. He is also a Board Member of the UNESCO International Centre for Global-Scale Geochemistry, the Regional Councillor for Africa of the Association of Applied Geochemists and a (former) Councillor for Geoscience of the International Medical Geology Association.

**Theophilus Davies – Africa**

Prof. Theophilus Clavell Davies is a Chartered Geologist who currently holds the position of Visiting Professor of Environmental Geochemistry at the University of Nigeria at Nsukka. His teaching and research activities encompass such themes as ‘combating environmental health impacts of mining in Africa’ and ‘isolating and obviating the influence of geochemical co-factors in disease causation in Africa’. His work includes field and laboratory studies, and he has published over 200 papers in high-impact journals. Prof. Davies has received several distinguished fellowships and research awards, including the prestigious Alexander von Humboldt Fellowship of Germany and the 2014 Nigerian Mining and Geosciences Society Shell Petroleum Award. He is also a Board Member of the UNESCO International Centre for Global-Scale Geochemistry, the Regional Councillor for Africa of the Association of Applied Geochemists and a (former) Councillor for Geoscience of the International Medical Geology Association.

**Benedetto De Vivo – Southern Europe**

Benedetto De Vivo studied at the University of Napoli Federico II (Italy) and graduated in the geological sciences in 1971. From 1971 to 1976 he worked for private companies operating in Italy, Africa and Central America in the field of ore deposits, geochemical prospecting, environmental geology, and hydrogeology. From 1976 to 1987, he worked as researcher at Consiglio Nazionale delle Ricerche (Rome, Italy). From 1987 to 2000, he was an associate professor in applied geochemistry at the University of Napoli Federico II, where, in 2000, he became a full professor in geochemistry. Benedetto was a research fellow at the Colorado School of Mines (USA) in 1978 and also with the US Geological Survey (Virginia, USA) in 1982 and 1992. He was invited to serve as a visiting scientist at the Geological Survey of Japan in 1990 by the EU-Japan Centre for Industrial Cooperation.

He has been Chairman of the Inclusions in Minerals Working Group of the International Mineralogical Association, has been a member of the Editorial Board of *Geochemistry: Exploration, Environment, Analysis* (2004–2007) and Associate Editor of *American Mineralogist* (2012–2013). From 1996 to present, he has been a member of the Board of Associate Editors of *Mineralogy and Petrology*, and, since 2007, also Chief Editor of the Journal of Geochemical Exploration. Benedetto has been a member of different expert government committees for base-metal mining research activities and for the remediation of industrial sites in Italy. His current research interests include geochemical prospecting, fluid and melt inclusions studies, and environmental geochemistry. He has published 240 papers (most of them in international peer-reviewed journals), 30 educational articles, 30 monographs, has edited 36 special volumes in various international journals, and written 7 text books (in Italian) on geochemical prospecting and environmental geochemistry. In 2001, he was nominated as a Fellow of the Mineralogical Society of America, and in 2006 he was appointed as an adjunct professor at the Department of Geosciences at Virginia Tech (Virginia, USA). In 2016, he was appointed as an adjunct professor at Nanjing University (China).

**Pertti Sarala – Northern Europe**

Dr. Sarala specializes in applying Quaternary and surficial geology and geochemistry to mineral exploration. He joined the Rovaniemi office of the Geological Survey of Finland (GTK) in 2002 and worked in GIS database and management development and as a specialist of GTK’s geochemical data. Since 2008, he has worked as a senior scientist focusing on Quaternary and surficial geological research and the development of geochemical exploration methods. His focus has been on advanced, low-impact geochemical exploration techniques that leave minimal environment impact and are, therefore, suitable for northern regions.

Pertti obtained his MSc in surficial geochemical exploration in 1994 and his PhD in 2005, both from the University of Oulu (Finland). He has worked as a docent (adjunct professor) of Quaternary and surficial geology at the University of Oulu since 2009. From 1 June 2016 (for an initial 5-year tenure), Pertti was appointed a joint research professor of geochemical exploration at the GTK and at the Mining School of the University of Oulu. He has published ~40 papers and more than 150 other publications, including books, conference abstracts and working reports.

**Brian Townley – Chile**

Dr. Townley is an Associate Professor of Geology at the University of Chile who has over 25 years’ research experience in mineral deposits and applied geochemistry, specializing in Chilean metallogenesis. Over the past 10 years he has presented or published over 25 papers relating to applied geochemistry, ore deposits and mineral exploration in Chile. Currently, he is researching the continuity of the Miocene porphyry copper belt south of El Teniente, as well as the Upper Cretaceous porphyry copper deposits near the Maule River. He is also carrying out research at Los Bronces from the perspective of hydrothermal alteration modeling, mineral characterization and geometallurgy.

During his career, Dr. Townley has done consulting and applied research work for BHP-Billiton, Codelco, Yamana Gold, Angloamerican, Barrick, Antofagasta Minerals, Soquimich, and many other companies, for exploration and/or geometallurgy. These activities have been carried out in the Chilean districts of Escondida, Cerro Colorado, Spence, Chuquicamata, El Salvador, Los Pelambres, Rio Blanco–Los Bronces, El Teniente, Rosario de Rengo, El Peñon, among others. In his research work, he has led state, state/private partnerships and privately funded projects, as well as AMIRA International multi-client projects, all with a strong applied research component. In addition to publishing scientific papers, Dr. Townley keeps up-to-date by attending many short courses, including on-site short courses and workshops for industry, that take place in Chile, America, Argentina, Peru, Bolivia, Brazil and Canada. In parallel to mining industry–related research, Dr. Townley leads a state-funded research project on the impacts of geology, mineralogy and geochemistry on viticulture, part of the Vinos de Chile wine industry consortium.
CHANGING OF THE GUARD

In the academic publishing world, ‘December issues’ are a big deal. Indexes are prepared, lists of reviewers are compiled and cumulative lists of contents are assembled for those libraries that still bind their paper journals into volumes.

In learned societies, it is also the time when those volunteers who serve on some of our committees take their leave and are replaced by new ones. So, a big “Thank you” to Richard Pattrick and Andy Fleet (Custodian Trustees), to Andrew Kerr (Public Relations Officer), and to Council members Brian O’Driscoll and David Wray. Special thanks must go to Kathryn Goodenough, who has been the society’s General Secretary for the past six years. This is one of the most demanding posts in the society, and Kathryn has served in exemplary fashion. She’s not escaping entirely, however, as she will serve as chair of the Awards Committee from 2017–2019.

New people joining the MSGBI team are: Jana Horák – General Secretary; Philip Pogge von Strandmann – Public Relations Officer; David Wray – Custodian Trustee; John Bowles – Custodian Trustee; David Pyle – Distinguished Lecturer Coordinator; Members of Council: Clare Warren, Chiara Petrone, Sam Broom Fendley

Welcome all.

BOOK SALE

Our book sale continues until the end of January 2017. But please place an order soon to ensure that you don’t miss out. Many of our stocks are being depleted quickly (the whole purpose of the sale, of course!).

In particular, copies of Phoscorites and Carbonatites from Mantle to Mine: The Key Example of the Kola Alkaline Province are selling like hot cakes. Get ‘em before they’re gone.

Go to www.minersoc.org and click on the link for Online Shop.

‘REDOX’ MEETING IN 2017

In 2017, several of the society’s special interest groups (Geochemistry, Environmental Mineralogy, Geomicrobiology and Clay Minerals) are coming together to run a two-day meeting entitled, ‘Redox Processes’. The meeting will be held in Manchester (UK) from 21–22 June 2017. Registration details available soon.

MEMBERSHIP RENEWAL

At this time of year, you are asked to renew your MSGBI membership as soon as possible. It really helps when this is done promptly, avoiding the need for several reminders. Please renew as soon as the reminder pops into your mailbox. Thank you.

ONLINE ONLY JOURNALS FROM 2017 FORWARD

Beginning January 2017, our journals (Mineralogical Magazine and Clay Minerals) will become online only. We have listened to the vast bulk of our members who have told us that they don’t use the paper copy and prefer to access their chosen content online. This will also mean that we will have more money to publish more pages more quickly. Members should log in at www.minersoc.org to access the journals. The online version of Elements, which continues in paper form, will also be available from this aforementioned web page, without further barrier.

Note: We now have an online submission tool for Clay Minerals. Submit your next paper for that journal at http://www.edmgr.com/clayminerals/

WEBSITE SUGGESTIONS WELCOME

We are in the process of rebuilding our website. We’d like to hear from you if you have any suggestions about content/design. Send your thoughts to kevin@minersoc.org.
PRESIDENT’S LETTER

A Museum View of Mineralogy

When I considered running for the office in the Mineralogical Society of America (MSA) that leads to becoming president, I decided to see when the last time an MSA President was employed at a museum of natural history or science. I discovered it was Brian Mason in 1966 from the Smithsonian Institution (and one of my predecessors at the American Museum of Natural History, now 50 years ago. That is a long time considering that museums play a fundamental role in stimulating students and sustaining interest in mineralogy and its related subjects. So, I thought the museum perspective is a worthy topic for my first president’s letter. Moreover, as I am in the process of creating new exhibition halls of minerals and gems, the topic of minerals and museums is very much on my mind. Mineral exhibitions in museums are typically the first introduction a child has to crystals of minerals and their vast diversity, beauty, and significance. This contact, typically sustained over many visits, has been the foundation of many careers in the mineral sciences, as well as to the fascination of the vast community of mineral collectors. We are now challenged by the digital age and hand-held devices, which can offer (challenge?) museum visitors with a virtual “reality” as compared to the “real” stuff in an exhibition hall. Creating better displays—which engage visitors by connecting science, natural resources, culture, and good stories—is an ongoing challenge because one must merge a visual or tactile experience with the wider and deeper content. But, doing so is critical if we are to maintain or enhance the traditional flow of students into our sciences, let alone provide citizens with some sense of the mineral realm. Thus, we in the museum business take our role in mineralogy very seriously and recognize MSA as an ally in our activities of informal sciences, let alone provide citizens with some sense of the mineral experience to learn the basics of rocks and minerals. And many other resources can be found through the MSA website. Moreover, the society seeks new ways to publish and provide scientific content, so stay tuned for developments.

Moving on to a new role, now present in my own activities and found in most museums, I want to address teachers and their training. An advocacy that MSA can play in geoscience education is support for the training of teachers as well as academics. In the US, the Next Generation Science Standards (NGSS) are changing the framework of school education for the Earth sciences, such that they can be squeezed out of curricula unless integrated with the physical sciences or projected into aspects of the life sciences. Geoscientists and our societies, like MSA, must engage with the changing educational landscape, as pedagogy alone cannot. I will spend some time developing a strategy to promote this activity during my tenure and look forward to communicating with members and colleagues about it.

Finally, I encourage you to support MSA (as well as promote visiting museums with mineral displays).

