Curiosity’s Mission of Exploration
Images of the Gale Crater Landing Site
Elemental Chemostratigraphy
Martian Elemental Variability
Mars Mineralogy by X-ray Diffraction
Volatile and Isotopic Imprints of Ancient Mars
Phase identification and Rietveld refinement of Connemara marble with a benchtop X-ray diffractometer

Connemara marble is unique in the sense that it is only found in one place on earth – in Galway County on the scenic west coast of Ireland.

In addition to containing a limestone mineral (calcite), three other phases belonging to the serpentine mineral family are found in Connemara Marble. The main polymorphic forms are chrysotile, antigorite, and lizardite. X-ray diffraction is a viable technique to identify and pinpoint the exact phase of the serpentine family.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical Formula</th>
<th>Wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lizardite</td>
<td>Mg₃(Si₂O₅(OH)₄)</td>
<td>38.2</td>
</tr>
<tr>
<td>Calcite</td>
<td>CaCO₃</td>
<td>44.5</td>
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<tr>
<td>Chlorite lb</td>
<td>MgFeSiAlO₄OH</td>
<td>15.1</td>
</tr>
<tr>
<td>Dolomite</td>
<td>CaMg(CO₃)₂</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Specimens of Connemara marble were pulverized and analyzed with the Rigaku MiniFlex benchtop XRD. A Rietveld analysis was performed using the model obtained from these phases.
Mineralogy of Mars

Guest Editor: John P. Grotzinger

Curiosity’s Mission of Exploration at Gale Crater, Mars
John P. Grotzinger, Joy A. Crisp, Ashwin R. Vasavada, and the MSL Science Team

Images from Curiosity: A New Look at Mars
Linda C. Kah and the MSL Science Team

ChemCam: Chemostratigraphy by the First Mars Microprobe
Roger C. Wiens, Sylvestre Maurice, and the MSL Science Team

In Situ Compositional Measurements of Rocks and Soils with the Alpha Particle X-ray Spectrometer on NASA’s Mars Rovers
Ralf Gellert, Benton C. Clark III, and the MSL and MER Science Teams

Determining Mineralogy on Mars with the ChemCam X-Ray Diffractometer
Robert T. Downs and the MSL Science Team

Volatile and Isotopic Imprints of Ancient Mars
Paul R. Mahaffy, Pamela G. Conrad, and the MSL Science Team
PARTICIPATING SOCIETIES

The Mineralogical Society of America (MSA) is committed to serving the professional and scientific community interested in mineralogy, crystallography, and geochemistry. Founded in 1919, the Society promotes, through education and scholarly publication, the understanding and application of mineralogy by industry, universities, and the public. Membership benefits include special subscription rates for American Mineralogist as well as discounts on travel, insurance, and registration for MSA meetings and short courses.

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The Mineralogical Society of Great Britain and Ireland is an international society for all those working in mineralogy. The Society aims to advance the knowledge of the science of mineralogy and its application to other subjects, including crystallography, geochemistry, petrology, and allied fields. The Society is in pursuit of scientific excellence in mineralogy and the related disciplines of crystallography, geochemistry, and petrology, and fosters cooperation in the advancement of the knowledge in these fields. Membership benefits include a subscription to The Mineralogical Record and annual meeting discounts.

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The Mineralogical Association of Canada (MAC) 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 of science, who desires to be affiliated with the Association, is eligible for membership. Membership benefits include a subscription to the Mac. Mem. Newsl., as well as discounts to annual meetings and other MAC publications. Membership benefits include receiving the Mac. Mem. Newsl. and registration fee reductions for MAC 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 in the fields of clay science and technology. The CMS holds annual meetings, workshops, short courses, field trips, and publishes Clay and Clay Minerals and the CMS Workshop Lectures series. Membership benefits include discounts on annual meeting registration and discounts on the CMS Workshop Lectures series.

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The Geochemical Society (GS) is an international organization founded in 1955 for students and scientists interested in the study of geochemistry. Its programs include collecting the annual Goldschmidt Conference, editorial oversight of Geochimica et Cosmochimica Acta (GCA), supporting geochemical symposia through its Meeting Assistance Program, and supporting student travel grants. Membership benefits include access to the Society’s offerings, discounts, and special publications.

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

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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 main objective of the Society is to promote mineralogy and crystallography. Membership benefits include a subscription to the French Journal of Mineralogy and Elements, and reduced registration fees for SFMC meetings.

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The International Association of Geoanalysts (IAGC) was pre-eminent international geochemical organization for over 40 years. Its principal objectives were to foster cooperation in the advancement of 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, Management Committee, and ordinary members. Day-to-day administration is performed by a business office.

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The Polskie Towarzystwo Mineralogiczne (Polish Mineralogical Society of Poland), founded in 1969, draws together professionals and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The Society promotes the exchange of information on science and education through annual conferences, field trips, excursions, and publications. Membership benefits include subscriptions to Minerals and Elements.

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The Société Española de Mineralogía (Spanish Mineralogical Society) was founded in 1975 to promote research in mineralogy, petrology, and economic geology. The Society organizes annual conferences and holds training for young researchers via seminars and workshops. The Society 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, technical, and review articles. 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 organizes the annual Swiss Geoscience Meeting and publishes the Swiss Journal of Geosciences (Sve), a new journal containing scientific, technical, and review articles. Membership benefits include the European Journal of Mineralogy, Switzerland, and related disciplines. Membership benefits include receiving the European Journal of Mineralogy, Switzerland, and Elements, and a reduced registration fee for the annual meeting.

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www.smp-sve.ch

The Metecritological Society is an international organization founded in 1953 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, Metecritology & Planetary Science, reduced rates for Geochimica et Cosmochimica Acta, which we cosponsor, the Meteoritical Bulletin, and Elements. We organize annual conferences, workshops, and field trips, and support young researchers worldwide. Through our newsletters and awards, we recognize excellence in meteors 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 geosciences. Membership benefits include receiving the Journal of the Japan Association of Mineralogical Sciences (JAMS), the Gansui-Koubutsu-Kagaku (GKK), and Elements.

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The Japanese Society for Microscopic Sciences (JSMS) was founded in 2005 to promote research in mineralogy, petrology, and economic geology. The Society organizes annual conferences and holds training for young researchers via seminars and workshops. The Society 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, technical, and review articles. Membership benefits include the European Journal of Mineralogy, Minerals, and Elements.

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The Swiss Journal of Geosciences (Sve) is a new journal containing scientific, technical, and review articles in the fields of mineralogy, geochemistry, and petrology, but that do not themselves have a membership base.

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The Swiss Journal of Geosciences (Sve) is a new journal containing scientific, technical, and review articles in the fields of mineralogy, geochemistry, and petrology, but that do not themselves have a membership base.
HAS LIFE EVER EXISTED ON MARS?

This issue of Elements presents some of the remarkable scientific findings of the Martian rover Curiosity, which landed in Gale Crater on August 6, 2012. In preparing my editorial for the Mars issue, I felt compelled to reread the classic science fiction novel by H. G. Wells entitled *The War of the Worlds*. First published in 1898, this novel was about the invasion (Book One) and subjugation (Book Two) of Earth by extraterrestrials—in this case Martians—each of whom had two large dark eyes, a lipless mouth that “quivered and dropped saliva,” tentacles, “oily brown skin,” very large brains, and rounded bodies about 1.2 m in diameter (Wells 1898). Wells’ sci-fi thriller was essentially a metaphor for some of the major social, scientific, and technological changes occurring in the late 19th century (Taglieri 2012). This tale was set in Victorian London and the nearby countryside, and had Martians landing near London in metal cylinders. The Martians had three-legged fighting vehicles (Fig. 1) armed with heat rays and proceeded to overcome all human resistance. Eventually, the invading Martians were killed, not by humans but by lowly microbial organisms on Earth.

