Elements

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Geomicrobiology and Microbial Geochemistry

GREGORY K. DRUSCHEL and GREGORY J. DICK, Guest Editors

Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology

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

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COVER IMAGE: Outflow of Grand Prismatic Spring, Yellowstone National Park (Wyoming, USA). Color gradations are linked to changes in microbial communities and temperature (PHOTO CREDIT: E. BOYD). This area was first studied in detail by Dr. Thomas D. Brock. INSET: A false-color image of partially encrusted iron-oxidizing bacterial cells (PHOTO CREDIT: A. KAPPLER AND EYE OF SCIENCE, TUBINGEN, GERMANY)

Geomicrobiology and Microbial Geochemistry

Guest Editors: **Gregory K. Druschel** and **Gregory J. Dick**

DEPARTMENTS

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

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The Mineralogical Society of Great Britain and Ireland is an international society for all those working in the mineral sciences. The society aims to advance the knowledge of the science of mineralogy and its application to other subjects, including crystallography, geochemistry, petrology, environmental science and economic geology. The society furthers its aims through scientific meetings and the publication of scientific journals, books and monographs. The society publishes *Mineralogical Magazine* and *Clay Minerals*. Students receive the first year of membership free of charge. All members receive *Elements*.

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The Mineralogical Association of Canada was incorporated in 1955 to promote and advance the knowledge of mineralogy and the related disciplines of crystallography, petrology, geochemistry, and economic geology. Any person engaged or interested in these fields may become a member of the Association. Membership benefits include a subscription to *Elements*, reduced cost for subscribing to *The Canadian Mineralogist*, a 20% discount on short course volumes and special publications, and a discount on the registration fee for annual meetings.

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

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The Geochemical Society (GS) is an international organization founded in 1955 for students and scientists involved in the practice, study, and teaching of geochemistry. Our programs include cohosting the annual Goldschmidt Conference™, editorial oversight of *Geochimica et Cosmochimica Acta* (*GCA*), supporting geochemical symposia through our Meeting Assistance Program, and supporting student development through our Student Travel Grant Program. GS annually recognizes excellence in geochemistry through its medals, lectures, and awards. Members receive a subscription to *Elements*, special member rates for *GCA* and *G-cubed*, and publication and conference discounts.

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Founded in 1985, the **European Association of Geochemistry** is a non-profit organization dedicated to promoting geochemistry internationally. The society is an active and dynamic organization of over 2800 members that leads the European Goldschmidt conference organization, publishes *Geochemical Perspectives* and *Geochemical Perspectives Letters*, recognizes scientific excellence through awards, organizes a Distinguished Lecture Program, sponsors workshops and conferences in Europe, supports students and Early Career Scientists, publishes job opportunities, newsletters, blogs, press releases and partners with other learned societies to strengthen geochemistry internationally.

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

Society News Editor: Chris Gardner (iageochemistry@gmail.com)

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The Société Française de Minéralogie et de Cristallographie, the French Mineralogy and Crystallography Society, was founded on March 21, 1878. The purpose of the society is to promote mineralogy and crystallography. Membership benefits include the *European Journal of Mineralogy*, *Elements*, and reduced registration fees for SFMC meetings.

Society News Editor: Anne-Marie Boullier (Anne-Marie.Boullier@obs.ujf-grenoble.fr)

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The Association of Applied Geochemists is an international organization founded in 1970 that specializes in the field of applied geochemistry. It aims to advance the science of geochemistry as it relates to exploration and the environment, further the common interests of exploration geochemists, facilitate the acquisition and distribution of scientific knowledge, promote the exchange of information, and encourage research and development. AAG membership includes the AAG journal, *Geochemistry: Exploration, Environment, Analysis*; the AAG newsletter, *EXPLORE*; and *Elements*.

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The Deutsche Mineralogische Gesellschaft (German Mineralogical Society) was founded in 1908 to "promote mineralogy and all its subdisciplines in teaching and research as well as the personal relationships among all members." Its great tradition is reflected in the list of honorary fellows, who include M. v. Laue, G. v. Tschermak, P. Eskola, C. W. Correns, P. Ramdohr, and H. Strunz. Today, the society especially tries to support young researchers, e.g. to attend conferences and short courses. Membership benefits include the *European Journal of Mineralogy*, *GMit*, and *Elements*.

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The Società Italiana di Mineralogia e Petrologia (Italian Society of Mineralogy and Petrology), established in 1940, is the national body representing all researchers dealing with mineralogy, petrology, and related disciplines. Membership benefits include receiving the *European Journal of Mineralogy*, *Plinius*, and *Elements*, and a reduced registration fee for the annual meeting.

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The International Association of Geoanalysts is a worldwide organization supporting the professional interests of those involved in the analysis of geological and environmental materials. Activities include the management of proficiency-testing programmes for bulk-rock and micro-analytical methods, the production and certification of reference materials and the publication of the association's journal, *Geostandards and Geoanalytical Research*.

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

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The Sociedad Española de Mineralogía (Spanish Mineralogical Society) was founded in 1975 to promote research in mineralogy, petrology, and geochemistry. The society organizes annual conferences and furthers the training of young researchers via seminars and special publications. The *SEM Bulletin* published scientific papers from 1978 to 2003, the year the Society joined the *European Journal of Mineralogy* and launched *Macla*, a new journal containing scientific news, abstracts, and reviews. Membership benefits include receiving the *European Journal of Mineralogy*, *Macla*, and *Elements*.

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The Swiss Society of Mineralogy and Petrology was founded in 1924 by professionals from academia and industry and amateurs to promote knowledge in the fields of mineralogy, petrology, and geochemistry and to disseminate it to the scientific and public communities. The society coorganizes the annual Swiss Geoscience Meeting and publishes the *Swiss Journal of Geosciences* jointly with the national geological and paleontological societies.