NOTES FROM CHANTILLY

- MSA Council decided on the 2017 award recipients at its Fall Council Meeting in Denver (Colorado, USA). The Roebling Medal is awarded to Edward M. Stolper (California Institute of Technology, USA); the Dana Medal to Thomas W. Sisson (U.S. Geological Survey, Menlo Park, California, USA); the MSA Award to Dustin Trail (University of Rochester, New York, USA); and the Distinguished Public Service Award to David W. Mogk (Montana State University, USA). Fellows newly elected for 2017 are Jay J. Ague, Bernardo Cesare, Elizabeth Anna Cottrell, Glenn A. Gaetani, Tomoo Katsura, Yan Liang, Wendy R. Panero, James Kelley Russell, Sean R. Shieh, and Michael J. Walter.

- The 2017 recipients for the research grants in mineralogy and petrology from MSA’s Mineralogy/Petrology Research Fund are: Allan Lerner (University of Oregon, USA) for his study, “Developing a Volcanic Degassing Model for Mount St. Helens Volcano” and Jessica Hamilton (Monash University, Australia) for her study, “Enhancing Mineralogical Trapping of CO₂ Within Ultramafic Mine Tailings Material.” The 2017 recipient for the research grant in crystallography from the Edward H. Kraus Crystallographic Research Fund is Gabriela Aylin Farfan (Woods Hole Oceanographic Institution, USA) for “Probing Coral Aragonite Crystallography under Changing Ocean Conditions using Synchrotron-based Ca-EXAFS.”

- All 2015 and 2016 MSA members have been contacted by mail, electronically, or both about renewing their membership for 2017. If you have not renewed your MSA membership, please do so. If you have not received a notice by the time you read this, please contact the MSA Business Office. You can also renew online at anytime.

George Harlow, MSA President

The 2017 16-month calendar showcases wulfenite. The calendar is published by Lithographie, LLC, in cooperation with MSA, and is available from MSA. See http://www.minsocam.org/.

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

http://www.minsocam.org/
**MAST STUDENT GRANT Awardees**

**Gabriela Aylin Farfan** (Woods Hole Oceanographic Institution, Massachusetts, USA) received the 2017 Grant for Research in Crystallography, as funded by the Edward H. Kraus Crystallographic Research Fund for her proposal “Probing Coral Aragonite Crystallography under Changing Ocean Conditions using Synchrotron-based Ca-EXAFS.” Ocean conditions continue to change at unprecedented rates (e.g., increasing ocean acidification, higher ocean temperatures, anthropogenic pollution), one result of which is that coral species face increasing risk of death and even extinction. Many studies have investigated the biological response to external stressors, but few have explored corals from a mineralogical and crystallographic perspective to understand how these same stressors will influence the development and stability of coral skeletons and subsequent coral health. Ms. Farfan proposes to quantify the effect of increasing ocean temperatures on coral biomineralization by probing the crystallography of coral larval skeletons grown under an array of temperature conditions using crystallographic and synchrotron-based techniques.

**Jessica Hamilton** (Monash University, Australia) received one of the 2017 Grants for Student Research in Mineralogy and Petrology for her proposal “Enhancing Mineralogical Trapping of CO₂ within Ultramafic Mine Tailings Material.” Carbon mineralization is a natural weathering process, whereby carbon dioxide (CO₂), which is a greenhouse gas, is removed from the atmosphere and stored in the structures of minerals. Sequestration of this greenhouse gas in minerals is the only known form of permanent CO₂ storage; carbonate mineral products are themselves environmentally benign, safe, and are currently utilised in several industries. Jessica’s research aims to develop and test novel, low-cost treatments for carbonating the mineral waste generated by mining by conducting a series of column experiments using mine tailings to simulate a range of tailings management strategies using crystallographic and synchrotron-based techniques.

**Allan Lerner** (University of Oregon, USA) received one of the 2017 Grants for Student Research in Mineralogy and Petrology for his proposal “Developing a Volcanic Degassing Model for Mount St. Helens Volcano.” Monitoring changes in rates or types of gas emissions are critical for recognizing early signs of volcanic unrest. Sulfur dioxide is the most routinely monitored volcanic gas because sulfur is relatively abundant in magmas, and SO₂ strongly absorbs ultraviolet light and has very low background atmospheric levels, making volcanic SO₂ relatively easy to detect. However, our SO₂ measuring capability has largely outpaced our ability to understand what SO₂ emissions actually represent in volcanic systems. The solubility and degassing behavior of SO₂ depends on physical parameters (e.g., pressure, temperature) and geochemical parameters (e.g., melt composition, oxygen fugacity) that vary widely between different volcanic centers and are often poorly constrained. Consequently, effectively utilizing SO₂ emissions as a volcanic monitoring tool is hampered by a lack of degassing models specific to the volcano in question. Allan proposes to develop a petrologic degassing framework for one of the most threatening volcanoes in the US, that of Mount St. Helens (Washington, USA), and compare ongoing gas monitoring with predictions from the degassing model.

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**AWARD NOMINATIONS**

**Nominations Sought for 2018/2019 Awards**

Nominations must be received by 1 June 2017

The **Roebling Medal** (2018) is MSA’s highest award and is given for eminence as represented by outstanding published original research in mineralogy.

The **Dana Medal** (2018) is intended to recognize continued outstanding scientific contributions through original research in the mineralogical sciences by an individual in the middle of their career.

The **Mineralogical Society of America Award** (2018) is given for outstanding published contribution(s) prior to 35th birthday or within 7 years of the PhD.

The **Distinguished Public Service Medal** (2019) is presented to an individual who has provided outstanding contributions to public policy and awareness about mineralogical topics through science.

Society **Fellowship** is the recognition of a member’s significant scientific contributions. Nomination is undertaken by one member with two members acting as cosponsors. Form required, contact committee chair or MSA home page.

**MINERALOGICAL SOCIETY OF AMERICA**

Submission requirements and procedures are on MSA’s home page: [http://www.minsocam.org/](http://www.minsocam.org/)

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**IN MEMORIAM**

**Henry L. Barwood** – Member, 1989
FROM THE PRESIDENT

More than 700 scientists, many of whom were young scientists, attended the second European Mineralogical Conference (emc2016) in Rimini (Italy). The catering was excellent and the location was ideal to promote friendly and fruitful exchanges between participants of different nationalities during the breaks. Many thanks are due to Giuseppe Cruciani and Bernardo Cesare for organizing emc2016, and thanks also go to Heidi Höfer, who was our DMG correspondent during the preparation phase. The European mineralogical communities all agreed that this type of meeting should continue once every four years. Two countries have offered to be potential hosts for the next EMC meeting in 2020.

This year, the committee of the Paul Ramdohr Award could not meet directly at the end of emc2016 but made the decision, a few days later, to give the award to Martin Kutzschbach (TU Berlin und GFZ Potsdam). Congratulations also go to Gerhard Brey (Abraham Gottlob Werner Medal in Silver), Ulrich Förstner (Georg Agricola Medal), Christoph Burkhardt (Victor Moritz Goldschmidt Prize), Sarah Incel (Beate Mociek Prize) and to the two honorary fellows (Ehrenmitglieder) Herbert Kroll and Herbert Palme!

After two years as president of the DMG it is already time for me to pass my responsibilities on to Reiner Klemd (University of Erlangen–Nürnberg, Germany), who has my best wishes for the forthcoming two years. With Reiner, the society will have a president with a scientific focus on the formation of ore deposits, and I am happy to see this subdiscipline once again becoming attractive among the German geoscientific community and in universities. My work as president was largely facilitated by your support, and I would like to thank everybody who helped in the various tasks related to the DMG board and to the commissions (more than 60 persons in total!), but in particular our secretary, Klaus-Dieter, for his constant and effective assistance. I would also like to encourage the numerous foreign geoscientists (and scientists generally) who have jobs in Germany to participate in the life of our national societies. We would welcome you! German research facilities and the jobs they support are mainly funded by national companies and institutions: having a strong and well-organized national science society, such as the DMG (among many others), is necessary to adequately represent our total community at the national level.

I am looking forward to meeting many (hopefully new) DMG members at our next meeting in Bremen. And I wish all the members a happy and peaceful Christmas.

François Holtz (DMG President)

DMG AWARDS FOR 2016

At the emc2016 meeting in Rimini (Italy) the DMG announced the recipients of its 2016 awards (see also meeting report p. xxx).

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 allied fields. The 2016 medal was presented to Gerhard Brey (Goethe University, Frankfurt). Gerhard Brey is an internationally renowned mineralogist, petrologist and geochemist. His work spans an exceptionally wide range of disciplines and includes geothermobarometry in 4-phase leherzolites, isotope and trace element geochemistry of mantle rocks, carbonate sediment–peridotite interaction, partitioning of trace elements between carbonatic melts and mantle minerals, inclusions in diamonds, determining the oxidation state of Fe by electron microprobe, and archaeometry.

The Georg Agricola Medal of the DMG recognizes outstanding achievements in the field of technical and applied mineralogy. Ulrich Förstner (Technical University Hamburg-Harburg) received the medal for his fundamental contributions to water protection and the remediation of contaminated soils. He developed new geochemical engineering concepts and technologies for the management of contaminated sediments on the scale of river basins. His book on methods of cleaning up environmental contamination, Umweltschutztechnik, was first published in 1990 by Springer: the 9th edition is planned for 2017.

The Victor Moritz Goldschmidt Prize is given to young researchers for outstanding contributions to mineralogical science. In 2016, the prize was awarded to Christoph Burkhardt of the University of Münster for his exceptional contributions to the fields of geochemistry and cosmochemistry. He showed that Earth’s precursor bodies, when compared to chondritic meteorites, were enriched in neodymium that had been produced by slow neutron capture nucleosynthesis. Taking this into account, the Nd142/Nd144 ratios of chondrites and the accessible Earth are nearly indistinguishable.

Consequently, chondrites are suitable proxies for Earth’s bulk chemical composition, although they formed at greater heliocentric distances and contained a different mix of presolar components than did Earth (Burkhardt et al. 2016, Nature 537, pp 394–398). Christoph Burkhardt will give a plenary talk at the next DMG meeting in Bremen (GeoBremen 2017).
The Paul Ramdohr Award is given for the best student contribution at the annual meeting of the DMG. At last year’s meeting, GeoBerlin 2015, two students were honoured. Maria Stuff (TU Berlin and GFZ Potsdam) presented the talk “Experimental Constraints on Fe Isotope Fractionation between Silicate and Carbonate Immiscible Melts” and Aurelia Zirner (Steinmann Institute, Bonn University) was awarded for her poster, “Anorthositic Dykes in Cyprus – Precipitates of Magmatic Fluids?”.

The Beate Moeck Prize is dedicated to supporting mineralogical research by young female scientists, in particular in the fields of petrology and geochemistry. This year’s award was given to Sarah Incel (Ecole Normale Supérieure de Paris, France). Within the context of the European Marie Curie Initial Training Network known as “ZIP – Zooming In-between Plates”, she performed a set of experiments to characterize the mechanics and rheology of the oceanic and continental crust during eclogitization. Her project also involved field study (to the Western Gneiss Region of Norway) in the hope of linking laboratory microstructures with structures observed in natural rocks. Sarah will use the prize’s financial support to perform additional experiments at the Advanced Photon Source (APS) in Chicago (USA).