Wells’ novel was one of the first to raise the question of possible life on Mars. This possibility has become one of the major scientific drivers for NASA to send numerous orbiters, landers, and rovers to Mars. This issue of Elements focuses on the rover Curiosity, whose primary mission is to determine if Mars ever had environments that could support life.

The question of life on Mars has fueled the imagination of many earthlings since Wells’ novel, but answering it has not been straightforward or without controversy. For example, in 1907 A. R. Wallace published the book *Is Mars Habitable?* (Wallace 1907), which criticized Lowell’s 1906 claims of canals on Mars built by intelligent beings; Wallace concluded that complex life on Mars was impossible. More recently, the 1976 Viking missions to Mars were thought to have produced evidence of microbial life on the Red Planet based on the detection of key organic molecules. However, many scientists think the results were inconclusive (e.g. Navarro-González et al. 2006). Twenty years later, David McKay of the Johnson Space Center led a team of scientists who claimed to have found evidence for fossil life forms in a Martian meteorite known as Allan Hills 84001, recovered from Antarctica. The resulting paper (McKay et al. 1996) concluded that “the PHs, the carbonate globules, and their associated secondary mineral phases and textures could thus be fossil remains of past martian biota,” referring to their analyses of ALH84001. On August 7, 1996, NASA announced these findings, and on the same day President Bill Clinton held a press conference at the White House and cautiously praised the effort, stating, “If this discovery is confirmed, it will surely be one of the most stunning insights into our universe that science has ever uncovered. Its implications are as far-reaching and awe-inspiring as can be imagined.” Following this provocative study, there was negative reaction to it by the scientific community; for example, it was suggested that the objects thought to represent fossil nanobacteria were too small to support metabolism and did not contain the amount of DNA, ribosomes, enzymes, lipids, etc. needed to support life as we know it (Maniloff et al. 1997), and that ALH84001 was contaminated by terrestrial organic material following its landing on Earth (Jull et al. 1998). More recently, Martian meteorite Yamato 000593 was found to contain carbonaceous matter and microtubular features similar to those formed by bioerosion in terrestrial basalts (White et al. 2014). So, the quest for past life on Mars continues, as it should.

This issue of Elements contains six articles that report the latest results from the Mars Science Laboratory (MSL) following 2+ years of exploration by the rover Curiosity. This is an amazing mobile laboratory equipped with a variety of high-resolution cameras and four major analytical instruments capable of determining the minerals in Martian rocks via X-ray diffraction, as well as the elemental isotopes, organic carbon, and volatiles present in Martian rocks, soils, and atmosphere via various types of spectrometry. Sedimentary rocks dominate the samples examined by Curiosity, and clear evidence was found for hydrous minerals (e.g. phyllosilicates and hydrated sulfates), alteration of primary minerals by circumneutral pH solutions, a warm past climate (i.e. above 0 °C), and lakes and rivers in Gale Crater. More importantly, the evidence gathered by Curiosity and interpreted by MSL Chief
TREMBLAY has “officially” retired after 10 years at the helm of Elements. In anticipation of Tom’s retirement, we posted an ad for a copy editor in August 2014. To our delight, we received almost 20 applications, all from qualified candidates. We are excited to announce that Patrick Roycroft joined our editorial team in January 2015. He is a PhD geologist, a talented copy editor, and an avid reader of Elements. Welcome Patrick!

The Elements editorial office has moved west and across the Canada–US border going from Québec City (Quebec) to Richland (Washington). The contact information for our new editorial office can be found on page 3. Even if you never have the opportunity to visit our office, you are invited to visit our website, www.elementsmagazine.org, and to explore our Facebook and LinkedIn pages!

INTRODUCING BERNIE WOOD, PRINCIPAL EDITOR 2015–2017

With the start of 2015, Bernard J. (Bernie) Wood joins the Elements team as a principal editor. Bernie is currently a professor of mineralogy in the Department of Earth Sciences, University of Oxford (UK). He previously held positions at Northwestern University (USA), the University of Manchester (UK), and the University of Bristol (UK).

By combining high-pressure, high-temperature experimental petrology with physicochemical theory, Bernie has made wide-ranging contributions towards understanding the relationships between melts and solids in the Earth. During his career he has applied experiments to problems such as the thermodynamic properties of minerals, geobarometry and geothermometry, the nature of the seismic discontinuities in the mantle, and the factors controlling crystal–melt partitioning of trace elements. Currently his principal interest is the accretion and differentiation of the Earth.

The significance of his contributions to the fields of mineralogy, geochemistry, and petrology is evidenced not only by the 15,000+ citations of his work but also by the long list of honors and awards that Bernie has received over his distinguished career. He has Fellow status with several of Elements sponsoring societies as well as the American Geophysical Union, the Geological Society of America, and the Royal Society. He has also received many awards, most recently the Harry H. Hess Medal (2013) from the American Geophysical Union and the Roebling Medal (2014) from the Mineralogical Society of America. We are delighted to have Bernie join the editorial team. Bernie will be responsible for the petrology content of Elements. He is already hard at work handling the October 2015 issue on suppergene deposits.

John Valley, Trish Dove, Gordon Brown, Bernie Wood, Pierrette Tremblay, and Jodi Rosso

REFERENCES


Wells HG (1898) The War of the Worlds. Heinemann, London, 104 pp


Scientist John Grotzinger and his team of experts indicates that habitable environments were present on Mars. To date, however, there is no clear evidence of current or fossil life forms in Martian minerals and rocks. A special section on the MSL mission was published in the New York Times on December 9, 2014, that addresses some of these findings. A major unanswered question is: did these environments exist long enough for life to evolve? Although it may be disappointing to some that Curiosity did not find Martians similar to those described by Wells, or even lowly bacteria, NASA’s latest mission to Mars is a spectacular technological and scientific success that provides humankind with definitive new information on our sister planet and new insights into the geological processes that have shaped its surface.

Gordon E. Brown, Jr.  Principal Editor
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SXFiveFE EPMA analysis of «Paris» meteorite (classified as CM chondrite) exhibiting a complex Calcium-Aluminum rich inclusion (CAI). The high resolution X-ray map shows the typical condensation sequence - hibonite, perovskite and grossite - in spinel. Evidence of zoning in hibonite.

Sample courtesy of Dr. B. Zanda (Muséum d’Histoire Naturelle de Paris) and Dr. R. H. Hewins (Rutgers University).

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Right: Oxygen isotopic compositions of Itokawa minerals compared with those of San Carlos forsterite and Miyake-jima anorthite crystals.

From: Oxygen Isotopic Compositions of Asteroidal Materials Returned from Itokawa by the Hayabusa Mission.


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SUGGESTIONS FOR APPLYING FOR A MASTER’S OR PHD DEGREE

Penny L. King*, Rachel S. Kirby*, Liane M. Loiselle*, Leo R. Pure* and Christian J. Renggli*

There is an old joke that if you can’t decide what to do in your life, then you should do a graduate degree – a master’s or PhD. While there may be an element of truth to this joke, there are many reasons why you might want a graduate degree, including:

- Personal satisfaction and knowledge expansion
- An opportunity to build professional skills and make new discoveries while completing original research
- As a requirement for certain careers

The questions then arise: How do you apply for graduate studies? What options do you have?