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The Meteoritical Society is an international organization founded in 1933 for scientists, collectors, and educators to advance the study of meteorites and other extraterrestrial materials and their parent asteroids, comets, and planets. Members receive our journal, *Meteoritics & Planetary Science*, reduced rates for *Geochimica et Cosmochimica Acta*, which we cosponsor, the *Meteoritical Bulletin*, and *Elements*. We organize annual meetings, workshops, and field trips, and support young planetary scientists worldwide. Through our medals and awards, we recognize excellence in meteoritics and allied fields.

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The Japan Association of Mineralogical Sciences (JAMS) was established in 2007 by merging the Mineralogical Society of Japan, founded in 1955, and the Japanese Association of Mineralogists, Petrologists, and Economic Geologists, established in 1928. JAMS covers the wide field of mineral sciences, geochemistry, and petrology. Membership benefits include receiving the *Journal of Mineralogical and Petrological Sciences* (*JMPS*), the *Ganseki-Koubutsu-Kagaku* (*GKK*), and *Elements*.

Society News Editor: Toru Inoue (inoue@sci.ehime-u.ac.jp)

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Affiliated Societies
The International Mineralogical Association, the European Mineralogical Union, and the International Association for the Study of Clays are affiliated societies of *Elements*. The affiliated status is reserved for those organizations that serve as an "umbrella" for other groups in the fields of mineralogy, geochemistry, and petrology, but that do not themselves have a membership base.

TOWARD A STABLE EARTH SYSTEM … OR A JOURNEY TO POINTS UNKNOWN?

Patricia Dove

Dear Friends. As our final issue of *Elements* goes to press for 2015, the news bulletins over the past year call out for introspection about the future. For example, critical events have precipitated a tremendous migration from the Middle East to points unknown. This massive current of humanity is a reminder of the broader fact that our entire civilization has embarked on an uncharted journey. As the year ends with seven billion people, we continue the march to a world population of nine billion within only 35 years.

What does the future hold for Earth's environments and human civilization as our population grows exponentially? This question has been around for decades, but the urgency is new. The urgency is now.

One hopeful approach is to integrate the best data that exists today into a picture that assesses vulnerabilities. By evaluating our proximity to critical thresholds of environmental change—tipping points—or to unacceptable levels of loss of resilience, a science-based analysis of risks from planetary changes becomes possible.

This is indeed the approach taken by 28 renowned scientists who are developing the concept of "planetary boundaries" (Steffen et al. 2015). These boundaries are the proverbial "line(s) in the sand" that should not be crossed if we wish to avert a high risk of destabilizing the Earth system. While recognizing the many shortcomings of attempting to describe the complexity of Earth's environments, Steffan and his coworkers first identify Earth system processes and potential biophysical thresholds, which, if crossed, could generate unacceptable environmental change for humanity (Stockholm Resilience Center 2015). Using this science-based approach, they have developed a paradigm that puts the risks of these changes into perspective. Their approach integrates the (continued) development of human societies with their impacts on the Earth system.

The planetary boundary concept proposes nine parameters within land, water, and air settings that are critical to the functioning of the global system. The scientific community has generally agreed that these parameters regulate critical Earth system processes: 1) Climate change; 2) Change in biosphere integrity (biodiversity loss and species extinction and their implications for the functioning of ecosystems); 3) Stratospheric ozone depletion; 4) Ocean acidification; 5) Biogeochemical flows (phosphorus and nitrogen cycles); 6) Land-system change (e.g. deforestation); 7) Freshwater use; 8) Atmospheric aerosol loading (microscopic particles in the atmosphere that affect climate and organisms); 9) Introduction of novel entities (e.g. organic pollutants, radioactive materials, nanomaterials, microplastics). These parameters help define globally aggregated boundaries, which are complemented by regional-level boundaries for biosphere integrity, biogeochemical flows, land-system change, and freshwater use.

While there is much that we don't fully know about each parameter, and how they interrelate, the "planetary boundary" construct offers a powerful way to evaluate major Earth processes that are being changed by human activities.

Our readership recognizes the urgency of understanding these systems. Moreover, I suspect that most of us are actively working in related areas. If so, please pause to receive your *golden epaulettes*. You have earned them for seeking new knowledge in spite of social skepticism about science.

Still wondering if you qualify? Then take this simple test: Are you deciphering the past responses of Earth environments to change, investigating behavior of modern systems, or considering how to best manage or sustain resources? Or are you teaching the next generation about these issues and the challenges? If you answered yes to any of these, then *congratulations*!

Can you pause to admire your nouveau accoutrements? No. There is no time. You and our colleagues have found ample evidence that some variables will likely have highly nonlinear responses to increasing human pressures on Earth systems. This is particularly likely to be true of parameters affecting atmospheric properties and climate. These systems may react with cascading and/or coupled consequences that are irreversible on a human timescale.

To take current knowledge to the next level, an increasingly integrative approach will be required. For example, there is an urgent need to deconvolve the complexities and cross-scale interactions in natural systems. This is particularly important for determining the threshold for rapid changes, or tipping points, which are not yet well established for any large system. We also need to know if the progressive growth in population will cause Earth's environments to suffer a similar progression in environmental degradation or loss of resilience that could trigger an environmental tipping point. Such a point simply must not be crossed.

For societies, sensible planning demands preparations for the coming changes. But changes to what? How do we prepare for a mind-melting increase from seven billion to nine billion people? By using the "planetary boundaries" paradigm, which is rooted in natural science, we have a useful framework for where to redouble our efforts. In research, education, and policy, the time is now for societies to choose pathways for our future development and to safeguard a stable and resilient Earth system.

Patricia Dove, Principal Editor

Steffen W and 17 coauthors (2015) Planetary boundaries: guiding human development on a changing planet. Science 347, doi: 10.1126/science.1259855

Stockholm Resilience Center (2012) Tipping toward the unknown. http://www.stockholmresilience.org/21/research/research-news/9-23-2009-tipping-towards-the-unknown.html, Accessed 14 November 2015

THIS ISSUE

Microbiology (or biology) may not be your favorite subject. Or maybe you dreaded taking “life science” courses while at the university. Even if life science is not your preferred area of interest, we hope you read the articles in this issue. Earth science is inherently interdisciplinary because on planet Earth, the lithosphere, atmosphere, hydrosphere, and biosphere interact. We can’t comprehensively study one “sphere” without knowing something about the other “spheres.” The articles in this issue illustrate how scientists are researching the intersection of all four spheres. If you are uncertain about delving into the microbial world, start by reading the perspective from Ken Nealson, who has been researching this intersection of “spheres” for almost 40 years. Hopefully, he will motivate you to read more. Then dive right into the thematic articles to learn more about geomicrobiology and microbial geochemistry.