CPKM AND AMITU WORKSHOP 2017

The next joint workshop of DMG’s sections Chemistry, Physics and Crystallography of Minerals (CPKM) and Applied Mineralogy in Technique and Environment (AMITU) will take place 22–24 February 2017 in Bad Windsheim (Germany), which is in the northern region of Bavaria. As always, the major aim of the workshop is to bring students in contact with experienced scientists in order to discuss the students’ recent and future scientific work. For further information, contact Christoph.berthold@uni-tuebingen.de.

GEOLOGY OF ORE DEPOSITS (GOOD) MEETING

Leibniz University Hannover
8–11 March 2017

Continuing the successful 1st Geology of Ore Deposits (GOOD) conference in March 2016 in Freiberg (Germany), we invite all young researchers in the field of ore deposit geology to the 2nd GOOD meeting. The 2nd meeting will take place 8–11 March 2017 at the Institute for Mineralogy at the Leibniz Universität Hannover (Germany). The attendance fee is €40.

The conference aims to connect young professionals from all disciplines in ore deposit geology. All participants will have the opportunity to present and discuss their research results with an audience on a level playing field. The conference program will be completed by keynote speakers from scientific and industrial backgrounds, and there will be an icebreaker event and some regional field trips.

For further information, please contact us or have a look at www.dmg-home.org (working group: Rohstoffforschung).

Lennart Fischer, Malte Junge (Hannover)

DMG SHORT COURSES 2017

In 2017, the DMG will support eight short courses. All courses will be aimed primarily at advanced-level undergraduate and graduate students but, as always, are open to more senior researchers as well. Nonlocal student members of the DMG will be eligible for travel support to the amount of €50. Further information can be found at www.dmg-home.org/aktuelles/doktorandenkurse/.

1) High-Pressure Experimental Techniques and Applications to the Earth’s Interior, Bayerisches Geoinstitut/University Bayreuth (Germany), Dr. Stefan Keyssner, 20–24 February 2017 (stefan.keyssner@uni-bayreuth.de)

2) Rietveld Refinement: Basic Principles and Applications (Grundlagen und Anwendung der Rietveld-Verfeinerung): Max Planck Institute for Solid State Research (Stuttgart, Germany), Prof. Dr. Robert E. Dinnebier, 6–9 March 2017 (r.dinnebier@fkf.mpg.de)

3) Solid-State NMR Spectroscopy (Anwendungen der Festkörper-NMR-Spektroskopie in der minerallogischen und geowissenschaftlichen Forschung), Institute for Geology, Mineralogy and Geophysics, Ruhr University Bochum (Germany), Dr. Michael Fechtelkord, 6–9 June 2017 (michael.fechtelkord@rub.de)

4) Mineralogy, Mineral Physics, and Seismology of the Earth’s Mantle (Mineralogie, Mineralphysik und Seismologie des Erdmantels), Bayerisches Geoinstitut/University Bayreuth (Germany), Dr. Hauke Marquardt (BGI), Prof. Christine Thomas (University Münster, Germany), tba for summer 2017 (hauke.marquardt@uni-bayreuth.de)

5) In situ Analysis of Isotopes and Trace Elements by Femtosecond Laser Ablation ICP-MS (In situ-Analyse von Isotopen und Spurenelementen mit (LA-) ICP-MS gekoppelt mit Femtosekunden-Laserablation), Institute for Mineralogy, Leibniz Universität Hannover (Germany), organized by Prof. Dr. Stefan Weyer and others, 9–13 October 2017 (s.weyer@mineralogie.uni-hannover.de)

6) Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences, Helmholtz Centre Potsdam–GFZ German Research Centre for Geosciences (Germany), Dr. Michael Wiedenbeck, 13–17 November 2017 (michael.wiedenbeck@gfz-potsdam.de)

7) SEM-based Automated Mineralogy, Helmholtz Centre Dresden–Rossendorf (Germany), Dr. Axel Renno (HZDR), Prof. Bernhard Schulz (Freiberg), tba for October/November 2017 (a.renno@hzdr.de)

8) Application of Ion Beam Analysis in Mineralogy and Geochemistry, Helmholtz Centre Dresden–Rossendorf and Helmholtz Institute Freiberg for Resource Technology (Germany), Dr. Axel Renno, Dr. Frans Munnik, Dr. René Heller, 20–24 November 2017 (a.renno@hzdr.de)
Japan Association of Mineralogical Sciences

http://jams.ja.coocan.jp

JAPAN ASSOCIATION OF MINERALOGICAL SCIENCES Awardees

The Japan Association of Mineralogical Sciences (JAMS) is proud to announce the recipients of its 2016 society awards. The 2016 Japan Association of Mineralogical Sciences Award for Young Scientists is being awarded to three scientists under 37 years of age, all of whom have made exceptional contributions to mineralogy or related sciences. The Japan Association of Mineralogical Sciences Award for Applied Mineralogy is being awarded to one scientist who has made remarkable contributions in the field of applied mineralogy. The Japan Association of Mineralogical Sciences Research Paper Award is being awarded to the authors of excellent papers that were published in the Journal of Mineralogical and Petrological Sciences (JMP) and the Ganshiki-Kobutsu-Kagaku (GKK) in the previous three years. Congratulations to the awardees!

JAMS Award for Young Scientists: Tatsuya Sakamaki

Tatsuya Sakamaki is an assistant professor at the Graduate School of Science and Faculty of Science, Tohoku University (Japan). He received his PhD from Tohoku University (supervised by Professor Eiji Ohtani) on pressure-induced changes in the property/structure of magma and its correlation to its macroscopic property and microscopic structure. The goal was to better understand magma behavior from the magma ocean in the early Earth to present-day volcanism. Dr. Sakamaki demonstrated, using density measurements at high pressures and temperatures (notably through X-ray absorption), that hydrous magma at the base of the upper mantle was gravitationally stable. His results indicated a rapid reduction of the partial molar volume of H₂O in the magma with pressure, causing sufficient densification for the hydrous magma to become stagnant. On this basis, he proposed a “ponded magma model” at the lithosphere–asthenosphere boundary due to a decrease in magma segregation rate. This model can help explain the geophysically observed anomaly at or near that boundary. In addition to Earth’s magma, he also investigated basaltic magma, and found a density crossover between this magma and the lunar mantle at a certain depth. Based on this result, he suggested that subducted magma could create chemical heterogeneities and be the cause of the low-velocity anomaly observed in the lunar mantle using seismic tomography.

JAMS Award for Young Scientists: Koichi Momma

Koichi Momma is a researcher at the National Museum of Nature and Science in Tokyo (Japan). He has been studying such topics as the growth mechanism of quartz twins, accurate electron density analysis using the maximum entropy method (MEM), the development of crystallographic visualization software, X-ray crystal structure refinement, and the description of new minerals. In the study of quartz, he successfully modeled the structures of the Japanese twin law (1122) twin boundaries by using molecular dynamics simulations. He also investigated the growth history of natural Japanese twin quartzes using optical microscopy, scanning electron microscopy, and cathodoluminescence. The results of these observations were then interpreted from the perspective of atomistic models of twin boundary structures. Dr. Momma revealed the interesting roles played by the (1122) twin boundaries: (1) they are the only coherent and energetically stable composition plane that requires no dangling bonds; (2) they are the preferential site for crystal growth; (3) they are the source of dense Brazil law twin lamellae. A Japanese law twin grows about 1.5–2 times faster than a single crystal when, and only when, the composition plane is (1122), and this preferential growth is due to the structural nature of the (1122) twin boundaries, which allow for a variety of configurations of the SiO₄ tetrahedral linkages.

To conduct accurate electron density analyses using MEM, Dr. Momma developed the MEM-analysis software Dysnomia, which can converge to the true MEM solutions instead of approximate solutions, and can be used for the MEM-based pattern fitting of powder X-ray diffraction data in combination with the Rietveld analysis code RIETAN-FP. An appropriate weighting for the observed structure factors has been noted as necessary to obtain reasonable electron density distributions using MEM. Dr. Momma revealed the physical meaning of the weighting and also pointed out that different weighting factors should be used for X-ray and neutron diffraction data.

Dr. Momma has also contributed to descriptive studies of new minerals, and the development of the widely used crystallographic visualization software VESTA.

JAMS Award for Applied Mineralogy: Kunio Ishikawa

Kunio Ishikawa is a professor at the Department of Biomaterials, Faculty of Dentistry, Kyushu University (Fukuoka, Japan). His key interest is the reconstruction or regeneration of hard tissues (teeth and bones) using calcium phosphates or calcium carbonate. His key technique is the dissolution–precipitation reaction known as the setting reaction of gypsum. For example, it takes 30–60 minutes for apatite cement (tetra-calcium phosphate and dicalcium phosphate anhydrous) to set and form hydroxyapatite, a reaction that is based on the dissolution–precipitation reaction. Prof. Ishikawa analyzed the reaction using a chemical potential method and found that the supply of the phosphate to the reaction media was the rate-determining step. He developed a fast-setting apatite cement, which sets within only 5 minutes, by adding sodium phosphate to the liquid phase of the cement. This fast-setting cement is now the world standard for apatite cement. Recently, he has been developing a carbonate apatite (CO₃Ap) as a bone replacement. In the 1970s, sintered hydroxyapatite (s-HAp) was found to show excellent tissue response and good osteoconductivity. However, bone apatite is not HAp but CO₃Ap. Prof. Ishikawa fabricated CO₃Ap based on the dissolution–precipitation reaction using calcium carbonate as a precursor in a sodium phosphate solution. The CO₃Ap gets resorbed by the osteoclast and new bone is formed by the osteoblasts. As a result, CO₃Ap is replaced by bone similar to the graft bone. In addition, CO₃Ap was found to up-regulate the proliferation of osteoblasts. Thus, CO₃Ap demonstrated a much higher osteoconductivity, even when compared to HAp. Granules of CO₃Ap are now under clinical trial.

JAMS Award for Applied Mineralogy: Hiroshi ISOBE

Hiroshi ISOBE (Takaaki Gondo (2013)) Dendritic magnetite crystals in rapid quenched fine spherules produced by falling experiments through the high temperature furnace with controlled gas flow. Journal of Mineralogical and Petrological Sciences 106-4: 227-237

Japan Association of Mineralogical Sciences Research Paper Award

Hiroshi ISOBE
The year 2017 is knocking at the door, and it is time for all participants to organize their travel to Granada (Spain) for the 16th International Clay Conference, the quadrennial AIPEA meeting. The conference will be organized by the Sociedad Española de Arcillas (Spanish Clay Society), under the chairmanship of Dr Alberto Lopez Galindo (University of Granada). The five-day meeting will take place 17–21 July 2017 at the Science Park in Granada. With the theme “Clays: from the Oceans to Space”, the conference will embrace the universe of micro- and nanominerals, confirming, once again, the central role that AIPEA plays in promoting multidisciplinary activities in theoretical and applied clay science. The meeting will be an excellent occasion for sharing ideas and knowledge with scientists working in the diverse scientific fields of microminerals. It will also be a great opportunity to meet old and new friends, and to visit the wonderful city of Granada. More information can be found at the website www.16icc.org.