WHERE TO FIND OUT ABOUT GRADUATE OPPORTUNITIES

Of course, the Web provides one-stop shopping for graduate opportunities, but if you want a personal touch, perhaps the best place to start investigating options for graduate studies is at your undergraduate university. Most academics at your institution have completed a graduate degree and are a potential source of guidance – they may even be looking for new graduate students. If they don’t already have projects that you might want to pursue or if you plan to undertake graduate studies elsewhere, they can potentially recommend colleagues who might be looking for students. Another port of call is the departmental administrator or university officer who deals with graduate student admissions. They can provide advice on the processes involved in applying to graduate school at the university and/or elsewhere. Also, graduate students in your department are a great source of information because they have recently gone through this process themselves. Many universities and conferences organize events where institutions present themselves. These events are great opportunities to get information about different degrees and application processes as well as to talk to students who live somewhere else.

Some students continue their graduate studies at their undergraduate institution, which can be beneficial in terms of logistics and lifestyle. However, many students see an advantage to changing their academic environment and geographic setting in order to learn more and expand their professional networks. In the end, the choice of whether you should stay or move comes down to personal preference and circumstances.

FINDING A SUPERVISOR, TOPIC AND UNIVERSITY

A graduate degree is a big deal, and so you will want to find a supervisor with whom you communicate well and a research topic that you enjoy. A supervisor with similar research interests to yours will ensure that you are both on the same page at the beginning of your degree. Some people say that your relationship with your supervisor is one of the most important in your life. If things go well, your supervisor will promote your research, provide sufficient funding and support and help lay the foundation for a fulfilling career. If things don’t work out, then the path may be unexpectedly bumpy, but remember that a range of different outcomes may result and eventually you will discover new options.

You can find potential supervisors and projects on most university websites or in professional organizations’ publications, websites and e-mail lists. Once you have found some potential supervisors, you would be well advised to read some of the publications from their group to figure out if their research will motivate you through your degree. Pay close attention to whether the research topics are compelling and seem tractable. Check out what the students in the group are doing and whether you are inspired by their work.

Once you have identified a supervisor, send a succinct e-mail. Be sure to highlight any previous research experience, and show that you are genuinely interested in this particular supervisor and their specific research interests. You may want to include a few comments about your achievements (e.g. an A+ average and research experience) and attach your curriculum vitae (CV) and unofficial transcript. Some people won’t open attachments, and so it is a good idea to put your CV below the e-mail message as well as attaching a pdf. If someone recommends that you contact the potential supervisor, include their name in your e-mail once you have obtained permission to do so.

What if you get no reply after two weeks? Resend the e-mail with a different subject line. The most likely scenario is that your e-mail has scrolled off the potential supervisor’s screen before they had an opportunity to reply. What if you still don’t get a reply? You can send a third message or write to the graduate administrator indicating an interest in working with the potential supervisor. Remember, if the potential supervisor doesn’t answer your message it does not necessarily indicate how they view you. There are many possible reasons why the supervisor does not answer. Supervisors can be busy, lack funding for graduate students, are travelling or doing remote field work. Or, your message went into their junk mail.

If the potential supervisor expresses interest, try to either meet in person (for example, at their university or at a conference) or set up an Internet meeting. Find out whether the university pays for visits by top applicants or accepted students. Such a visit gives you a chance to talk not only to the potential supervisor but also to current graduate students about how they like the university, supervisor and group, and you can check the location. Remember to take some students’ comments with a “grain of salt” because not everyone will respond to situations or people in the same way as you. During your visit, pay attention to the opportunities that the university provides – you are responsible for evaluating if the potential program of study is the right fit for you. Are there field trips for graduate students? Are classes offered? Are the appropriate resources easy to access (lab, library, etc.)? Does the department seem to run well? What is the research ranking of the university? Does the potential supervisor have many students and what is the track record of their graduates? What are the supervisor’s expectations regarding their students? Does the university offer professional development opportunities (e.g. grant writing, communication skills and teaching opportunities)?

DECIDING ON A MASTER’S VERSUS A PHD DEGREE

A PhD is viewed by many as a research degree and a master’s as a smaller research project that prepares you for a range of jobs. Some people believe that doing a PhD will make you “overqualified” for jobs outside academia. The question to ask here is: would you want to work for a boss who does not value your PhD? However, if you are uncertain, start with a master’s degree because if you dislike graduate work it is easy to leave quickly. It is much harder to start a PhD and then switch to a master’s because the term used to describe this move is a “down-grade.” Although, if completing a master’s gets you to a place you’d like to be, it is not a “down-grade” but a smart move!
In mainland Europe and some North American universities, a master’s degree is required before moving on to a PhD. The time involved in doing two degrees may seem daunting, but remember that you will be more qualified in the end. In other countries a year-long honours degree is open to only the top students and represents a “mini-master’s” that provides direct entry into a PhD.

WHAT DOES AN APPLICATION REQUIRE?

Application guidelines vary between universities and countries and so it is important to check them carefully. Pay particular attention to whether you should submit the application to the university or the department. If you are an international student, there may be extra requirements, such as financial statements indicating that your family has sufficient funds to support you. The following list is not exhaustive but includes some of the common application requirements.

1. Minimum Requirements
   - An undergraduate degree with appropriate grades
   - Some universities require two semesters of calculus, chemistry, physics, and a field camp.

2. Information about You and a Statement of Purpose
   - Provide a résumé or CV showing relevant qualifications.
   - Academic transcripts must be submitted for each university or college attended.
   - Write a letter or statement that indicates:
     - the type of research that you would like to pursue
     - the name(s) of potential supervisor(s)
     - your background information and research experience
     - why you have chosen this particular university and advisor
     - your academic and professional goals

3. Letters of Recommendation – Generally Two to Four
   - Letters from individuals who know you professionally (as a student and/or in the workplace). Note, the potential supervisor generally writes a separate letter.

4. Test Results
   Each university will have its own requirements for test results, and these may include:
   - Graduate Record Examinations (GRE) General Test scores (www.ets.org/gre) for many North American universities.
   - Results from the Test of English as a Foreign Language test (TOEFL, www.ets.org/toefl) for students who have not attended an institution with English-language classes. Some universities require recent TOEFL scores, e.g. within the last 2 years.

5. Non-refundable Application Fee
   Each university has its own application fees.

FINANCIAL SUPPORT

It is important to make sure that you will be adequately supported throughout your degree. Make sure that you know the answers to the following questions:

<table>
<thead>
<tr>
<th>Income</th>
<th>Expenses</th>
<th>Research costs</th>
<th>International students</th>
</tr>
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<tbody>
<tr>
<td>How much funding is supplied?</td>
<td>What is the cost of living?</td>
<td>Will you receive a computer or need to buy one yourself?</td>
<td>Is your visa covered?</td>
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<td>Is funding based on working as a teaching assistant?</td>
<td>How much does tuition cost and does it differ for residents versus non-residents?</td>
<td>How is access to field and laboratory facilities arranged and paid for?</td>
<td>Are travel expenses covered? Plane flight?</td>
</tr>
<tr>
<td>Are research assistantships available?</td>
<td>Is funding available in the summer or only during the academic year?</td>
<td>How will you be supported for travel to scientific meetings?</td>
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<tr>
<td>Are any scholarships provided? If so, do they continue for your entire degree or just a set time?</td>
<td>Are there university service fees in addition to tuition?</td>
<td>Are you expected to pay for binding your thesis?</td>
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<tr>
<td>Are there limits on whether you can work outside the university?</td>
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</table>

FINAL WORDS

You will likely receive a lot of advice, and often it will be conflicting. What is most important is that you do something that you really like; the rest will fall into place. What is best for you may well be different from what is best for other people. Finally, don’t give up! There are many opportunities out there; so if your first preference falls through, just keep trying. Good luck!