THANKS!

In our final issue of 2015, we like to take a moment to extend our appreciation to the guest editors and authors who contributed to the six issues of volume 11. These men and women not only succeeded at writing compelling articles for *Elements*‘ scientifically diverse audience and in adhering to the journal’s deadlines and guidelines, but they were also patient with our editorial staffing changes. We also thank our feature editors (Ian Parsons, Penelope King, Michael Wiedenbeck, Cari Corrigan, David Vaughan, Andrea Koziol, and Pierrette Tremblay) 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, copyeditors, proofreaders, 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: Analytical Instrument Systems Inc., Bruker Daltonik, Cambridge University Press, CrystalMaker, Excalibur Minerals Corporation, FEI, Geol Soc London, Gübelin AG, International Centre for Diffraction Data, IGC Meeting, International Mineralogical Association, IsotopX, Lithographie, National Electrostatics Corporation, Olympus, *Periodico di Mineralogia,* ProtoXRD, Rigaku, *Rocks & Minerals,* Savillex, SEG, Selfrag, SPEX Sample Prep, Springer, Tescan, Wiley, and Zeiss. Special mention goes to **AHF Analysentechnik**, **Australian Scientific Instruments (ASI)**, **Bruker Nano GmbH**, **CAMECA**, **Excalibur Minerals Corporation**, **The Geochemist’s Workbench**, **JEOL**, and **Savillex**, who advertised in each issue during 2015.

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

2016 PREVIEW & FUTURE ISSUES

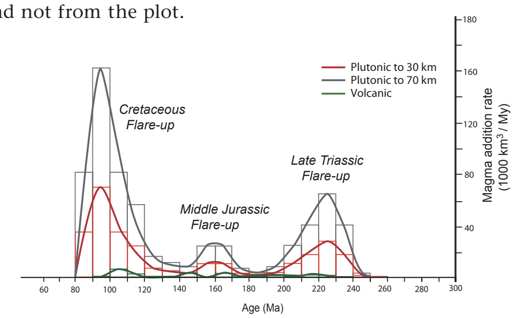
Eleven years old and going strong. With this issue, *Elements* has now covered 65 topics in the Earth sciences. Our lineup is complete through 2016 (see our lineup for 2016 on pages 382 and 383), but there is so much more to cover. If you have ideas for a thematic issue, contact one of our principal editors and consider submitting a proposal. We always welcome new proposals. More information about publishing in *Elements* can be found at www.elementsmagazine.org/forms.htm.

Best wishes to everyone for the coming year.

Patricia Dove, **Gordon Brown**, and
Bernie Wood, Principal Editors
Jodi Rosso, Executive Editor

ERRATA – v11n2

In Paterson and Ducea (2015; *Elements* v11n2), Figure 1C (p 92) and its reproduction in Figure 5A (p 96) have a labeling error in the vertical axis. To prevent any propagation of incorrect data, a revised figure is included below. Peak MAR (magma addition rates) values thus change, but the timing, plutonic/volcanic ratios, and other implications of the plot discussed in the text do not change since these were determined from spreadsheet calculations and not from the plot.



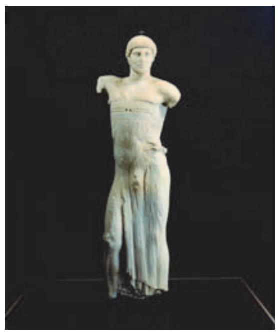
THEMATIC TOPICS IN 2016

Volume 12, Number 1 (February)

EARTH SCIENCES FOR CULTURAL HERITAGE

GUEST EDITORS: **Gilberto Artioli** (University of Padova, Italy) and **Simona Quartieri** (University of Messina, Italy)

Archaeometry and conservation science are connected to the geosciences in three ways. Earth scientists can perceive the complexity of natural materials and of the artifacts produced by human activities, they understand the geological and physico-chemical processes acting on them, and they have a mastery of the techniques used to investigate heritage materials at different scales. Many techniques can be applied non-invasively, preserving the integrity of art/archaeological objects that are often characterized by uniqueness, fragility, high complexity, and heterogeneity. The goal is to understand the fine interplay between human activities, georesources, and natural processes: in short, the history of mankind and human societies on Earth. This issue uses selected examples to demonstrate how the geosciences offer a way to better understand, interpret, and preserve our past.


Giovinetto di Mozia, 450-440 BC

- **The role of modern geosciences in cultural heritage studies**
  Gilberto Artioli (University of Padova) and Simona Quartieri (University of Messina)
- **Non-destructive imaging techniques for heritage assessment: archaeological geophysics and built heritage applications**
  Roger Sala (SOT Archaeological Prospection, Catalonia-Spain), Robert Tamba (Universitat de Barcelona), and Ekhine Garcia (Euskal Herriko Unibertsitatea)
- **Geochronology beyond radiocarbon: optically stimulated luminescence dating of palaeoenvironments and archaeological sites**
  Constantin D. Athanassas (C.E.R.E.G.E., Aix-en-Provence) and Günther A. Wagner (Geographisches Institut der Universität Heidelberg)
- **The Earth sciences from the perspective of an art museum**
  Federico Carò, Elena Basso, and Marco Leona (The Metropolitan Museum of Art, New York)
- **Chemical imaging at the micro- and macroscale: tools for virtual archaeology of (altered) paintings**
  Koen Janssens, Frederik Vanmeert, Stijn Legrand, Geert Van der Snickt (University of Antwerp)
- **Synchrotron advanced imaging of paleontological specimens**
  Pierre Gueriau (CNRS IPANEMA Synchrotron SOLEIL), Sylvain Bernard (IMPMC, Sorbonne Universités, Paris), and Loïc Bertrand (CNRS IPANEMA Synchrotron SOLEIL)