Cont’d from page 434

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Original Articles

Mineralogical characterization of radioactive particles from Fukushima soil using p-XRD with synchrotron radiation – Satoko MOTAI, Hiroki MUKAI, Tetsu WATANUKI, Kenji OHWADA, Tatsu FUKUDA, Akihiko MACHIDA, Chisaki KURAMATA, Ryosuke KIKUCHI, Tsuyoshi YAITA and Toshihiro KOGURE

Color-inducing elements and mechanisms in nephrites from Golmud, Qinghai, NW China: Insights from spectroscopic and compositional analyses – Haiyan YU, Rucheng WANG, Jichun GUO, Jianguo LI and Xiaowen YANG

U-Pb ages and Hf isotopic composition of zircon and bulk rock geochemistry of the Dai Loc granitoid complex in Kontum massif: Implications for early Paleozoic crustal evolution in Central Vietnam – Pham Trung HIEU, Nguyen Thi DUNG, NGUYEN Thi Bich Thy, Nguyen Trung Minh and Pham Minh

Geothermobarometry of amphiboles in intermediate to basic rocks from the Almogholah pluton in western Iran – Manuchehr AMIRI, Ahmad AHMADI KHALAJI, Zahra TAHRASBI, Reza ZAREI SAHAMI and Hassan ZAMANIAN

Internal texture and U–Th–total Pb isochron ages of monazite in metamorphic rocks from the Southwestern Highland Complex, Sri Lanka – D. Nuwan Sanjaya WANNIARACHCHI and Masahide AKASAKA

Structural refinement of köttigite-parasymplesite solid solution: Unique cation site occupancy and chemical bonding with water molecules – Akira YOSHITASA, Yumiko MIYANO, Hiroshi ISOBEM, Kazumasa SUGIYAMA, Hiroshi ARIMA, Akihiko NAKATSUKA, Koichi MOMMA and Ritsuro MIYAWAKI

CALL FOR AWARD NOMINATIONS

Nominations are now sought for 3 awards: the AIPEA Medal, an AIPEA Fellowship, and the AIPEA Bradley Award.

AIPEA Medal – This medal was established to award clay scientists for outstanding contributions to advancing our knowledge of clays and clay minerals. A maximum of two medals will be awarded at the 16th International Clay Conference (17-21 July 2017 in Madrid, Spain). All candidates must be active clay scientists, meaning that they have published a minimum of three publications in refereed and internationally recognized journals in the last two years. Candidates can be proposed by affiliated societies or by AIPEA members and should include supporting letters from at least three individual AIPEA members.

AIPEA Fellowship – The AIPEA Fellowship program was established to recognize and reward clay scientists for a lifetime of activity in promoting clay science and in supporting the clay science community through AIPEA or other bodies. Fellows must be current members of AIPEA. Nominations can be submitted by a member of the AIPEA Council, by a national society liaison officer, or by a national or regional society of clay scientists. The proposal should contain publications and appropriate supporting documentation (e.g., supporting letters, curriculum vitae, etc.). and should be submitted to the president of AIPEA by 31 December 2016. Selection will be made by the AIPEA Council. The successful nominee will be invited to take part in the 16th International Clay Conference, and AIPEA will pay for the registration fee.

AIPEA Bradley Award – The Bradley Award offers financial assistance to the recipient to enable him or her to participate in an International Clay Conference for the purpose of presenting a scientific contribution. Persons eligible for the award shall be under 35 years of age on the closing date for submission, and no restriction is placed on the sex or nationality of the candidate or the nature of his or her employment. Every application must be supported in writing by two members of AIPEA. Deadline for the receipt of applications is 31 December 2016. Candidates must submit an electronic copy, preferably in Microsoft Word, of a 4,000-word paper on a topic relevant to one of the sessions at the conference. The paper should be written in a format acceptable for publication in an international journal. Assessment will be based on scientific content only and the winning entry shall form the substance of a paper to be presented by the successful candidate at the conference to which the award relates.

Finally, to support students (or those under 35 years of age) to participate in the 16th International Clay Conference, AIPEA will assign financial contributions. To participate in the Student Travel Funds program, the student should submit an abstract and his/her curriculum vitae. This submission must be supported in writing by two members of AIPEA. Deadline for the receipt of applications is 31 December 2016. Candidates must submit a 2,000-word paper on a topic related to one of the sessions at the conference. The paper should be written in a format acceptable for publication in an international journal. Assessment will be based on scientific content only and the winning entry shall form the substance of a paper to be presented by the successful candidate at the conference to which the award relates.

All correspondence related to the awards must be addressed to Dr. Saverio Fiore, President of AIPEA, by email (president@aipea.org). Further information can be found at www.aipea.org.

Saverio Fiore, AIPEA President
The 79th Annual Meeting of the Meteoritical Society was held Sunday 7th– Friday 12th August 2016 in Berlin (Germany). The meeting took place in the Henry-Ford-Bau of the Freie Universität Berlin. With 539 registered participants, this annual meeting was amongst the largest ever. And it was the tops in terms of student participation: 136 students. In total, 544 abstracts were accepted for 289 oral and 255 poster presentations. Oral presentations were scheduled in three parallel sessions from Monday to Friday, and all posters were on display for the duration of the conference week.

Of the 539 registered participants, 244 were members, 117 non-members, 87 student members, 49 non-member students, 37 accompanying persons, and 5 guests. A total of 60 travel awards were allocated to student members, early career scientists, and scientists from low-income countries through generous sponsorship to the combined amount of $76,000, which had been donated by the Barringer Crater Company, the NASA Cosmochemistry Program, the International Meteorite Collectors Association (IMCA), the Planetary Studies Foundation (PSF), Elsevier, and the Meteoritical Society Endowment Fund. A grant from the Deutsche Forschungsgemeinschaft (DFG) allowed several student assistants to be employed, who then could also participate in the scientific sessions.

The conference kicked off with registration in the Thaersaal of the Humboldt University of Berlin, followed by the Welcome Function, which was sponsored by the Museum für Naturkunde and that was held amidst the museum’s exhibitions. The welcome party also provided an opportunity for a preview of the museum’s special exhibition: “Comets – The Rosetta Mission, A Journey to the Origins of the Solar System.” The scientific program covered 21 topics. These included the processes and evolution of Solar System materials (interplanetary dust particles, chondrites, achondrites, asteroids, and Mars); the chronology, mineralogy, and chemical compositions of extraterrestrial materials; aspects of impact cratering; planetary sciences, including evolution and dynamics of the planets, the Moon, and small planetary bodies. There were five special sessions: “Presolar Grains - A Session in Honor of Ernst Zinner”; “From Meteorites to Planets – A Session in Honor of Heinrich Wänke”; “Small Meteorite Impacts – From Atmospheric Entry to Environmental Effects”; “Surface and Interior Dynamics of Meteorite Parent Bodies”; and, “Planetary Evolution: Advances in Meteoritical and Lunar Isotopic Analysis.” Within the “Presolar Grains” session there was a special invited lecture, sponsored by the Meteoritical Society’s Endowment Fund, that was given by Maria Lugaro (Budapest, Hungary) with the title, “Stellar Grains in the Laboratory: Messengers from the Sky!”.

The main conference program was preceded by a two-day workshop entitled Shock Metamorphism and High Pressure Phases in Meteorites and Terrestrial Impactites that was convened by O. Tschauner, T. Sharp, and D. Stöffler and that included the special session “Microstructure and Geochronology of Shocked Accessory Minerals” (convened by A. Cavosie and N. Timms). The workshop was attended by 58 participants. The Annual Barringer Invitational Lecture was presented by Professor Mark McCaughrean of the European Space Agency (Nordwijk, The Netherlands) on Monday evening in the Henry-Ford-Bau auditorium. His fabulously illustrated lecture, “Rosetta: To Catch a Comet!”, was very well received by an audience of some 400. Mark’s presence on Tuesday morning (9th August) also enhanced the public opening of the Rosetta exhibition.

The Meteoritical Society’s Award Ceremony, plus talks by recent medalists Hiroko Nagahara (Leonard Medal) and Keith Holsapple (Barringer Award) took place on Wednesday morning (10th August). This event also included a special appreciation of the late Gerald (Jerry) Wasserburg (1921–2016), which was given by Gary Huss.

Following the award ceremony, most conference attendees embarked on the two bus tours: the City of Contrasts tour, and the Excursion to Potsdam tour. Later that evening, the annual conference banquet was held at the former Berlin sewage works, the Wasserwerk venue, which provided a novel ambience. Following the four-course dinner, late-night revelers enjoyed dancing until 1:00 am. To conclude on the topic of festivities, both poster sessions on Tuesday and Thursday evenings were well catered for, and the conference concluded on Friday afternoon with an impromptu farewell function.

Four excursions took place around the conference. Preconference trips went to the old mining-town of Freiberg and to the Ore Mountains in Saxonia (to the southeast of Berlin), and there was a 5-day tour that
explored the Nördlinger Ries and Steinheim Basin impact craters and that sampled the cultural and culinary delights of southern Germany. Following the conference, a small group of participants investigated the Morasko impact-cratner field near the Polish city of Poznan, while others travelled to Norway to partake in an expedition to the Rietland impact structure in the mountains west of Oslo. The excellent excursion guides deserve our compliments.

The conference program and abstract volume can be accessed on the website of the Lunar and Planetary Institute (http://www.lpi.usra.edu/meetings/metsoc2016/) and on the dedicated conference website (http://www.metsoc-berlin.de/). A sizable and impressive image gallery put together by Hans Knöfler is accessible at https://metsoc.naturkunde-berlin.de/.

The meeting was generously supported by the Barringer Crater Company, the Museum für Naturkunde Berlin - Leibniz Institute for Evolution and Biodiversity Science, the Humboldt-Universität zu Berlin, the Freie Universität Berlin, NASA’s Cosmochemistry Program, the Lunar and Planetary Institute, the Geo.X Alliance for Geoscience in Berlin-Potsdam, the International Meteorite Collectors Association, the Deutsche Forschungsgemeinschaft (DFG), the Planetary Studies Foundation, Meteorite Times Magazine, Elsevier, AMETEK, Bruker Nano, JEOL, Thermo Fisher Scientific, DFG (the Collaborative Research Centre TRR170 Late Accretion onto Terrestrial Planets), and the Meteoritical Society.