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History is replete with entertaining anecdotes of meteorites found and lost on Earth. That chronicle has recently been expanded to include the exotic saga of meteorite search, discovery, and assessment on another planet using roving spacecraft. The inventory of confirmed and candidate meteorites on Mars currently stands at a minimum of 21 finds from three widely separated rover landing sites (Table 1). Using a combination of remote sensing and direct-measurement instruments on Opportunity and Spirit (Mars Exploration Rovers, MERs), and most recently on Curiosity (Mars Science Laboratory, MSL), a morphologic and chemical database has been compiled for this suite of rocks. Finding nonindigenous materials on Mars forces us to rethink meteoritical definitions and language (for example, to avoid confusion about whether the term Martian meteorites refers to meteorites found on Mars or to the SNC meteorite association). Here we will refer to these rocks as Martian finds.

THEORY
Martian finds provide new ways to address a variety of science topics (e.g. Chappelow and Sharpton 2006; Yen et al. 2006; Chappelow and Golombek 2010; Ashley et al. 2011a). For example, the reactive metallic iron in most meteorites provides clues to aqueous alteration that indigenous rocks do not. This is significant for the purpose of assessing weathering processes near the Martian equator (where the Mars rovers are conveniently located). On Earth, weathering is a serious nuisance to the study of a meteorite's preterrestrial history (e.g. Velbel 2014). On Mars the effects of mineral-water interactions permit the probing of aqueous geologic scenarios and related paleoclimate/habitability questions. Moreover the occurrence of meteorite falls throughout Mars' history means that some falls (if their residence times can be determined) may assist understanding of subtle reactions related to the low water–rock ratios of more recent (Amazonian age) climate situations—a valuable tool for Mars science (e.g. Kraft et al. 2014). A reference library of thermal emission spectra for fresh and weathered meteorites was prepared to assist with the detection and evaluation of weathering effects using the miniature thermal emission spectrometers (Mini-TES) on the MER rovers (Ashley and Wright 2004). The approach was based on the weathering behavior of ordinary chondrites in Antarctica, a Mars-analog environment. Current understanding of meteorite delivery mechanisms and inner Solar System dynamical models predicts that meteorite-type proportions on Mars would approximate those found on Earth, where some 94 percent are stony (chondrite and achondrite) varieties.

OBSERVATIONS
As with most discoveries in the planetary sciences, some observations confirm theory while others raise baffling questions. For example, to date not a single chondritic meteorite has been identified on Mars, and the suite is dominated instead by large (30–200 cm) iron–nickel meteorites (see Table 1). A selection bias probably results from the nature of meteorite survival, preservation, and the built-in mission requirements that tend to overlook small rocks, but identifying this lost population would solve an important mystery (Ashley et al. 2015). The Mini-TES was indeed useful for identifying the first meteorites found on another planet, but not in the manner anticipated. Steve Ruff, of Arizona State University’s Mars Space Flight Facility, recognized that the spectrum measured for Heat Shield Rock at Meridiani Planum was similar to the spectrum of the Martian sky. Only a metallic object has the reflectivity to produce these spectra, and so a meteorite was suspected and later confirmed (Schröder et al. 2008). Zhong Shan and Allan Hills, located in Gusev Crater on the opposite side of the planet, were identified in a similar way. Subsequent iron discoveries were identified based on morphology, mineralogy, texture, luster, and chemistry. Other anomalies are found among the stony-iron candidates. They are brecciated and contain varying amounts of kamacite (an Fe–Ni alloy) and troilite (FeS), but they do not resemble known meteorite varieties (Schröder et al. 2010). They may represent either a type of meteorite not found in Earth-based collections or some species of impact breccia that preserves materials from the impacting bolide. If meteoritic, the rocks are probably members of a single-fall strewn field. Further studies are underway. The tendency for most iron to be found in groups is also almost certainly an indication of specimens being members of common falls (“pairing” in meteoritics vernacular).

Overall, the observed effects of weathering in Martian finds are complex and are likely combinations of relic/fossil components and products of contemporary processes. Our knowledge of each rock depends on how complete rover reconnaissance has been on a case-by-case basis, which is largely a function of mission priorities at each time of discovery. Unknown residence times for the meteorites complicate the difficulty of sorting out their Martian histories. The irons tend to present rounded and pitted morphologies with enlarged hollows and sculpted surfaces that are likely the result of eolian abrasion (Fig. 1). However the intensities of these features vary among specimens and even within the same specimen, from virtually unmodified to cavernously excavated. This is consistent with some terrestrial examples, where similar morphologies led Buchwald to

| Table 1 LIST OF METEORITE CANDIDATES FOUND ON MARS. The Opportunity discoveries were on Meridiani Planum while the Spirit and Curiosity finds were in Gusev and Gale craters, respectively. |
|---|---|---|---|---|
| Meteorite | Rover | First sol encountered | Type (suspected or confirmed) | Instrumentation employed |
| Barberton | Opportunity | 121 | stony-iron | PancamNavcam |
| Heat Shield Rock* | Opportunity | 339 | IAB complex iron | MTES/Pancam/APXS/MB/MI |
| Allan Hills | Spirit | 858 | iron | MTES/Pancam/Navcam |
| Zhong Shan | Spirit | 858 | iron | MTES/Pancam/Navcam |
| Santa Catarina | Opportunity | 1034 | stony-iron | MTES/Pancam/APXS/MB/MI |
| Joacaba | Opportunity | 1046 | stony-iron | MTES/Navcam |
| Mafra | Opportunity | 1151 | stony-iron | MTES/Navcam |
| Paloma | Opportunity | 1190 | stony-iron | MTES/Navcam |
| Santorini | Opportunity | 1713 | stony-iron | Pancam/APXS/MB/MI |
| Kasar | Opportunity | 1889 | stony-iron | Pancam/APXS/MB/MI |
| Block Island | Opportunity | 1961 | IAB complex iron | Pancam/APXS/MB/MI |
| Shelter Island | Opportunity | 2022 | IAB complex iron | Pancam/APXS/MB/MI |
| Mackinac Island | Opportunity | 2034 | iron | PancamNavcam |
| Oilean Ruaidh | Opportunity | 2368 | iron | PancamNavcam |
| Ireland | Opportunity | 2374 | iron | PancamNavcam |
| Bingag Cave | Opportunity | 2642 | iron | PancamNavcam |
| Dia Island | Opportunity | 2642 | iron | PancamNavcam |
| Canegress | Opportunity | 3346 | unknown | PancamNavcam |
| Lebanon | Curiosity | 634 | iron | Mastcam/ChemCam RMI |
| Lebanon B | Curiosity | 634 | iron | Mastcam/ChemCam RMI |
| Littleton | Curiosity | 634 | iron | Mastcam/ChemCam RMI |

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* Official name: Meridiani Planum (Connolly et al. 2006)
speculate on the role of sulfuric acid produced when troilite nodules are exposed to water on Earth (Buchwald 1975); indeed, this mechanism is the preferred explanation for many (but not all) of the hollows observed on the Martian examples. Thus, separating eolian scouring effects from the effects of acidic corrosion is not always straightforward.