Volume 12, Number 2 (April)

THE ENIGMATIC RELATIONSHIP BETWEEN SILICIC PLUTONIC AND VOLCANIC ROCKS

GUEST EDITORS: **Craig C. Lundstrom** (University of Illinois, USA) and **Allen F. Glazner** (University of North Carolina, USA)

The relationship between silicic volcanic and plutonic rocks has long puzzled geologists. Although the compositional evolution for volcanic and plutonic rock suites are virtually identical, there is much debate whether rhyolites form as melt extracted from granite plutons or whether the two rock types reflect wholly separate origins. This issue discusses the broad set of observations from petrology, geochronology, thermal modeling, geophysical techniques, and geochemistry that lead to contradictory interpretations and no simple description for the relationship. Discerning how silicic volcanic and plutonic rocks are connected will affect important Earth science questions such as “how is continental crust formed?” and “can we predict supereruptions?”

- **Silicic magmatism and the volcanic–plutonic connection**
  Craig C. Lundstrom (University of Illinois) and Allen F. Glazner (University of North Carolina)
- **Geophysical evidence for crustal melt: where, what kind, and how much?**
  Matthew E. Pritchard (Cornell University) and Patricia M. Gregg (University of Illinois)
- **The pace of plutonism**
  Drew S. Coleman (University of North Carolina), Ryan D. Mills (University of North Carolina), and Matthew J. Zimmerer (New Mexico Institute of Mining and Technology)
- **Experimental constraints on the formation of silicic magmas**
  Bruno Scaillet (University of Orleans), François Holtz (University of Hannover, and Michel Pichavant (University of Orleans)
- **The life and times of silicic volcanic systems**
  Colin J.N. Wilson (Victoria University) and Bruce L.A. Charlier (The Open University)
- **Magmatic processes in silicic systems from the perspective of heat transfer**
  Catherine J. Annen and Jon D. Blundy (University of Bristol)

Volume 12, Number 3 (June)

COSMIC DUST

GUEST EDITORS: **Susan Taylor** (Cold Regions Research and Engineering Laboratory, USA), **Donald E. Brownlee** (University of Washington, USA), and **George Flynn** (SUNY–Plattsburg, USA)

Cosmic dust is submillimeter debris shed by comets, asteroids, moons, and planets. In the Solar System, this dust scatters sunlight (the zodiacal light), and it is detected around other stars by its infrared emission. Cosmic dust enters Earth’s atmosphere at high speeds and at a rate of 100 tons a day. These small particles are the largest source of extraterrestrial material accreting on the present-day Earth and include interplanetary dust particles and micrometeorites. Although atmospheric entry heating and terrestrial weathering have modified many, some particles are pristine primitive extraterrestrial materials that contain high abundances of isotopically anomalous presolar grains and primitive carbon compounds that have not been altered since their formation. Cosmic dust analysis provides invaluable information on initial planetary building materials.


Cosmic dust particles: a smooth, 200 μm micrometeorite (top) and a porous, 1 μm interplanetary dust particle (bottom)

- **Cosmic dust: building blocks of planets – falling in our backyard**
  Donald Brownlee (University of Washington)
- **Dust in the cosmos**
  Diane Wooden (NASA Ames Research Center), John Bradley (University of Hawaii), and Hope Ishii (University of Hawaii)
- **Collecting cosmic dust: finding a needle in a haystack**
  Susan Taylor (Cold Regions Research and Engineering Laboratory), Luigi Folco (University of Pisa), and Scott Messenger (NASA Johnson Space Center)
- **Cosmic dust: sources, compositions and implications for the early solar system**
  George Flynn (SUNY–Plattsburg), Cecile Engrand (CNRS/Université Paris), and Larry R. Nittler (Carnegie Institution)
- **Carbon, nitrogen and water in cosmic dust: astrobiological implications**
  Scott Sandford (NASA Ames Research Center), Cecile Engrand (CNRS/Université Paris), and Alessandra Rotundi (Parthenope University of Naples)
- **Geochemical tracers of extraterrestrial matter in sediments**
  Bernhard Peucker-Erhenbrink (Woods Hole Oceanographic Institution), Gregory Ravizza (University of Hawaii), Gisela Winckler (Lamont-Doherty Earth Observatory)

THEMATIC TOPICS IN 2016

Volume 12, Number 4 (August)

DEEP-MINED GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE

Guest Editors: **Bruce Yardley** (Radioactive Waste Management Ltd., UK), **Rodney Ewing** (Stanford University, USA), **Robert Whittleston** (Hitachi Europe Ltd., UK)

The construction of geological disposal facilities for radioactive waste has been a long time in the discussion and planning, but will become a major focus of geological, mineralogical, and geochemical effort in coming years. Underground laboratories have been operating for many years in a variety of rock types. A number of national projects that will dispose of heat-producing waste are nearing the licencing stage: sites have been selected, and planning is moving forward in many countries. Geological disposal raises complex technical issues, but it is also at the centre of social and political controversy.

Different countries have very different waste inventories and quantities of waste; they may also have different geological settings available to host a repository. The issue of *Elements* will present case studies of the concepts for repositories hosted in the range of possible host rocks that have been considered worldwide. The varied approaches to selecting a site that is acceptable to local communities will be reviewed.