This report would not be complete without us thanking the numerous colleagues and students whose tireless efforts made it all possible. We want to emphasize the dedicated support from the members of the Local Organizing Committee, the Scientific Program Committee, and the Travel Award Committee, and from all those who made themselves available as judges of student presentations, guides on conference tours, student assistants, and as general helpers. Staff of CPO Hanser provided expert event management support.


SOCIETY AWARD WINNERS

The Meteoritical Society gives four major awards each year. For more information on individual awards see the Call for Nominations and the society’s webpage.

LEONARD MEDAL This is the society’s highest and oldest award and is given to individuals who have made outstanding original contributions to the science of meteoritics or closely allied fields. It is named for Frederick C. Leonard, who was a founder and the first president of the society. The 2016 winner is Hiroko Nagahara (University of Tokyo, Japan), for her fundamental contributions to understanding the origin and evolution of primitive planetary materials, including chondrule formation and the kinetics of gas-solid reactions. The citation was given by Shogo Tachibana.

BARRINGER MEDAL AND AWARD This is sponsored by the Barringer Crater Company and was created in memory of D. Moreau Barringer Sr. and his son, D. Moreau Barringer Jr. The award is given for outstanding work in the field of impact cratering. This year, the Barringer Award goes to Keith Holsapple (University of Washington, USA) for his significant contributions to crater scaling laws. His work was important in establishing scaling relationships relating the size of impactors to that of the resulting craters. The citation was given by Guy Consolmagno.

NIER PRIZE The 2016 Nier Prize for young scientists in the field of meteoritics goes to Gregory Brennecka of the University of Münster (Germany). Gregory receives this award for his significant contributions to our understanding of isotopic variations and the chronology of the early Solar System. The citation was given by Meenakshi Wadhwa.

SERVICE AWARD The 2016 Meteoritical Society Service Award goes to Gisela Posges who works at the Ries Crater Museum (Germany). Gisela receives this award for her effort in establishing the Ries Crater Museum and in keeping it up to date, inspiring young students in the field, and communicating information about the Ries Crater to schools and their students. The citation was given by Alex Deutsch.

GORDON MCKAY AWARD This award is given for the best oral presentation by a student at the annual meeting. In 2016, the award goes to Danielle Simkus (University of Alberta, Canada) for her talk “Compound-specific Carbon Isotope Compositions of Aldehydes and Ketones in the Tagish Lake Meteorite”, which she gave in Berlin (Germany) at the 79th Annual Meeting of the Meteoritical Society. The award comes with a prize of US $1,000 and a certificate.

WILEY-BLACKWELL AWARDS Wiley-Blackwell, publishers of Meteoritics and Planetary Science, sponsored four awards of US$500 each for outstanding presentations by students at the 79th Annual Meeting of the Society in Berlin. The winners were Timo Hopp (University of Münster, Germany) for “Ruthenium Isotope Fractionation During Crystallization of Planetesimal Cores”; Gavin Kenny (Trinity College, Dublin, Ireland) for “Impact Crater Environments as Potential Sources of Hadean Detrital Zircons”; Kelly Miller (University of Arizona, USA) for “Copper Sulfides in the R Chondrites: Evidence of Hydrothermal Alteration in Low Petrologic Types”; and Sheryl Singerling (University of New Mexico, USA) for “Synchrotron X-ray Fluorescence Analysis of Trace Elements in Focused Ion Beam Prepared Sections of Carbonaceous Chondrite Iron Sulfides (CM and CR) and Associated Metal (CR)*.”

CALL FOR AWARD NOMINATIONS

Please consider nominating a colleague for one of the society’s awards. Nominations should be sent to Secretary Michael Weisberg (metsocsec@wiley.com) by 15 January 2017 (31 January 2017 for the Pellis-Ryder Award and the Service Award). For more information and details on how to submit a nomination for any of these awards, please see the latest Newsletter at the Meteoritical Society’s website, or email the secretary.

ANNUAL MEETING SCHEDULE

2017 – 24–28 July, Santa Fe (New Mexico, USA)
2018 – Dates to be decided (tbd), Moscow (Russia)
2019 – Dates tbd, Sapporo (Japan)
2020 – Dates tbd, Glasgow (Scotland)

RENEW YOUR MEMBERSHIP NOW!

Please renew by 31 March 2017; after that date, a $15 late fee will be assessed. You can renew online at: http://metsoc.meteoriticalsociety.net
RENEW YOUR MEMBERSHIP FOR 2017

Geochemical Society (GS) members can renew quickly and securely on the GS website: www.geochemsoc.org. Renew by 15 January 2017 to save $5 off the regular dues and enjoy uninterrupted access to Elements, Geochemical News, and registration discounts to Goldschmidt2017 and 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 2-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.

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<th>2017 Dues Rates</th>
<th>Early (by 15 January 2017)</th>
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<tr>
<td>Professional</td>
<td>$30</td>
<td>$35</td>
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<tr>
<td>Senior</td>
<td>$15</td>
<td>$20</td>
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<tr>
<td>Student</td>
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The society also offers a Life Member option that eliminates the need to renew every year. The current life membership rate is 70 minus your current age times $35 USD, with a minimum rate of $175. Contact the business office at gsoffice@geochemsoc.org for more information on upgrading your membership to this convenient option.

GEOCHEMISTRY EVENTS CALENDAR

The GS shares information about conferences, workshops, and short courses on topics related to geochemistry through our website (www.geochemsoc.org/news/conferenceLinks). If you would like to share information about your event, please send it to gsoffice@geochemsoc.org with the following details: dates, title, website address, location, and abstract/regISTRATION deadlines. While there is no charge for this service, the society reserves the right to review submissions for relevancy to GS members before posting.

KEEP YOUR PROFILE CURRENT

Have you recently moved or changed your email address? Keeping your GS member profile current allows us to send Elements and Geochemical News to the right place every time. Updating your contact information is easy: just visit www.geochemsoc.org/contact and click the link to access your online member profile. You can also email the business office with updates or corrections at any time.

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VOLUNTEER APPRECIATION

The Geochemical Society thrives thanks to the efforts of many dedicated volunteers. Our sincere gratitude goes to the following GS members whose board and committee terms conclude in 2016.

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Thank you!
PROFESSOR EMILIO GALÁN BECOMES AN SEM HONORARY MEMBER

Professor Emilio Galán (University of Sevilla, Spain) has become a Spanish Mineralogical Society (SEM) Honorary Member, an accolade commemorated by his plenary lecture (“A New Methodological Approach for the Evaluation of Soil Pollution by Trace Elements”) at the 2nd European Mineralogical Conference 2016 (emc2016), which was held 11–15 September 2016 in Rimini (Italy). Spanish Mineralogical Society bylaws state that those awarded an SEM Honorary Member must be a prestigious researcher or must have significantly contributed to dignify and develop the SEM itself. Considering Prof. Galán’s scientific eminence in mineralogy, as demonstrated by the publication of outstanding original scientific research and by the impact of this research on the mineral sciences, as well as his contribution to the establishment and function of the Spanish Mineralogical Society, the SEM General Assembly (held 2 July 2014 in Granada) approved his appointment as SEM Honorary Member.

Professor Emilio Galán has received many honours over his career. These include the prestigious Pioneer in Clay Science Lecture Award of the Clay Minerals Society, the Medal of the University of Pavia, and is an Honorary Member with clay societies and groups from Italy, Spain and the Czech and Slovak Republics.

Emilio has also played an important role in the Spanish Mineralogical Society. He was Founder Member of our society in 1975 (member number 2) and assumed the responsibility of treasurer until 1980. After 20 years of intense scientific activity with the SEM, as well as with other clay and mineralogical societies, Emilio returned to the Executive Board of the SEM as president from 2002 to 2005. During this period, he advocated changes to the structure and the objectives of the SEM. Two important changes were carried out regarding the international projection of the society and the organization of our meetings. From the international point of view, in 2003 the Spanish Mineralogical Society became a partner in the European Journal of Mineralogy, together the German, French and Italian mineralogical societies. Regarding the organization of the SEM meetings, Emilio reinvented it such that, since 2003, every meeting has included a workshop that explores the latest advances in selected topics of current interest, the proceedings of which are published in the Seminar series of the Spanish Mineralogical Society. And, since 2003, the abstracts presented at the annual meeting have been published in the journal Macla.

Emilio has a rare ability to detect topics of interest to the SEM. For example, he has pioneered studies that have led to important new directions in clay minerals science and technology as applied to environmental problems or to the remediation and conservation of cultural heritage. As consequence of this scientific activity, he has supervised more than 22 PhD students and trained several generations of researchers on metallic mineral deposits, industrial minerals, clay minerals, protection and conservation of cultural heritage, and environmental mineralogy. He has been author or co-author of more than 300 articles in journals with a high impact factor, has edited 18 books and has been a principal researcher or a significant contributor to 74 research projects. He has participated in 70 national and international meetings, either as member of the Scientific Committee, Organizing Committee, Chairman of scientific sessions or as an invited lecture. He has presented more than 150 communications at these meetings.

The Spanish Mineralogical Society thanks Professor Emilio Galán deeply and warmly for agreeing to accept the award of Honorary Member. He was never in the society to take something from us: he was always here to help our society and to further the understanding of mineral science.

Juan Jiménez, SEM President

YOUNG RESEARCHER AWARDS FOR THE BEST LECTURES

Two awards were given to the best lectures given by young Spanish researchers at emc2016. The winners were Javier García Rivas (University of Salamanca) for “Geochemistry and Biomarker Analysis of the Bentonites from Esquivias (Madrid)” and Alba Lozano Letellier [Institute of Environmental Assessment and Water Research (IDAEA-CSIC)] for “REY mineralogy of wastes from acid mine drainage treatment” [REY = rare earth elements and yttrium]. Congratulations to the awardees!

NEW SEM COUNCILLORS

On 13 September 2016, during the general assembly held at emc2016, SEM members voted in the council election. We thank all the SEM members who participated and we are specially grateful to all the candidates who agreed to stand. The new members of council will be Asunción Alias (University of Murcia), Agustina Fernández (University of Salamanca), Carlos Rodríguez (University of Granada), Antonio Romero (University of Sevilla) and Núria Sánchez (University Complutense of Madrid). All of them will join the SEM council in January 2017. Welcome to the new members!
Dear loyal patrons and contributors to *The Canadian Mineralogist*,

There have been concerns regarding the situation currently facing our flagship journal and where it is headed. As President of the Mineralogical Association of Canada (MAC), I would like to take this opportunity to formally and completely dispel these concerns and to reassure our valued readership and faithful contributors that the state of our journal is one that is both positive and bright. It is true that *The Canadian Mineralogist* has faced a series of unfortunate, challenging hurdles recently, culminating in unprecedented flooding in India where our journal was being laid out and typeset. This tragic event led not only to the complete destruction of the facility but also to the loss of a great number of finished, typeset articles, a combination of which, thus, led to major publication delays. Owing to this, the MAC Executive Council made the difficult decision to rectify the situation by changing to a new typesetter (Allen press), one that is both closer to home and has a demonstrable record of capability in this area. The relationship with Allen Press has surpassed our expectations and stabilized the cloudy situation that had been previously facing our journal. During this very challenging period, our editorial team of Dr. Lee Groat and Ms. Mackenzie Parker have worked diligently to clean up the backlog of submissions and to position *The Canadian Mineralogist* for future growth.