Comparing finds among sites can be a qualitative but thought-provoking pastime. Four of the Meridiani irons exhibit Widmanstätten patterns and iron oxide/oxyhydroxide coatings, while six show signs of cavernous weathering (see Schröder et al. 2008; Johnson et al. 2010; Ashley et al. 2011b; Fleischer et al. 2011). None of these features are obvious in the images of Gale Crater irons, where meteorite surfaces appear more polished (FIG. 1). Many reasons are possible for this, of course, including differences in residence time and incomplete reconnaissance by the rovers, as well as actual differences in site-specific weathering processes. Other features are unique to individual samples. Lebanon (see TABLE 1 for the locations of the meteorites) shows deep incision, presumably along internal weaknesses. Shelter Island shows large-scale differential mass removal, and Mackinac Island appears to have been hollowed to its core. The upper surface of Block Island presents a gaping pit decorated along its rim with delicate and highly angular protrusions (FIG. 2). Clearly a large mass of unknown mineralogy has been removed from its metal groundmass.

A beautiful sequence of events is recorded on Block Island, Shelter Island, and Oileán Ruaidh. The presence of acid-etched (or more likely sandblasted) Widmanstätten patterns (FIG. 2d) confirms postfall surface modification. The presence of iron oxide/oxyhydroxide coatings in crosscutting relationships with these features (FIG. 2d) shows that they too occurred after fall. They must therefore be a weathering product rather than fusion crusts produced during atmospheric flight. Finally, clear indications of rust destruction in the current epoch show that simple exposure to the small amount of oxygen in the Martian atmosphere is insufficient to produce the coating and that water (probably ice) was therefore involved. Moreover, it means that this exposure was recent, because otherwise the relatively soft coatings would have been removed by wind abrasion. Thus, we have recent rust formation by water at the Martian equator alternating with periods of eolian scouring (see Ashley et al. 2011b for further details). The most off-the-shelf explanation is one involving obliquity cycling where water ice is brought to equatorial latitudes every few hundred thousand years. An alternate hypothesis involves ripple migration (now dormant; Golombek et al. 2010) over the meteorites on comparable timescales, where frost forms on meteorite surfaces while buried (e.g. Yen et al. 2005). Future studies will seek to differentiate between these competing theories.

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My love affair with Mars started in the late 1960s when I was appointed a member of the Mariner 9 and Viking Orbiter imaging teams. The global surveys of these two missions revealed a geological wonderland in which many of the geological processes that operate here on Earth operate also on Mars, but on a grander scale. I was subsequently involved in almost every Mars mission, both US and non-US, through the early 2000s, and wrote several books on Mars, most recently The Surface of Mars (Carr 2006). I also participated extensively in NASA’s long-range strategic planning for Mars exploration, including assessment of the merits of various techniques, such as penetrators, balloons, airplanes, and rovers. I am, therefore, following the results from Curiosity with considerable interest.

The six papers in this issue outline some of the findings of the Mars rover Curiosity, which has spent the last two years on the Martian surface looking for evidence of past habitable conditions. It is not the first rover to explore Mars, but it is by far the most capable (Fig. 1). Included on the vehicle are a number of cameras, an alpha particle X-ray spectrometer (APXS) for contact elemental composition, a spectrometer (ChemCam/LIBS) for remote elemental composition, an X-ray diffractometer (CheMin) for mineralogy, and a mass spectrometer and gas chromatograph–laser spectrometer (SAM) for volatile and isotopic analysis. Although the rover has only recently reached its prime target (Mt. Sharp), it has already confirmed the former presence of habitable environments. Major questions remain, however, such as: How sustained were the habitable conditions? How widespread? When did they occur? Were they the result of just transient and local events or the result of global climate changes? And above all, did life ever exist on the planet?

Speculation that some form of life evolved on Mars has a long history dating back to the earliest telescopic observations. With the advent of the space age these speculations could be placed on a firmer footing. In the mid-1960s two Mars missions were approved. The Viking mission (1975 launch) placed two landers on the surface to analyze for organics and try to detect metabolism. Mariner 9 (1971 launch) prepared the way by searching for evidence of water or seasonal changes that might be life-related and by providing topographic and other data to support the Viking landings. While Mariner 9 found abundant evidence for past water activity, thereby raising hopes that there might be life, those hopes were dashed when the Viking landers found no organics in local soils and no evidence for metabolism (Klein 1979). Partly as a consequence of the negative Viking results, there followed an almost 20-year hiatus in Mars exploration.

A number of developments occurred that helped rekindle Mars exploration in the 1990s (NASA 1995). Life on Earth had been found surviving in much more extreme conditions than were thought possible in the 1970s. Evidence mounted that the search for life should focus less on detecting extant life and more on looking for evidence of life on early Mars where indications of water activity were most abundant. Miniaturization of instruments enabled more sophisticated payloads on modest-sized landed vehicles. Advances in guidance enabled landing at more interesting and promising places, and advances in robotics led to vehicles with more independent capabilities.

The geological exploration of Mars has proceeded in a very different way from that of the Earth. On Earth, numerous local ground observations were gradually integrated, sometimes over many years, into regional and global patterns. In contrast, on Mars, global patterns were identified first, and the details were subsequently filled in from higher-resolution remote sensing and then by ground observations. Since the year 2000, a number of missions have successfully landed on or orbited Mars, and, although large uncertainties remain, these missions have revealed the broad outlines of the geological history of Mars. The history can be divided into three eras (Scott and Carr 1978; Hartmann and Neukum 2001; Bibring et al. 2006): (1) the Noachian Era of heavy bombardment, which extended from the time of formation of the planet to roughly 3.7 billion years ago and was characterized, at least toward its end, by high impact rates, widespread fluvial erosion, and the presence of phyllosilicates; (2) the Hesperian Era, which extended from 3.7 to 3.0 billion years ago and was characterized by large floods and the formation of thick sulfate deposits; and (3) the Amazonian Era, which extended from 3.0 billion years ago to the present and is characterized by an oxidizing surface, with only rare indications of water activity.

The revitalized US Mars program of the late 1990s was initially guided by the invocation to “follow the water,” water being universally agreed as necessary for life. The orbiter and lander instruments were selected to help better understand the history of water; the landers were sent to places where the orbital data indicated past or present water activity. These developments led to the landing of the first rover on Mars in 1997, a tethered shoebox-sized rover called Sojourner that carried cameras and an APXS for elemental analysis. This was followed in 2004 by the rovers Spirit and Opportunity: Spirit to a large Noachian crater, Gusev, in which water was thought to have pooled; and Opportunity to Meridiani Planum, where remote sensing had revealed mineralogical indications of water activity. Both rovers found abundant evidence of water. Although there was little evidence for pooling of water on the plains within Gusev, its central peak revealed compelling evidence of aqueous alteration and hydrothermal activity (Squyres et al. 2006). In addition, the sediments on which Opportunity landed in Meridiani Planum appear to have been deposited in an area of dunes with intermittent, acidic, interdune lakes (Grotzinger et al. 2005). The success
of the various landers and orbiters in the early 2000s in finding abundant evidence for water led to a redirection of the exploration goal to not just follow the water but to determine where and when habitable conditions occurred.