The prototype Cannister Hole Boring Machine "Sanna", developed by Posiva, Finland. Source: Posiva Oy

- **Introduction to radioactive waste and geological disposal**
  Rod Ewing (Stanford University), Bruce Yardley (RWM), Rob Whittleston (Hitachi Europe)
- **Geological disposal in clay**
  Bernd Grambow (SUBATECH, Université de Nantes, France)
- **A Repository for spent nuclear fuel in crystalline rock**
  Allan Hedin, Olle Olsson (SKB, Sweden)
- **Geologic repository in salt**
  Thilo v Berlepsch, Bernt Haverkamp (DBE Technology, Germany)
- **Geological disposal in tuff: Yucca Mountain**
  Peter N. Swift, Evaristo J. Bonano (Sandia National Laboratories)
- **Selecting a site for a radioactive waste repository**
  Daniel S. Metlay (US Nuclear Waste Technical Review Board)

Volume 12, Number 5 (October)

STUDYING THE EARTH USING LA-ICPMS

Guest Editors: **Paul J. Sylvester** (Texas Tech University, USA) and **Simon E. Jackson** (Geological Survey of Canada)

Laser ablation – inductively coupled plasma mass spectrometry (LA-ICPMS) is a mature, but still developing, micro-analytical technique that has allowed significant research advances in many areas of the Earth sciences. The method produces quantitative elemental and isotopic analyses on the micrometer scale of most solid, and some liquid, materials across most of the periodic table. A key strength of the method is that it can detect changing conditions or processes over time by analysis of growth zones or domains in minerals and other objects. Recent developments in rapid-wash out ablation cells and data handling software permit elemental and isotopic mapping of materials. Because both inorganic and organic materials can be analyzed, abiotic and biotic processes, and their interactions, can be studied. This issue of *Elements* highlights applications of LA-ICPMS across the broad range of disciplines of interest to the Earth, environmental, and biological sciences that now rely on the technique and their interdisciplinary nature.

Progressive ablation of feldspar from left to right over 60 sec.

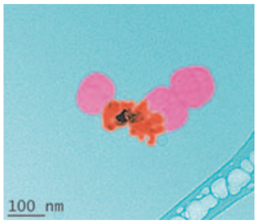
- **History and evolution of the LA-ICPMS technique**
  Paul J. Sylvester (Texas Tech University) and Simon E. Jackson (Geological Survey of Canada)
- **Major and trace element analysis of natural and experimental igneous systems**
  Frances E. Jenner (Open University), Ricardo Arevalo (NASA Goddard Space Flight Center), Hugh, St. C. O'Neill (Australian National University), Ashley Norris (University of Oxford) and Charlotte Allen (Queensland University of Technology)
- **Isotopic geochemistry/geochronology of the magmatic and sedimentary rock record**
  John Cottle (University of California, Santa Barbara), Jon Woodhead (University of Melbourne) and Matt Horstwood (British Geological Survey)
- **Fluid inclusion analysis of metamorphic and ore-bearing systems**
  Christoph A. Heinrich (ETH Zürich) and Thomas Wagner (University of Helsinki)
- **Climate change research**
  Stephen Eggins (Australian National University)
- **Applications of LA-ICPMS to forensic science**
  José R. Almirall and Tatiana Trejos (Florida International University)
- **Prospects for quasi non-destructive analysis of ancient artefacts**
  Patrick Degryse (Katholieke Universiteit Leuven) and Frank Vanhaecke (Universiteit Gent)

Volume 12, Number 6 (December)

THE ORIGINS OF LIFE: TRANSITION FROM GEOCHEMISTRY TO BIOGEOCHEMISTRY

Guest Editors: **Nita Sahai** and **Hussein Kaddour** (University of Akron, USA)

How life originated is one of the most important, and longstanding, questions that humans have attempted to answer, as reflected in our mythologies, religions, philosophy, and science. Furthermore, our understanding of the emergence of life on Earth could potentially contribute to the search for life in other parts of the Solar System and the rest of the Universe. The objective of our thematic issue is to highlight the potential role of minerals and the critical importance of using relevant conditions, plausible on early Earth, for designing experiments to model the emergence and early evolution of life. We believe that this approach is essential to bridging the gap in the field between biochemists/organic chemists, on the one hand, and geochemists/mineralogists, on the other.



Cryo-TEM image showing formation of model protocells (pink) in close interaction with a mineral surface (red).

- **Transition from Geochemistry to Biogeochemistry: Outlining the Problem of the Origins of Life**
  Nita Sahai and Hussein Kaddour (University of Akron)
- **Prebiotic Sources of Simple Organic Molecules**
  Sandra Pizzarello and Everett Shock (Arizona State University)
- **Geochemical Evolution of Aqueous Solutions on Early Earth**
  Martin Schoonen (Brookhaven National Laboratory)
- **Metal Sulfide Minerals and Enzymes and their Relevance to Prebiotic Chemistry**
  Sheref Mansy (University of Trento)
- **Ribozyme Activity under Early Earth Conditions**
  Marie-Christine Maurel (Pierre and Marie Curie University)
- **Towards a Protocell: Assembling the Components of Life**
  Pierre-Alain Monnard (University of Southern Denmark)

GEOMICROBIOLOGY AND MICROBIAL GEOCHEMISTRY: A VIEW FROM THE PAST

Kenneth H. Nealson*

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It might be a useful exercise to begin this overview of geomicrobiology and microbial geochemistry, or GMG (aka geobiology), to pose the question, "What has GMG done for me (or anyone else)?" The answer from my perspective is, "A huge amount of good!" Forty years ago there was no GMG. None of the techniques and approaches that we now take for granted were available, and most of what is highlighted in this issue was not even imagined. As you peruse the articles, you will find in each the excitement of making discoveries at the interface between various aspects of microbiology and geochemistry. A new type of young GMG scientist has emerged, unafraid of interdisciplinary work and open to collaboration with previously "unavailable" colleagues. For every one of the articles here (each packed with "good things") several others from this burgeoning field could have been added. Now for overview!