I have complete confidence in them, and it will be positive news to our membership to hear that we are on track to have caught up by the middle of 2017, after which, new initiatives will be forthcoming. Paraphrasing Mark Twain, that great American humorist: rumors of our demise have been greatly exaggerated. We have turned the corner. Paraphrasing Mark Twain, that great American humorist: rumors of our demise have been greatly exaggerated. We have turned the corner. On behalf of MAC, we sincerely thank you for your patience, understanding and support. We encourage you not only to continue to read, reference and support our highly valued journal but also to submit your manuscripts to *The Canadian Mineralogist*. The future is very bright, and we want you to be part of the journey in moving forward.

Sincerely yours,

Andy M. McDonald
President, Mineralogical Association of Canada

**Upcoming Issues of the Canadian Mineralogist**

Upcoming issues include:

- A thematic issue in honor of Frank Hawthorne (January 2016).
- A thematic issue covering the 12th International Platinum Symposium. Guest Editors are Federica Zaccarini and Tatiana Evstigneeva (March 2016).
- A thematic issue on pegmatites, based on presentations made at the PEGS 2015 conference (Ksiaz, Poland) (July 2016).

**Undergraduate Awards 2015–2016**

MAC undergraduate student awards are given annually to undergraduate students (2nd year of study or higher) at a recognized Canadian university or institute of higher education for excellence in one of the specialties supported by the Mineralogical Association of Canada (mineralogy, crystallography, geochemistry, petrology, mineral deposits). The recipients receive a one-year MAC membership (including electronic access to *The Canadian Mineralogist*), a subscription to *Elements*, a 20% discount on MAC publications, and a discounted registration fee at our annual meeting) and a $100 gift certificate redeemable on any MAC publication. Congratulations to the following students, all of whom are in Canadian universities, who received this award in 2015–2016:

- Carlee J. Akam (University of Victoria)
- Daniel M. Baker (University of Alberta)
- Allan A. Bieber (University of Manitoba)
- Inayat Dhaliwal (University of Calgary)
- Caleb Grant (St. Francis Xavier University)
- Tong Hong (University of Waterloo)
- Rilea Kynock (University of New Brunswick)
- Marika Labbé (Université Laval)
- Jackson Daniel Malone (Acadia University)
- Reid James Merrill (University of British Columbia at Okanagan)
- Mallory Metcalf (Queen’s University)
- Hoang Anh Tu Lavie Nguyen (University of Saskatchewan)
- Stacey Nicole Parmenter (Memorial University)
- Justin T Pentesco (Brock University)
- Forest R. Pimm (University of Victoria)
- Jamie Schmidt (University of Regina)
- Claudia M. Selles (McGill University)
- Aamna Asad Sirohey (Western University)
- Jessie Villeneuve (Université du Québec à Chicoutimi)
- Elliot Wehrle (Laurentian University)

**Upcoming GAC–MAC Joint Meeting**

14–18 May 2017
Queen’s University, Kingston, Ontario, Canada
www.kingstongacmac.ca

The 2017 annual meeting of the GAC–MAC in Kingston will coincide with the 175th anniversary of the founding of the Geological Survey of Canada (GSC) in Kingston. The GSC, Canada’s oldest scientific agency, was established by the legislature of the Province of Canada in 1842, in Kingston, Canada West.

The Department of Geological Sciences and Geological Engineering at Queen’s University (in Kingston) and the GSC will be hosting this celebratory event at Queen’s University.

Six proposed themed sessions will run concurrently, as follows:

Session 1: “Environmental Issues”
Session 2: “Quaternary Systems”
Session 3: “Geochemical Systems”
Session 4: “Tectonics”
Session 5: “Earth Surface Systems Past and Present”
Session 6: “Geological Engineering”

Special Lectures: “Past, Present and Future Status of the GSC”

**Elements December 2016**
**MAC Sponsored Short Courses**

**Novel Applications of Isotope Geochemistry**—organized by Kurt Kyser (Queen’s University)

Isotope geochemistry is an integral part of the Earth sciences, particularly in revealing the fourth dimension of our science (time). Isotopic data can reveal the processes involved in natural systems and trace the flux of elements between the geosphere and biosphere. As such, isotope geochemistry is built on a platform of pure and theoretical science, but is primarily an applied science that adds value to mineral exploration, environmental stewardship, whole earth ecology, timing and causes of evolution, palaeoclimates and even food authentication. As an applied science, isotope geochemistry has expanded from traditional light stable isotopes and long-lived decay systems studied by a few experts into studies involving most elements in the periodic table, additional geochronometers and enhanced integration with other aspects of Earth science by a broad range of users. This course addresses the recent applications of isotope geochemistry in the Earth sciences and how integration with other disciplines represents a paradigm shift in our understanding of the processes that operate in natural systems. Those involved in the course include the top isotope geochemists in Canada. The course will last for two days and will start two days prior to the GAC–MAC 2017 meeting.

**Geometallurgy**—organized by Gema R. Olivo (Queen’s University)

Environmental and socio-economic demands in the exploitation of future mineral resources require a comprehensive collection and evaluation of a given ore body’s mineralogical, geochemical, lithological, physical and metallurgical attributes and variability. The evaluation process must start during the exploration phase and continue into the ore processing phase and the later remediation of mine waste phase because the information accumulated has a direct impact on all aspects of mine development. Geometallurgy is the scientific discipline that integrates all of the mineralogical, geological, mining and processing data into an accurate ore-body model, one that can form the basis for optimizing production and environmental management during the entire life of the project. Geometallurgy reduces operational risks, optimizes recovery efficiency, and minimizes environmental impact within the framework of a sound financial model. The relationship between geometallurgical input variables and their processing responses is usually complex. This course will address: (1) The principles of geometallurgy and critical evaluation of sampling, mineralogical and geochemical methods; (2) Case studies of geometallurgy applications involving: innovative evaluation of mineral deposits; mineral exploration; resource estimation; applications and implementation of quantitative mineralogical and geochemical data; mining and ore processing; energy use; treatment of tailings and waste rock and their remediation; implementing geometallurgical models in mining and plant operations. The course will last for two days and will start two days prior to the GAC–MAC 2017 meeting.

**NOW AVAILABLE**

**Understanding the Gem Minerals: A Practical Guide**

Special Publication 12 of The Canadian Mineralogist

Gemstones have fascinated people for thousands of years because of their beauty, rarity, and monetary value. However, a true understanding of gemstones and their properties has only come about in the past two centuries resulting from the developing science of geology and mineralogy and an increasing need to distinguish natural gemstones from those that are treated or grown in the laboratory. Numerous books describe minerals, and a number of them report on the distinctive properties of gemstones, but there are almost no books that present a more detailed mineralogical description of the gem minerals, along with a clear explanation of basic concepts of interest from both mineralogy and geology. Written by William Revell Phillips and James Shigley, *Understanding the Gem Minerals: A Practical Guide* bridge this gap.
THE PRESIDENT’S CORNER

My first message, in the June issue of Elements, centered on the usefulness of the Clay Minerals Society (CMS) for you – clay scientists. I argued that the CMS provides essential services for the clay community. I hope it was convincing and that you agree that we need scientific societies as vehicles for pursuing certain common objectives. And that we, in particular, as people who work on clays, need the Clay Minerals Society. Assuming such common ground, I am going to consider the opposite aspect of this relationship: what you can do for the CMS.

The least demanding service you can provide is just being a member, which means—on the basic level—paying dues on time and voting for the society officers. This does not sound like much, but, for a society such as ours, it is absolutely essential. We are a small society, about 350 members strong, so every member makes a difference. And as a member, you are part of the community effort that provides the services that we all benefit from. We all know that there is no such thing as a free lunch. So, please consider the thoughts expressed here. The 2017 renewal deadline is coming.

You can also go one step further and encourage your colleagues to join and/or your institution to become a Sustaining Member, Patron, or Benefactor. Our society could not offer the level of service to the clay community that we do offer without such extra generous help from institutions and individuals.

The next level of involvement is serving on the society’s committees. We have 12 committees with over 40 people, most of whom serve 3-year terms. Some require more work, others less, but this common effort keeps the CMS running. Every year about a dozen positions have to be filled. Please have a look at the CMS website (http://www.clays.org/) where all committees are listed, and see where you could contribute best. If you decide that you could help, please let me know.

Finally, you can always come to the society with a new idea, one you think that if implemented would serve the community well, like the Source Clays project or the Reynolds Cup contest. Both these initiatives have had a very positive impact on our field worldwide, and the CMS is the natural vehicle for such initiatives to be realized. If you have a new idea and you feel that we could help implement it, do contact us. Serving your community is not just a good thing to do — it is a rewarding experience.

Jan Srodon (ndsrodon@cyf-kr.edu.pl)
President, the Clay Minerals Society

STUDENT RESEARCH SPOTLIGHT

Congratulations to Sanpreet S. Gill (Michigan State University, USA), Bhabananda Biswas (University of South Australia), and Ruhaida Rusmin (University of South Australia and Universiti Teknologi MARA, Malaysia), and Kath Rothwell (Newcastle University, UK) for winning 2016 CMS Student Research Grants!

Sanpreet Gill examines how bentonite and chabazite could be used to recover N and remove pathogens in urine-derived fertilizer products. Urine contains 80% of the N and 50% of the P in municipal wastewater, yet accounts for only 1% of the total wastewater volume. Urine can be captured using urine separation systems and used as a fertilizer, thereby increasing the recovery of N and P and reducing nutrient pollution in water bodies. Obstacles for adopting urine separation systems include urine storage, transport, spreading urine on fields, and the possibility of urine being contaminated by pathogens and pharmaceuticals. Adding affordable and abundant minerals such as clinoptilolite, bentonite and chabazite to urine separation systems will allow a better recovery of the N and P nutrients and will remove any pathogens from urine fertilizers. The use of such low-cost technologies can aid in closed-loop sanitation systems, reduce dependence on industrial fertilizers, and improve the lives of people around the globe.

Bhabananda Biswas studies the microbial degradation of environmental contaminants in synergy with clay and modified clay minerals. The remediation of organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs), is often limited by the poor bioavailability of these compounds and the inefficiency of microbial degradation in soils and sediments. Using a multidisciplinary approach that combines clay mineralogy, microbiology, and environmental science, Bhabananda examines the compatibility and synergy of potential PAH-degrading microorganisms with different modified clay products (e.g., organoclays) and applies this synergy to remediate PAHs from any contaminated soil and water. The CMS grant allowed him to use microscopic and metagenomic techniques to investigate the effect of organoclays on the functional and diversity changes in native soil microorganisms.