These earlier rovers, while highly successful explorers, had limited analytical capabilities. In contrast, Curiosity has a broad complement of analytical instruments capable of measuring elemental composition, mineralogy, isotopes, volatiles, and organics. It was well equipped to search for evidence of former habitable conditions. The 155 km diameter Gale Crater was chosen as the landing site because remote sensing indicated that its central mound, Mt. Sharp, was comprised of a stratigraphic column that extends from late Noachian phyllosilicate- and hematite-bearing sediments upwards into sulfate-rich Hesperian deposits. Thus, a range of environments could be sampled, with the base of the column being of most interest because of the clear evidence of the presence of aqueous alteration products that dated back to the time for which we have the best evidence of conditions different from the present. The spacecraft landed on the level crater floor, as close to the central mound as the landing error ellipse (20 km × 7 km) allowed, and has since been making its way towards the central mound, pausing occasionally to make measurements on the materials of the crater floor. The results presented in this issue were acquired mainly during this traverse since, at the time of this writing, Curiosity had only recently arrived at the base of the central mound.

The plains on which Curiosity landed are comprised mostly of fine-grained sedimentary rocks with isolated outcrops of cemented pebbly conglomerates. To the north of the landing site is an alluvial fan fed by a channel that cuts through the northern rim of the crater. The conglomerates were probably deposited in channels cut into distal parts of this and other fans. The main rocks over which Curiosity travelled toward the central mound are, however, thinly bedded sandstones and mudstones. Drilling into the mudstones exposed materials in a reduced state, in contrast to the universally oxidized surface. This is an important finding in the search for life, for it may imply long-term preservation of organics within the rock materials. The mudstones are comprised of a nonequilibrium assemblage of primary basaltic phases, secondary phases such as clays, sulfates, and iron oxides, and an amorphous component. Chemical trends suggest that the secondary minerals are the result of isochemochemical alteration of the primary basaltic debris at their depositional site by groundwater or lake water rather than the result of weathering elsewhere and transport of chemically fractionated components to the landing site. The diagenesis appears to have taken place in a habitable environment with moderate pH and low salinity that persisted for thousands to millions of years. The finding of diagenetic minerals, particularly the phyllosilicates, in the floor sediments was a surprise. Their presence had been masked by dust at the surface. But it led to early confirmation of habitable conditions well before the main target, the clay-rich deposits at the base of Mt. Sharp, was reached. The neutral pH contrasts with the acidic pH under which the sulfate-rich deposits at the Opportunity site in Meridiani accumulated. But it led to early confirmation of habitable conditions well before the main target, the clay-rich deposits at the base of Mt. Sharp, was reached.

Understanding the evolution of the atmosphere is crucial for assessing past habitable conditions and the conditions under which the valleys formed. The isotopic ratios of volatiles in the atmosphere evolve as lighter isotopes are preferentially lost to space and inventories are partly replenished by outgassing and the solar wind. SAM has the capability of measuring isotopic ratios both in the atmosphere and in rock samples. The deuterium/hydrogen ratio is of particular importance. The fact that the present atmosphere is highly enriched in deuterium (heavy hydrogen) has been used to constrain the total amount of water on the planet to very small values on the assumption that the enrichment is due to losses over the last few billion years. Early results from SAM showed, however, that the water fixed in the >3-billion-year-old sediments was already considerably enriched, so this loosens significantly the constraint on the exchangeable water reservoir. Analyses of isotopes of other gases will provide further insights. SAM also detected the components necessary for life (C, H, N, S, P, etc.) and chlorinated hydrocarbons in samples of the sediments. The implications of the hydrocarbons are still being debated.

In summary, Curiosity has travelled approximately 7 km from its landing site to its prime target at the base of Mt. Sharp. The rocks traversed were mostly fluvial and lacustrine mudstones and sandstones that subsequently underwent aqueous alteration under neutral pH conditions. Elemental and isotopic analyses of gases evolved from the sediments indicate the presence of components necessary for life and will provide new insights into how surface conditions have evolved over time. The seemingly reduced conditions preserved at shallow depths within the rocks sampled enhance the possibility that organics are preserved and accessible in near-surface rocks. All these results are encouraging in the search for life and will provide important guidance for the next step in the exploration of Mars, which we hope is sample return.

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It is difficult to imagine any greater goal for science than searching for life beyond Earth. Everything we know about life is based on a sample of one: life on Earth. We can only imagine the consequences of discovering life elsewhere, provided it had a separate origin. That, ultimately, is why we are exploring Mars. However, in the process, we are learning about the origin and evolution of the Solar System.

Mars preserves a very ancient history that has largely been destroyed on Earth by tectonic recycling processes.

The Mars Science Laboratory (MSL) rover, Curiosity, is one of the latest in a long series of missions to Mars that started in 1960 with launches by the former Soviet Union and later the USA. The first successful mission was NASA’s Mariner 4, which was launched on 28 November 1964, half a century ago. More recently, the European Space Agency launched very successful missions, followed by an Indian Space Agency mission, and the Japanese have also joined the quest. There have been more than 40 attempted missions, of which about half were successful at least to some extent. MSL is perhaps the most amazing mission of all. Who can forget the “seven minutes of terror” that constituted the landing sequence?

NASA’s two Viking missions in the 1970s were the first, and still the only (apart from the failed Beagle2), missions with the explicit goal of searching for life on Mars. For some the results were equivocal, but most consider that no evidence for life was found. Maybe that was because the landing sites were frigid deserts, or maybe the instruments were not sensitive enough, but in any event the consensus is that there were no positive detections.

As recently as the 1950s, it was thought by serious scientists that there could be advanced forms of life on Mars – not little green people but ferns and other vegetation. That was because seasonally changing patterns of colour had been observed from Earth-based telescopes. We now know that these result from seasonal dust storms. And, of course, modern imagery has revealed that there are no canals, pyramids, or faces. So now the search for life on Mars focuses on microbes (Walter 1999).

From these numerous missions we have learned that early in its history Mars was warm and wet, like the Earth at the same time, more than three billion years ago. We have a record of life on Earth at that time, and it was microbial. If life arose here, why not there?

Thus the question is, with a whole planet to explore, how can we possibly expect to find anything microscopic? This seems like the ultimate needle in a haystack problem. Well, we can find the needles, for many reasons. Studies of Earth’s biology, geology, and palaeontology over more than a century have taught us a lot. We know how to define prebiotic conditions that might have existed early in Earth’s history. We know how to search for conditions, perhaps without oxygenic photosynthesisers but still with some organisms that reacted to light (this seems to be an important component of stromatolite-building communities)

The Pilbara region is also in Western Australia. Here we find some of the oldest well-preserved rocks in the world; they are up to 3.5 billion years old (Van Kranendonk et al. 2007). Such rocks are extremely rare because of subsequent tectonic reworking. The only other comparable area known is in the Barberton Mountainland of northeastern South Africa.

The Pilbara preserves the oldest convincing evidence of life on Earth (FIG. 3). That does not mean it is the oldest life, just that it is the oldest preserved in the rock record (e.g. Allwood et al. 2006; Van Kranendonk et al. 2008). Older rocks in Greenland are considered to preserve evidence of life, but in my opinion it is not convincing. In the context of...
searching for past life on Mars, the Pilbara is particularly significant. The fossils are within the age range when Mars was warm and wet, and they are our best model for what may have lived on Mars.