In 1977, after a few years as an assistant professor at Scripps Institution of Oceanography (University of San Diego, California, USA) (SIO), I presented a seminar on the subject of bacterial regulation of bioluminescence. After the talk, Ed Goldberg, a crusty (to be polite) marine geochemist came up to me and said, "Very nice and interesting work: why don't you do something important?" Given that all the advice I had received from Ed in my first four years at SIO had been good, I responded, "What would you suggest?" Ed's answer was, as always, a bit irreverent, but to paraphrase, he said that the geochemistry of neither iron nor manganese in the ocean was well understood, and he suspected it was because of bacterial activities. This conversation, along with discussions with Gustav Arrhenius (a geologist at SIO) and a chance meeting in Israel with a group of microbiologists that included Bo Jorgensen, Yehuda Cohen, and Wolfgang Krumbein (who all have excelled in various aspects of GMG), convinced me to join in the geobiological fun. I set up a series of enrichment cultures for manganese-oxidizing bacteria ("The Nealson Museum") and continued working on bioluminescence until I received tenure (sage advice from Professor Arrhenius). In late 1978, the enrichments were opened and the fun began—and has continued until today.

I mention this scenario because so many early developments in GMG arose through similar interactions between microbiologists, geologists, and geochemists. In a young field, colocation of potential colleagues can be of great importance, and being on the same campus with several marine geochemists and geologists was key to my own progress in geobiology. It was surprisingly easy to find students who wanted to work at the "microbe–mineral interface," as it would soon be called: one of whom has written a textbook on marine sediment geochemistry (Burdige 2006); another who is a coauthor of an article in this issue (Hansel et al. 2015 this issue).

But the transition was difficult: most microbiologists had not been properly trained for geobiology. In general, it was far easier and safer to do reductionist studies of an organism that had a name and grew well in culture than to isolate an unknown microbe that was difficult, if not impossible, to grow and that was equally difficult to identify. To put it bluntly, microbiology was not up to the task. The revelation of the so-called "great plate count anomaly" made it clear that much of our microbiological world resided in the area of the unknown: in most environments, only 1% or less of the organisms seen in a given sample were able to be cultivated (Whitman et al. 1998). This wasn't news to most of us, it was just the first time anyone had openly admitted it—microbial ecology was being done with only a few percent of the microbes. New techniques were needed!

What was not clear in the mid-1970s was that a great explosion (in techniques and approaches) was about to occur. There were changes taking place that had the potential to deliver us from the "dark ages" of environmental microbiology, previously characterized by limited abilities to identify microbes and by a lack of knowledge of the basics. The coming changes (outlined below) would be major enablers of the progress in GMG.

WHERE DID GMG COME FROM?

New fields arise and grow for several reasons, but I like to view it as a three-phase, interactive process, with positive feedbacks between all phases. In the case of GMG, those asking the questions had neither the academic training nor the technology to answer them. The questions come from one field (phase I), and the answers come from bringing new skills and techniques to what becomes a new field (phase II). In the case noted above, as is often the case with geobiology, the question was one of kinetics—rates of metal oxidation and reduction far too fast to be explained by geochemistry. Altering kinetics is perhaps a microbes' greatest forte—using enzyme catalysts that are both specific and very effective. Phase III is the resulting technology and methods that are developed in response to the newly generated questions, allowing more questions to be asked and, in turn, answered. To summarize this:

PHASE I: One field, geochemistry in this case, identifies problems for which it is unprepared to solve, either with regard to academic training (ideas), or experimental methodology, or through experimental approaches.

PHASE II: A second field, microbiology in this case, which was not aware of the questions, embarks on a new kind of science using the known array of ideas and techniques. Some answers are provided; these generate other questions; and the need for new methods and new technologies (and sometimes new approaches) is thereby created.

PHASE III: Developments in both technology and methodology provides higher resolution and new abilities, driving the science forward, and making it possible to ask (and answer) new questions.

Other drivers included the discovery of things so new and unexpected that many recruits (young and old!) were attracted to the interdisciplinary world of environmental microbes in ways that couldn't have been predicted. A few examples of such discoveries make the point:

1. Extremophilic microbes that live under conditions of temperature, pH, salinity (and so on) previously thought to be impossible.
2. The hydrothermal vent communities with symbiotic chemolithotrophic bacteria forming the base of food chains in the deep dark ocean.
3. Quorum sensing, and the ability of microbes to communicate with one another.
4. The formation, properties, and ubiquity of bacterial biofilms.
5. Anaerobic methane oxidation, thought to be impossible.
6. The longevity of microbial DNA.
7. The extent (and strangeness) of the microbial world in the deep subsurface.
8. The ability of bacteria to use solid substrates (metal oxides or even electrodes) both as electron acceptors and/or donors.

Another, albeit indirect, driver of the geobiological revolution was the development of new methods for **molecular taxonomy and phylogeny**. As discussed by Dick and Lam (2015) in this issue, Carl Woese (in the late 1970s) devised, revised, and popularized the beginnings of what we now call molecular taxonomy/phylogeny, resulting in the widespread use of the 16S rRNA gene sequence as the universal micro-

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bial "dog tag" (Woese and Fox 1977), and the establishment of the three domains of life (and the establishment of the domain Archaea) (Woese et al. 1990; Woese 2004). The many Woese "disciples" (Norm Pace, Steve Giovanoni, Ed Delong, and others) have forever changed the landscape of microbial taxonomy, using fluorescence in situ hybridization (FISH) probes of rRNA to locate, identify, and quantify microbes in situ. Furthermore, as more samples were examined, it became clear that many of the numerically dominant members in most environments were not yet successfully cultivated. Yikes! ... we were surrounded by uncultivated microbes of unknown function!

GENOMICS AND THE "OMICS" REVOLUTION(S)

As sequencing approaches continued to improve, it became clear that microbial genomics would be possible, and several major efforts were put forward to sequence genomes of both archaea (because they were very small), and bacteria (particularly pathogens). The first geobiologically relevant bacteria to have their annotated genomes displayed to the public were from two metal oxide–respiring microbes, *Shewanella* (Heidelberg et al. 2002) and *Geobacter* (Methé et al 2003). This involved several years of work, and cost more than a million dollars each! Compare that to today's technology, scarcely more than a decade later, and it is mind-boggling that microbial genomes can now be sequenced for thousands of dollars and done only in days!