Ruhaida Rusmin is investigating whether Australia’s palygorskite clay minerals can be used as potential adsorbents to remove lead (Pb) from aqueous solutions. She modifies palygorskites through chemical activation and the incorporation of biopolymer chitosan and superparamagnetic iron oxide nanoparticles; she then tests whether the modified clay can remove Pb from water. If successful, her modified clay techniques could be used for water remediation. She integrated spectroscopic and microscopic approaches to examine the textural evolution and the interaction with Pb of the modified palygorskites. The CMS Student Research Grant allowed her to use multiple scientific facilities within Australia to characterize the clays.

Kath Rothwell studies redox processes at the clay mineral-water interface and how these processes facilitate organic contaminant transformation. She evaluates the reactivity of iron-bearing clay minerals and representative inorganic and organic components of sediments and soils. She has studied how aqueous Fe(II) and complexes of Fe(II) and organic ligands representing natural organic matter affect the reactivity of Fe-bearing clay minerals towards nitroaromatic probe compounds. The funds, provided by the CMS research grant, will allow Kath to investigate how microbial exudates, acting as chelating ligands and electron shuttling moieties, affect clay mineral redox reactivity. Kath is eager to bridge the gap between laboratory and field based data, to explore emerging properties of real-world systems, and to highlight the importance of clay minerals for contaminant transformation.

CMS MEMBERSHIP RENEWAL

Don’t forget to renew your membership for 2017!

Bhabananda Biswas
Ruhaida Rusmin
Kath Rothwell
In 49 BC, Julius Caesar led a legion of his army across the river Rubicon in northeast Italy, which separated Cisalpine Gaul from Italy proper. This was in defiance of a law which forbade such an action, and it spawned the term “crossing the Rubicon”, a phrase that today means ”passing the point of no return”. Of the 700 or so delegates who attended the second European Mineralogical Conference (emc2016) in Rimini 11–15 September 2016, many crossed the river Rubicon in their journey to the seaside city of Rimini in the northeast of Italy.

The foundation of the European Mineralogical Conference series began with a meeting in Cambridge in 2007, ‘Frontiers in Mineralogy’, followed by a meeting in 2009 in Edinburgh, ‘MAPT – Micro-Analysis, Processes, Time’, and ultimately, to the first European Mineralogical Conference in Frankfurt in 2012. Giuseppe Cruciani and Bernardo Cesare led the organizing team for the emc2016 which was attended by delegates from 50 countries. In their welcome message, our Italian colleagues promised that “emc2016 will showcase the state-of-the-art of mineralogical sciences, promoting exchange of new research results between Europeans and beyond”. The title of emc2016 was ‘Minerals, Fluids and Rocks: Alphabet and Words of Planet Earth’ and was conceived to echo an aphorism by the late Charles V. Guidotti (1935–2005) “Minerals, the alphabet of geology; and rocks, the words of geology”. The conference title was intended to convey the message that dealing with mineral sciences in their broadest sense consists simply of trying to understand what the dynamic Earth is telling us and that the big picture may be reconstructed by carefully putting together the small parts.

Over the five-day program, the 28 scientific sessions (see Box 1) and six plenary lectures delivered by world-renowned scientists were designed to allow cross-over between all sub-disciplines of mineralogy. The programme encouraged student presentations and interaction with field-leaders for all and was, thus, ideal in that it allowed lots of time for essential networking. The mineralogical community is especially grateful to those who helped to organize all these sessions. This work, of course, is the foundation of any successful conference.


Workshops and Schools

There were several workshops and schools held prior to or after the emc2016 meeting. A well-attended Association of Italian Crystallography International Crystallography School entitled ‘Polymorphism, Stability and Phase Transitions in Crystals: Theory, Experiments, Applications’ was run on 7–11 September 2016 in conjunction with the Italian Mineralogical Society (SIMP). There was the one-day workshop, ‘Solid Inclusions in Minerals as Records of Geological Processes’, which was organized by Matteo Alvaro and Ross Angel and was run at the end of the conference (16 September 2016). And, the European Mineralogical Union ran a Mineral Reaction Kinetics school, which took place 19–23 September 2016 in Vienna (Austria). Forty people attended, and a book will be published by the end of 2016 consisting of the papers presented during the school.

Attendance by Students

There was a large cohort of student delegates, many of whom were able to attend under the terms of the ‘student-volunteering programme’. The student delegates in question were very distinctive because of the brightly coloured t-shirts they wore!

The programme also served to promote attendance by students, an initiative which was appreciated enormously, as evidenced by the comments below:

“The student-volunteering program allows graduate students and post-docs to receive free entry and free accommodation and, at the same time, to experience the working of an international science conference. This not only promotes the participation of young researchers, but also helps them to develop a network of peers in the same field of study.” – Chiara Anzolini (University of Padova, Italy)

“The conference was a great opportunity for me to meet some of the best experts in the field (metal behaviour in polluted river systems under different hydrogeological conditions), and it was an honour to know and help them. Thanks to the great organisation, the attenders were able to listen to many scientific sessions. Some of the talks on environmental issues were outstanding and they inspired me and suggest new ideas to answer my research questions.” – Patrizia Onnis (John Moores University, Liverpool, UK)

“The fields still unexplored and the in-depth analysis of where the research is moving, stimulate curiosity and let you understand that your land is still a source of new discoveries and ideas.” – Norma Tallarigo (University of Ferrara, Italy)

“From a scientific and intellectual point of view, all these aspects have created a stimulating atmosphere from which I took inspiration to further expand my research horizons within the mineralogical world.” – Giada Beltrami (University of Ferrara, Italy)

“emc2016 was for all of us the first conference where we participated as student helpers, and we hope that it will not be the last one. It was an exciting experience that allowed us to meet other students and discover their research fields. We were able to participate actively in the scientific sessions, showing our research through posters and oral presentations. It was so thrilling!” – PhD/Masters students in mineralogy at the University of Pavia (Italy).

Mineralogical Societies – Administrative Meetings and Joint Awards Ceremony

The running of mineralogical societies and groups, both national and international, was aided by many administrative meetings during emc2016. The Italian, Spanish, French and German mineralogical societies held their annual business meetings in Rimini. In addition, books were discussed, special issues of journals were arranged, invited speakers for the next meeting were proposed, and much more – stuff that helps to make the mineralogical world go around.
There were also many society awards presented during a ceremony held on Wednesday morning, September 14th. The significance of these awards is enhanced when shared in this way with large numbers of colleagues present. Our congratulations to all recipients.

Exhibitors and Banquet
The local committee, and in particular Diego Gatta, had assembled a strong cast of exhibitors, many of whom had scientific instruments on display. Delegates and others are encouraged to follow up on enquiries made during the conference in order that these exhibitors can be encouraged to attend future such events.

Italy is, of course, the home of social intercourse, where people gather to enjoy good food, good wine and to talk about the important points of the day. Rimini, being a tourist resort, is replete with good restaurants, and at all price ranges, that accommodated the many hungry delegates during the week. Colleagues in Italy also arranged for a delightful conference banquet at Casa Zanni where the red wine flowed until the small hours. Lunch and coffee breaks were also amply stocked with drinks and food for the travelling army that is the EMC!

In summary, emc2016 was a resounding success, due largely to the efforts of the local organizing committee, and in particular Giuseppe Cruciani and Bernardo Cesare. Our Italian colleagues certainly kept their promise! The next EMC event will be in 2020 and is already being discussed with interest from a number of possible hosts. And their promise! The next EMC event will be in 2020 and is already being discussed with interest from a number of possible hosts. And their promise! The next EMC event will be in 2020 and is already being discussed with interest from a number of possible hosts. And their promise! The next EMC event will be in 2020 and is already being discussed with interest from a number of possible hosts.

Kevin Murphy, Klaus-Dieter Grevel, Hans-Peter Schertl, and the many people who posted photographs to the EMC Facebook page

Box 1  THE 28 SESSIONS HELD AT emc2016

1. Diamonds: Open Windows in the Earth’s mantle
2. Evolution of the Earth’s Mantle and Primitive Magmatism through Time
3. Volatiles in the Deep Earth: Storage, Mobility and Implications
4. Fluids in the Crust
5. The Cycling of Hydrogen, Carbon, and Mobile Elements in the Subduction Factory
6. Metamorphism, Crustal Melting and Granite Magmas from Start to Stop and from Inclusions to Intrusions
7. From Deep Magmatic Processes to Volcanic Eruption
8. Diffusion, Mineral Reaction and Deformation Mechanisms from Low to High Temperatures: Flow and Brittle Processes of the Earth’s Interior
9. Inclusions in Minerals as Record of Geological Processes: New Analysis Methods and Application
10. Mineral Reaction Kinetics: Microstructures, Textures, Chemical and Isotopic Signatures
11. Reading and Understanding Metamorphic Rocks
12. Clays, Zeolites and Nanostructured Minerals: From Mineralogy to Applications in Industry and Environment
13. Ores, Minerals and Geomaterials in Industrial Processes and Human Activities
14. Advances in Computational and Experimental Mineralogy: A Journey from the Surface to the Deep Earth and Beyond
15. Structural Behaviour and Energetic Properties of Minerals
16. New Minerals, Modular Structures and Mineral Groups
17. Mineral Diversity, Complexity and Evolution
18. Planetary Materials: From Dust to Planets and Early Earth
19. Gem Materials
20. High-tech Metal Minerals in Europe
21. Mineralogy, Geochemistry and Valorization of Industrial and Mining Wastes
22. Platinum Group Minerals and Accessory Minerals: Development in their Characterization
23. The Future of Critical Metals: Mineralogy, Metallogenesis and Geometallurgy
24. The Petrology–Geochronology Connection
25. Biogeochemical Interfaces and Environmental (Bio)Mineralogy
26. Mineral Hazards. The Environmental and Human Health Problem Represented by Raw and Man-processed Mineral Phases
27. Mineral Sciences for the Understanding of Cultural Heritage
At the 2nd European Mineralogical Conference (emc\textsuperscript{2016}) held in September 2016 in the beautiful Adriatic resort town of Rimini (Italy), Professor Rod Ewing (University of Michigan, USA) was awarded the IMA Medal of Excellence for 2015 (\textit{Elements}, v11 p 300) and gave a plenary lecture on radiation effects in minerals. Also at the conference, the IMA inaugurated its PhD Student Award, which is aimed at supporting young talent in mineralogy and related disciplines (\textit{Elements}, v12, p 133). In addition to a certificate, each awardee receives a travel grant to attend a major international meeting. In 2016, the IMA Council selected three students to sponsor, based on achievements and contributions, to present their research at emc\textsuperscript{2016}. The recipients were Petra Jakubová from Masaryk University (Brno, Czech Republic), Mattia Luca Mazzucchelli from the University of Pavia (Italy) and Liene Spruzeniece from Macquarie University (Sydney, Australia). Petra’s research, which was presented at the session “Inclusions in Minerals as Record of Geological Processes”, is concerned with the origin of microdiamonds from the North Bohemian granulites (Czech Republic) and involves an impressive array of advanced analytical techniques. Mattia’s work also involves high-pressure inclusions but his main objective is to expand the current limits of elastic geobarometry using numerical methods. Liene’s research integrates experiments, field studies and electron microscopy to explore fluid–rock interaction in complex systems. Her latest experimental findings on symplectite growth mechanisms were presented at the session “Reading and Understanding Metamorphic Rocks”.