There are many other areas that are informative as Earth analogues. One of the most signifi cant is Yellowstone National Park in Wyoming, USA. It was there that research fi rst revealed the high temperature tolerance of some microbes (FIG. 4). Scientifi c work there goes back to the 19th century (Weed 1889), and modern work on the microbiology of the hot springs was pioneered by Dick Castenholz and Tom Brock (e.g. Brock 1978). Any credible exploration model for life elsewhere must factor in the environmental limits of life on Earth, something we have yet to fully deifi ne. The research in Yellowstone has perhaps been eclipsed by that on the “black and white smoker” hot springs on our ocean floors, but it remains critical for our understanding of “extremophiles.” Such environments must have existed on Mars (Walter and Des Marais 1993): the combination of volcanism and water make that inevitable, and some candidate sites have been identifi ed (e.g. Brown et al. 2010).

MSL has confi rmed that early in its history, Mars was warm and wet, with evidence for the former presence of lakes, rivers, and deltas. The layered structure of Mt. Sharp provides an excellent opportunity to read part of the history of Mars as the rover climbs the slopes – up in geological time – just as would a geologist on Earth. MSL is not designed to search for life, but it will continue to provide a wealth of new data on the past habitability of Mars.

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Benton C. Clark III trained as a biophysicist and is deeply involved in planetary geochemistry investigations. He developed the first inorganic analyzer for Mars, which was hosted on the two Viking lander missions in 1976. He participated on science teams for the Phoenix polar lander and the three Mars rover missions. One of his specialties is the analysis of element composition to constrain the mineralogy of samples and their alteration history. He has also participated in the NASA robotic sample-return missions: Stardust samples from comet Wild 2, Genesis samples from the Sun (solar wind), and the upcoming OSIRIS-REx samples from the carbonaceous asteroid Bennu.

Pamela G. Conrad is an astrobiologist and planetary scientist in the planetary environments laboratory at NASA Goddard Space Flight Center. She received a PhD from the George Washington University, and was a predoctoral research fellow at the Geophysical Laboratory of the Carnegie Institution of Science. Her research focus is on planetary habitability and the development of approaches for its measurement on Earth and other planets, especially Mars. She is the deputy principal investigator for the Sample Analysis at Mars (SAM) suite that is on board the rover Curiosity.

Joy A. Crisp is a planetary geologist at the Jet Propulsion Laboratory. She received an undergraduate degree from Carleton College and a PhD from Princeton University. Her scientific expertise is in the mineralogy and formation of volcanic rocks on Earth and Mars. For the Mars Pathfinder Project, she was the Assistant Rover Scientist and the Alpha Proton X-ray Spectrometer Investigation Scientist. For the Spirit and Opportunity rover missions, she was the project scientist for six years. She is currently a deputy project scientist for the Mars Science Laboratory mission.

Robert T. Downs is a professor of mineralogy and crystallography at the University of Arizona. He received a BS from the University of British Columbia, followed by a PhD at Virginia Tech and a postdoc at the Carnegie Institution’s Geophysical Laboratory. Along with being a Chemin instrument co-investigator on the MSL mission, Downs is a builder of mineralogical databases, including RRUFF—the American Mineralogist Crystal Structure Database—the NASA Planetary Materials Database, and the Mineral Evolution projects. His research interests include high-pressure and high-temperature crystallography and the analysis of bonding in minerals.

Ralf Gellert is an associate professor in the Department of Physics at the University of Guelph. An experimental physicist by training, his interests lie in developing and building instruments for space exploration using nuclear physics methods. He has been the lead engineer for the APXS instruments on MER and Rosetta and the software engineer for the Mössbauer spectrometers on MER. Gellert performed the calibration for the APXS instruments and developed the analysis method and programs. He is the principal investigator for the MSL and MER APXS instruments.

John P. Grotzinger is the Fletcher Jones Professor of Geology at the California Institute of Technology. He received a BSc from Hobart College, an MSc from the University of Montana, a PhD from Virginia Tech, and was a postdoctoral fellow at Lamont-Doherty. He is interested in the evolution of surficial environments on Earth and Mars. Field-mapping studies are his starting point for more topical laboratory-based studies involving geochemical, geological, and geochronological techniques. He is the past project scientist for the Mars Science Laboratory mission and is member of the Mars Exploration Rover Science Team and the HiRISE team on Mars Reconnaissance Orbiter.

Linda C. Kah is a professor at the University of Tennessee. She holds degrees in geology from the Massachusetts Institute of Technology and Harvard University. Linda and her students focus on integrating sedimentology, stratigraphy, geochemistry, and paleobiology in understanding the evolution of the Earth’s biosphere. Her research spans geologic time from the Proterozoic to the Holocene, and her field areas include arctic Canada, Mauritania, and the high Andes of Argentina. In addition to conducting Earth-based research projects, she is also investigating potential habitable environments on Mars as a co-investigator on the MSL mission.

Paul R. Mahaffy is a planetary scientist based at NASA’s Goddard Space Flight Center. He participates in the study of planetary atmospheres and surface environments and in the development of space-qualified instrumentation. His main research interests are the chemical and isotopic composition of planetary atmospheres and surfaces, advanced instrument development for organic and light isotope analysis in planetary targets, and analog studies for Martian environments. He is the principal investigator for the Sample Analysis at Mars instrument suite on the Curiosity rover currently operating on the surface of Mars, and he serves as the lab chief of Goddard’s Planetary Environments Laboratory.

Sylvestre Maurice is a planetary physicist and an instrument scientist at the Institut de recherche en Astrophysique et Planétologie in Toulouse, France. He has worked on orbital missions around Saturn, Jupiter, the Moon, Mercury, and Mars. For the inner planets, he has focused on the search for and discovery of water at remote distances. With Roger Wiens, he codirected the development of the ChemCam instrument on Curiosity, and they are now leading the development of SuperCam for NASA’s Mars 2020 rover. He also is codirecting the development of the Raman instrument for ESA’s ExoMars mission.

Ashwin R. Vasavada is a planetary scientist at the Jet Propulsion Laboratory, and the deputy project scientist for NASA’s Curiosity rover. His research interests include the climate history of Mars, the weather on Jupiter and Saturn, and the possibility of ice at the poles of the Moon and Mercury. He has participated in the operation and analysis of data from NASA spacecraft missions, including the Galileo mission to Jupiter, the Cassini mission to Saturn, and the Lunar Reconnaissance Orbiter.

Roger C. Wiens is a senior researcher at Los Alamos National Laboratory, USA. He has pursued planetary science ever since writing the first PhD dissertation on the Martian atmosphere as analyzed in a terrestrial laboratory (via an SNC meteorite). He played a leading role in the first mission to return samples from beyond the Moon—the Genesis mission—a breakthrough that yielded isotopic compositions of heavy elements in the Sun. He has led ChemCam development and exploration with the Curiosity rover. In 2014, he was selected, with Sylvestre Maurice, to develop a more advanced version—SuperCam—for NASA’s Mars 2020 rover.
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Landed missions to the surface of Mars have long sought to determine the material properties of rocks and soils encountered during the course of surface exploration. Increasingly, emphasis is placed on the study of materials formed or altered in the presence of liquid water. Placed in the context of their geological environment, these materials are then used to help evaluate ancient habitability. The Mars Science Laboratory mission—with its Curiosity rover—seeks to establish the availability of elements that may have fueled microbial metabolism, including carbon, hydrogen, sulfur, nitrogen, phosphorus, and a host of others at the trace element level. These measurements are most valuable when placed in a geological framework of ancient environments as interpreted from mapping, combined with an understanding of the petrogenesis of the igneous rocks and derived sedimentary materials. In turn, the analysis of solid materials and the reconstruction of ancient environments provide the basis to assess past habitability.