The perspective of seeing an organism's "operating system" laid out gene-by-gene was remarkable to us old-timers, and the follow-on studies of transcriptomics, proteomics, and now, metabolomics have impacted all fields of microbiology. That this can be done in mixed cultures to the "meta" levels of all parts of "omics" simply could not have been imagined only a few years ago (Dick and Lam 2015).

Other new technologies and approaches have also been drivers of the GMG revolution and have been combined with modern molecular taxonomy/phylogeny and the "omics" approaches. Some of these are outlined below:

1. Development of stable isotope fractionation technologies for a wide range of nontraditional isotopes including metals.
2. Development of stable isotope "probes" for the identification of active members of microbial communities.
3. Nano-SIMS technology for the analysis of single-cell activities.
4. Microelectrode approaches for the study of community properties and activities.
5. Development of many variations of FISH probes and technologies.
6. Incorporation of synchrotron methods for analysis and imaging.
7. Development of deep drilling technologies and improvement of drilling ships for sample acquisition and analysis.

CHALLENGES AND PERSPECTIVES

There are many problems (old and new) for which answers are being obtained, with evolving technologies providing new levels of resolution and understanding. But what are the important challenges in GMG? There are several large gaps in our knowledge that could stall or stop progress in the field. Five questions that need answers are the following:

1. **What are all these "noncultivable" microbes doing?** Are there metabolic niches (and new metabolisms) that we don't understand, or are they simply surviving and waiting for a different or better environment to come along?
2. **What is going on in the deep subsurface of our planet?** Work in the last decade has suggested that a huge biomass of microbes resides in the deep subsurface, surviving under conditions of severe nutrient limitation.
3. **What are the role(s) of microbes as members of the microbiomes?** Probably every plant and animal (including humans) contains specific bacterial cohabitants (in our case, several hundred bacteria for each of our own cells) called the microbiome. The same is almost certainly true of every GMG-relevant environment, with its complex microbial communities. But what are they doing?
4. **What are the factors that lead to stable microbial communities, from biofilms to sediment populations?**
5. **What are all the genes of unidentified function doing in microbes?**

Each of these questions will, of course, generate many more specific questions that will keep GMG scientists occupied for many years to come.

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Meet the Authors

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Eric Boyd is an assistant professor and NASA Early Career Fellow in the Department of Microbiology and Immunology at Montana State University (USA). After receiving a BS in biology at Iowa State University (USA), he moved to Bozeman (Montana) where his doctoral work focused on the geomicrobiology of hydrothermal environments. As a NASA Astrobiology Institute postdoctoral fellow, Boyd expanded his work to include subglacial and hypersaline environments and investigated the interplay between geochemical variation and the diversification of microbial life and the metabolic processes that support it. His current research focuses on the ecology and physiology of extremophile microorganisms, as viewed through the lens of evolutionary biology.

Gregory J. Dick is an associate professor in the Department of Earth and Environmental Sciences at the University of Michigan (USA). He received his PhD from the Scripps Institution of Oceanography (California, USA) in 2006 and was a postdoc at the University of California, Berkeley (USA) from 2007 to 2008. Greg has long been interested in the interplay between microbes and geochemistry, including the geomicrobiology of deep-sea hydrothermal vents. Recently, he has become intrigued by cyanobacteria and their influence on Earth and the environment. He is now studying modern microbial mats (as analogues of ancient ecosystems) and harmful cyanobacterial algal blooms.

Gregory Druschel is an associate professor at Indiana University–Purdue University Indianapolis (IUPUI) (USA). He earned a BS in geology at Muskingum University (Ohio, USA) in 1995, an MS in geology from Washington State University (USA) in 1998, and a PhD in geology from the University of Wisconsin (USA) in 2002. He was a postdoc at the College of Marine Studies at the University of Delaware (USA) between 2002 and 2004 and was an assistant, then associate, professor at the University of Vermont (USA) before moving to IUPUI in 2012. His research centers on the redox chemistry of biogeochemical systems past and present, with interests focused on sulfur cycling and the biotic and abiotic controls on intermediate S chemistry, the role of Fe and Mn cycling on nutrient fluxes that drive harmful algal blooms, and on the fundamental reactivity of particles in lung fluids.

Tim Ferdelman is a senior scientist in the Biogeochemistry Department at the Max Planck Institute (MPI) for Marine Microbiology in Bremen (Germany). Prior to joining the MPI in 1992, Tim received his BS from Miami University (Ohio, USA) and his MSc and a PhD in oceanography from the University of Delaware (USA). His research concerns the cycling of bioactive elements in marine environments, and he has sailed on numerous oceanographic and ocean drilling expeditions. Tim employs radiochemical and liquid chromatography methods to investigate the marine sulfur cycle.

David A. Fike is an associate professor in the Department of Earth and Planetary Sciences and Director of the Environmental Studies program at Washington University in St. Louis (WUSTL) (Missouri, USA). He received his PhD in isotope geochemistry in 2007 from the Massachusetts Institute of Technology (USA) by investigating Ediacaran biogeochemical cycling, after which he did a postdoc at the California Institute of Technology (USA) where he applied high-resolution isotopic analyses to microbial ecology. He joined the WUSTL faculty in 2009 and now focuses on understanding the biological, sedimentological, and diagenetic processes that generate and alter isotopic signatures in modern marine sedimentary phases and, ultimately, how these are preserved in the rock record.

Colleen Hansel is an associate scientist in the Department of Marine Chemistry and Geochemistry at the Woods Hole Oceanographic Institution (Massachusetts, USA). Colleen received her BS in geology from California State University, Sacramento (USA), her MS in soil chemistry from the University of Idaho (USA), and her PhD in biogeochemistry from Stanford University (California, USA) where she stayed on for postdoctorate research in molecular microbial ecology. She is broadly interested in the role of microbial activity and physiology in shaping geochemical and mineralogical landscapes. More specifically, she integrates laboratory experiments and marine field measurements to identify the biogenic metabolites and reactive intermediates that are involved in coupled elemental cycling and mineralization.