The IMA also held two business meetings at Rimini. Patrick Cordier was elected 1\textsuperscript{st} vice president of the IMA and Catherine McCammon and Mark Welch are two new councillors. Sergey Krivovichev passed on the presidential gavel to Peter Burns; Sergey is now past president. We say “Thank You!” to Walter Maresch, who is retiring as past president and who has served the IMA for many years.

The IMA council members at emc\textsuperscript{2016} in Rimini: Anhui Lu (councillor), Catherine McCammon (councillor), Hans-Peter Schertl (secretary), Patrick Cordier (1\textsuperscript{st} vice president), Peter Burns (president), Walter Maresch (former past president), Marco Pasero (councillor), Sergey Krivovichev (past president), Jane Gilotti (councillor), Stuart Mills (2\textsuperscript{nd} vice president). Not present: Bob Downs (treasurer), Anton Chakhmouradian (communication officer), Mark Welch (councillor).

IMA Past President Sergey Krivovichev (far left) and 1\textsuperscript{st} Vice President and Chair of the PhD Student Award Committee Patrick Cordier (far right) with the recipients of the IMA PhD Student Award for 2016: (1 to R) Petra Jakubová, Mattia Luca Mazzucchelli and Liene Spruzeniece.
MEETING REPORT

4th INTERNATIONAL WORKSHOP ON HIGHLY SIDEROPHILE ELEMENT GEOCHEMISTRY

Attendees of the 4th International Workshop on Highly Siderophile Element Geochemistry

The 4th International Workshop on Highly Siderophile Element Geochemistry was held 11-14 July 2016 at Durham University (UK). The workshop was attended by 75 delegates from all over the globe, their 73 abstracts offering all attendees both broad and exciting science for the week.

The scientific programme covered a range of topics in Earth and planetary sciences, exploring mineralogical and textural observations, highly siderophile element (HSE) abundances and their fractionation, stable and radiogenic isotope systems, and chalcophile element data that included S-Se-Te variations and isotopic compositions. The variety of data on all aspects were shown to trace low-temperature processes such as environmental contamination, Earth’s geochemical cycles and erosion processes, and to high-temperature processes, such as those linked to ore formation, mantle melting on Earth, and some of the major phases of planetary evolution. A full day was devoted to the presentation of new findings arising from meteoritical and lunar studies, and a number of related posters were presented during the mid-week poster session. A public talk titled “How do meteorites tell us the story of our Solar System” was delivered by the workshop’s keynote speaker, James M. D. Day (SCRIPPS, University of California San Diego, USA), and effectively advocated for the collection and study of planetary materials: it was well received by a mixed audience of workshop delegates, academics from the wider university, members of the Royal Astronomical Society, and the general public. This talk was recorded and is available online: https://www.youtube.com/watch?v=NA9kkvr-VKes.

Twelve student travel bursaries (totaling ~3500 pounds) were awarded by the Meteoritical Society, the Geochemical Society, and the European Association of Geochemistry. Two student talks supported by the Meteoritical Society, which was well-attended and engaged a broad scientific audience.

Prior to our meeting, a successful affiliate session titled “Tracing Ocean Circulation – Past and Present” was convened by Ruza Ivanovic, Tina van de Flierdt and David Wilson at the 2016 Annual Goldschmidt Meeting. Following the HSE workshop, Fienke Nanne and Thomas Kruijer chaired a special session titled “Planetary evolution: Advances in meteoritical and lunar isotopic analyses” at the 79th Annual Meeting of the Meteoritical Society, which was well-attended and engaged a broad scientific audience.

In relation to the Durham workshop, a Geochemica et Cosmochimica Acta (GCA) special issue, provisionally titled “Highly Siderophile Element [and closely-related] Constraints on Low- and High-Temperature Earth and Planetary Processes”, is in preparation and will enable the timely publication of pertinent contributions of new research findings. We are soliciting relevant high-calibre contributions from workshop delegates and the wider community. The deadline for submission is midnight (GMT) on 28 October 2016. All prospective authors must meet the fundamental criteria for publication in GCA. This includes a high degree of novelty and broad geochemical significance, as well as quality of data and presentation. Further information: http://www.hseworkshop.co.uk/special-issue-gca.

We’d like to thank the workshop sponsors, including the Meteoritical Society, the Geochemical Society, the European Association of Geochemistry, Engineering Design Plastics, Thermo, Nu Instruments, and four groups from the UK: the Geochemistry Group, the Applied Mineralogy Study Group, the Mineral Deposits Study Group and the Volcanic and Magmatic Studies Group. Gratitude is offered to the organising committee and voluntary team for their tireless efforts that ensured the success of the workshop and its fieldtrip. Edward Inglis and Katie Schweitzer arranged an excellent ice-breaker, and Fienke Nanne coordinated a highly successful, and very memorable, banquet, complete with a ceilidh! Geoff Nowell contributed much and provided a number of informative laboratory tours. Chris Ottley is thanked for coordinating the panel of judges and supporting some of the student prizes. Chris Dale and Alex McCoy-West were responsible for the scientific aspects of the programme. Chris Dale is also thanked for scheduling volunteers and session chairs. Marc-Alban Millet and Paul Savage formed and ably guided the bursary committee. Kevin Burton, Helen Williams, and Dave Selby are thanked for their encouragement and advice.

Isle of Rum field party, 4th International Workshop on Highly Siderophile Element Geochemistry. Expert field leader, Brian O’Driscoll, is second from the left in the front row.

Alexandra Witze, 2016 winner of AGU’s David Perlman Award for Excellence in Science Journalism, wrote a feature article in the August 6th edition of the online journal ScienceNews. This edition had the workshop as its cover page and included a discussion on the constraints that iron-loving elements place on Earth’s evolution: see https://www.sciencenews.org/article/iron-loving-elements-tell-stories-earth%E2%80%99s-history?tgt=nr.

FROM LEFT TO RIGHT: Kate Horan (Best Poster), Leanne Staddon (Highly-Commended Poster), President of the Geochemical Society Laurie Reisberg, Fienke Nanne (Best Talk), and Luke Daly (Highly-Commended Talk).

The successful post-conference field trip to the Isle of Rum (Scotland) was coordinated by Pierre Bouihol (Durham University, UK) and involved a party of approximately 30 delegates and workshop committee members. The excursion was very ably led by Brian O’Driscoll (University of Manchester, UK).
2016

December 10–11 Short Course: Measurements, Theories and Applications of Non-Traditional Stable Isotopes. Lawrence Berkeley National Laboratory, CA, USA. Web page: www.minsocam.org/msa/sc/

December 12–16 American Geophysical Union Fall Meeting. San Francisco, CA, USA. Web page: fallmeeting.agu.org/2016/

2017


January 22–27 41st International Conference and Expo on Advanced Ceramics and Composites, Daytona Beach, FL, USA. Web page: ceramics.org/icacc2017


February 26–March 2 TMS Annual Meeting & Exhibition, San Diego, CA, USA. Web page: tms.org/meetings/annual-17/AM17/home.aspx


April 2–5 AAPG 2017 Annual Convention, Houston TX. Web page: www.aapg.org/events/conferences/ace

April 2–6 258th ACS National Meeting & Exhibition, San Francisco, CA, USA. Web page: www.acs.org


April 17–21 2017 MRS Spring Meeting & Exhibit, Phoenix, AZ USA. Web page: www.mrs.org/spring2017/


May 7–11 EMAS 2017 / IUMAS-7: European Workshop on Modern Developments and Applications in Microbeam Analysis, Konstanz, Germany. Web page: www.microbeam-analysis.eu

May 9–11 Chondrules as Astrophysical Objects, Vancouver, BC, Canada. Web page: chondrules.phas.ubc.ca/


May 26–30 American Crystallographic Association Annual Meeting, New Orleans, LA, USA. Web page: www.amcrystallassn.org/content/pages/main-annual-meetings


July 23–28 Annual Meeting of the Meteoritical Society, Santa Fe, NM, USA. Details forthcoming

August 4–9 Magmatism of the Earth and Related Stratigraphic Metal Deposits, Missas, Russia. Web page: emmsnd.ru/


August 20–24 258th ACS National Meeting & Exhibition, Washington, DC, USA. Web page: www.acs.org


August 21–27 XXIV Congress and International Assembly of the International Union of Crystallography, Hyderabad, India. Website: www.iucr2017.org/

September 12–14 Annual Meeting of Japan Association of Mineralogical Science, Ehime, Japan. Details forthcoming.


September 17–22 Applied Isotope Geochemistry 12 (AIG-12), Copper Mountain, CO, USA. Website: to be announced

September 18–22 11th International Kimberlite Conference (11IKC), Gaborone, Botswana. Web page: www.11ikc.com

September 18–22 Basalt 2017, Kladan, Czech Republic. Details forthcoming


October 22–25 Geological Society of America Annual Meeting, Seattle, WA, USA. E-mail: meetings@geosociety.org. Web page: www.geosociety.org/meetings

November 26–December 1 MRS Fall Meeting, Boston, MA, USA. Web page: www.mrs.org/fall2017/

December 11–15 AGU Fall Meeting, New Orleans, LA, USA. Details forthcoming

2018

January 21–26 42nd International Conference and Expo on Advanced Ceramics and Composites (ICACC’18), Daytona Beach, FL, USA. Details forthcoming

March 18–22 255th ACS National Meeting & Exhibition, New Orleans, LA, USA. Web page: www.acs.org

May 20–23 AAPG 2018 Annual Convention, Salt Lake City, UT, USA. Web page: www.aapg.org/events/conferences/ace

June 16–21 Canadian Institute of Mining, Metallurgy and Petroleum (CIM), Geological Association of Canada (GAC) and Mineralogical Association of Canada (MAC) Joint Meeting, Vancouver, BC, Canada. Web page: rfg2018.org/

June 24–29 Zeolite 2018, Krakow, Poland. Web page: www.inza.unina.it/


August 13–17 20th International Sedimentological Congress, Quebec, QC, CANADA. Web page: www.isc2018.org/

August 19–23 258th ACS National Meeting & Exhibition, Boston, MA, USA. Web page: www.acs.org

October 14–18 Materials Science & Technology 2018, combined with ACRS 120th Annual Meeting (MS&T18), Columbus, OH USA. Details forthcoming

November 4–7 Geological Society of America Annual Meeting, Indianapolis, IN, USA. E-mail: meetings@geosociety.org. Web page: www.geosociety.org/meetings

December 10–14 AGU Fall Meeting, Washington, DC, USA. Details forthcoming

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

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