Andreas Kappler is a professor of geomicrobiology at the University of Tübingen (Switzerland). He received his MSc in chemistry and PhD in environmental microbiology from the University of Konstanz (Germany) and held postdoc positions at the Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz [Swiss Federal Institute of Aquatic Science and Technology, of EAWAG/ETH] (Zürich, Switzerland) in environmental chemistry, and in geobiology at the California Institute of Technology (USA). The major focus of his research is the biogeochemical cycling of iron and humic substances and the environmental fate of toxic metals and nutrients. Kappler also investigates the role that microbial iron oxidation played in the deposition of Precambrian banded iron formations, biochar (charcoal) as a soil amendment, and how to recover precious metals from incineration waste.

Phyllis Lam is lecturer of marine microbial biogeochemistry at the University of Southampton (UK). Her research focuses on the roles of microorganisms in biogeochemical cycling: specifically, in environments ranging from deep-sea hydrothermal vents, to the subsurface biosphere, to the suboxic water columns of oceans and lakes, to oligotrophic subtropical ocean gyres and in desert crusts. Lam combines molecular biological methods with biogeochemical measurements and has been the first to report on chemolithoautotrophic ammonia oxidation in deep-sea hydrothermal plumes, to demonstrate that there is a deep subseafloor biosphere, and to disentangle the closely coupled microbial N-cycling processes in oxygen-minimum zones where up to half of global marine N loss takes place.

Timothy W. Lyons is a distinguished professor of biogeochemistry at the University of California, Riverside (USA). His primary research themes are astrobiology, marine geochemistry, geobiology, and biogeochemical cycles through time. His career-long interests in anoxic marine environments, early biosphere oxygenation, and coevolving life have inspired the development and refinement of diverse geochemical tracers in modern settings for the "exploration" of ancient oceans and atmosphere. Much of this research revolves around the recognition of elemental and isotopic fingerprints of ancient microbial activity. Lyons is currently leading the NASA Astrobiology Institute's "Alternative Earths" team—designed with the mission of using the many diverse chapters of persistent habitability on a dynamic early Earth to inform the search for life elsewhere.

Everett Shock grew up in the heart of Orange County (California, USA), two miles from Disneyland. He received his BS in earth sciences from the University of California, Santa Cruz, where he met his wife Allison. After working for a couple years at the US Geological Survey, he entered graduate school at the University of California, Berkeley, where he earned his PhD in geology. He taught at Washington University in St Louis (USA) for 15 years before moving to Arizona State University (USA). Much of Shock's current research converges on understanding how planets become habitable: this is done through fieldwork in extreme environments, hydrothermal experiments, and thermodynamic interpretations of planetary geochemical processes.

Brad Tebo is a distinguished professor of marine and biomolecular systems in the Institute of Environmental Health at Oregon Health & Science University (USA). He investigates how metal transformations by microbes influence the living world at levels from planetary biogeochemical cycles to enzymatic reactions in living organisms. Tebo aims to comprehensively understand the mechanisms by which microbes transform soluble metals to insoluble forms by weaving together data from oceanographic field studies, laboratory microbiology, and high-energy X-ray spectroscopy. His particular focus has been on manganese because of its profound influence on other metals, and its crucial role in photosynthesis and carbon cycling.

Alexis Templeton is an associate professor in the Department of Geological Sciences at Colorado University, Boulder (USA). During her career, she has worked in active geo-hydro-biological systems in the western USA, New Zealand, Hawaii, Samoa, Oman, and the Canadian High Arctic. Currently, she leads a geomicrobiology and geochemistry research group specialized in the development and application of scattering and spectroscopic approaches capable of interrogating the redox reactions that occur at the interfaces between mineral surfaces, microorganisms, and fluids. Her research integrates mechanistic studies, in well-controlled experimental systems, with intensive fieldwork in settings where there are strong connections between the subsurface and the surface rock–hosted biosphere.

Aubrey L. Zerkle is a lecturer in geobiology at the University of St Andrews in Scotland (UK). A diverse research career has taken her from the geomicrobiology of modern Caribbean corals to the microbial modulation of the Archean atmosphere. Her current interests focus on understanding the coevolution of life with the evolution of Earth's surface environment over geologic timescales. Zerkle utilizes a multidisciplinary approach, combining microbiology, stable isotopes and trace metal geochemistry to examine biogeochemical cycling in modern and ancient ecosystems, with special focus on calibrating the isotope biosignatures of microbial activity and on investigating geosphere–atmosphere–biosphere feedbacks during important transitions in Earth's history.

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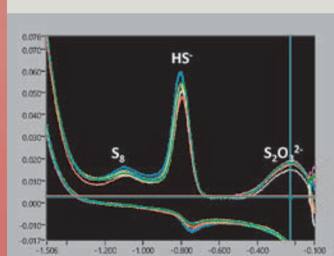
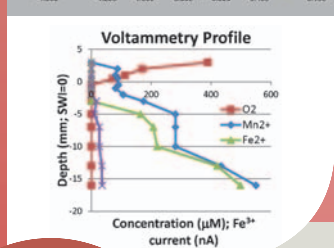
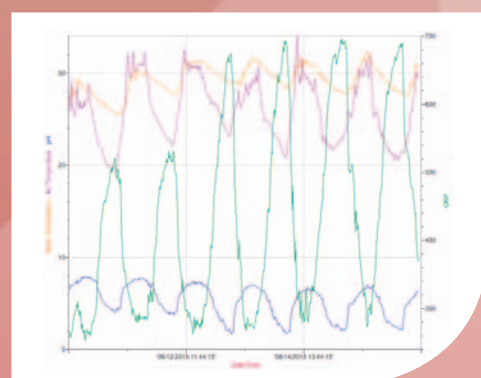


Typical voltammetric scan of microbial mat from Guerrero Negro.



Core collected from Missisquoi Bay, Lake Champlain and profiled using AIS DLK-70 and auto-manipulator.



Data was collected over 6 days in a local pond in New Jersey showing the interaction of pH, ORP, air, and water temperatures, during diurnal cycling.
blue = pH, green = ORP
purple = air temp, orange = water temp

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