**KEYWORDS:** Mars, Gale Crater, water, geochemistry, mineralogy, habitability

“And there lay, floating in the ocean, several miles off, an immense, irregular mass, its top and points covered with snow…”

*Two Years Before the Mast*  
Richard Henry Dana

**CURiosity ROVER, SCIENCE INSTRUMENTS, AND MISSION OBJECTIVES**

The Curiosity rover was designed and built to explore the surface materials of Mars and characterize its modern environment. Its overriding objective has been to search for ancient habitable environments. Such environments are recognizable through the characterization of the composition and mineralogy of rocks resulting from past rock–water–atmosphere interactions that might have been exploited by primitive microorganisms, if life had in fact evolved on Mars (Grotzinger 2009; Grotzinger et al. 2012; Grotzinger et al. 2014). Curiosity landed at Gale Crater on August 6, 2012. In the first year of operation, Curiosity discovered an ancient habitable environment consisting of a system of streams, a lake, and a groundwater network. In this environment, sediments composed of primary igneous minerals derived from rocks of basaltic composition were diagenetically altered to hydrated clay minerals, iron oxides, and minor chlorides. Diagenesis occurred at moderate pH, at low salinity, and under reducing conditions; crosscutting, late-diagenetic fractures were filled with hydrous and anhydrous calcium sulfate minerals (Grotzinger et al. 2014; Ming et al. 2014; Vaniman et al. 2014). During its nominal one-Mars-year mission (23 Earth months), Curiosity drilled or scooped five samples, made over twenty mineralogical and isotopic measurements and hundreds to thousands of compositional measurements, took hundreds of thousands of images that provided geological context for samples, and acquired millions of observations of the modern environment. Curiosity is the most advanced mobile geochemistry laboratory to have ever roved another planet, and it has been very productive.

Curiosity’s science payload (Fig. 1) includes a gas chromatograph–mass spectrometer and tunable laser spectrometer (SAM) that can measure isotopic compositions, volatile abundances, and organic carbon content in soils, rocks, and the atmosphere; an X-ray diffractometer (CheMin) that determines the mineralogical diversity of rocks and soils; an alpha particle X-ray spectrometer (APXS) for the in situ determination of rock and soil compositions; a laser-induced breakdown spectrometer (LIBS) to remotely sense the composition of rocks and minerals with high-resolution point imaging (ChemCam); cameras (MAHLI, MARDI, Mastcam) that can image landscapes and rock/soil textures in natural color; an active neutron spectrometer (DAN) designed to search for water in rocks/soil; a weather station (REMS) to measure modern-day environmental variables; and a sensor (RAD) designed for continuous monitoring of background solar and cosmic radiation. The various payload instruments work together to establish the geological and paleoenvironmental framework for the mineralogical and geochemical measurements. Potential targets for eventual drilling (or scooping) and sample delivery to the onboard analytical instruments (SAM, CheMin) are first studied with remote sensing instruments (Mastcam, ChemCam) and then by direct-contact
measurements (MAHLI, APXS). The atmosphere and environment around the rover are also studied to provide further context (RAD, REMS, DAN). The analytical instruments obtain samples via a sample acquisition, processing, and handling subsystem that acquires soil samples by scooping and rock samples by drilling. Details about instrument and sampling-system design and function and about mission planning can be found in Grotzinger et al. (2012).

**GALE CRATER EXPLORATION SITE**

The 154 km diameter Gale Crater (Fig. 2) was chosen as Curiosity’s field site based on several attributes: (1) the crater contains an interior mountain of ancient flat-lying strata extending over 5 km above the elevation of the landing site; (2) the lower few hundred meters of the mountain show an age progression in which phyllosilicate-bearing and sulfate-bearing strata are separated by an unconformity from overlying, likely anhydrous strata; (3) the 20 x 7 km landing ellipse is characterized by a mixture of alluvial fan and high-thermal-inertia/high-albedo stratified deposits; and (4) the site contains a number of stratigraphically/geomorphologically distinct fluvial features (Grotzinger et al. 2012). Gale has a well-defined regional context and shows strong evidence for a succession of multiple ancient aqueous environments, one of which has been shown to have been habitable (Grotzinger et al. 2014) and to have preserved trace amounts of organic carbon (Freissinet et al. 2014). These environments are represented by a stratigraphic record of extraordinary extent exposed along the flank of Gale’s internal mountain, Aeolis Mons. This mountain is informally known as Mt. Sharp, after pioneering planetary geologist Robert Sharp. Mt. Sharp was judged to preserve a rich record of the environmental history of early Mars. In essence, by choosing to explore Gale Crater, the Mars Science Laboratory (MSL) team was employing a tried and true exploration strategy used by resource exploration companies on Earth: to select a target with not just one but multiple objectives, as a way of reducing the risk of failure. That strategy succeeded.

By most measures the Gale Crater exploration site has been richly rewarding. The locations of analyses performed by ChemCam, by APXS, and during drilling are shown on Figure 3. Within a few months of landing, a Mars soil sample (dubbed “Rocknest”) had been scooped and analyzed, providing a wealth of information on a “typical” material that has been observed in all previous missions; this material is now understood in terms of its complete mineral composition (including amorphous materials) and volatile content. Following that, Curiosity drove a short distance away from Mt. Sharp, based on a hunch that thinly stratified bedrock observed in orbiter and rover image data may provide samples of an ancient lacustrine...
environment—regarded as a top prospect for Martian habitability. Curiosity drilled two holes, separated by a few meters, in the same rock unit (called the Sheepbed mudstone), and samples were analyzed by the laboratory instruments (see Downs and MSL Science Team 2015 this issue; Mahaffy et al. 2015 this issue), by APXS (Gellert et al. 2015 this issue), and by ChemCam (Wiens et al. 2015 this issue). This hunch paid off with a nice surprise. Samples collected from the drill holes showed a significant reduction in the quantity of primary igneous minerals relative to the Rocknest soil sample. In the drill samples, primary igneous minerals were replaced by ~30% alteration minerals composed of Fe–Mg-smectite and magnetite, inferred to have formed within an ancient lake bed during early diagenesis (McLennan et al. 2014; Vaniman et al. 2014). Early diagenesis was also recorded by the development of concretions, hollow nodules that possibly record gas production, and cement-lined syneresis cracks (Grotzinger et al. 2014; Siebach et al. 2014; Stack et al. 2014). In addition, Curiosity found a crosscutting set of sulfate-filled veins, formed during a period of post-lithification, late-stage diagenesis (Grotzinger et al. 2014; Gellert et al. 2015). All observations point to a former lake/groundwater composition that was characterized by moderate pH and low salinity, was chemically reducing, and persisted long enough (thousands to millions of years) to have prevented detection from orbit of the significant amounts of hydrated clay minerals that might otherwise have been observed using orbiter-based visible to near-infrared spectroscopic approaches. As in the exploration for mineral resources on Earth, this experience underscores the value of acquiring multiple, remotely sensed data sets for map generation and hypothesis formulation in the quest for ancient habitable environments on Mars.

Within a year of landing, Curiosity’s most important scientific objective had been fulfilled at Yellowknife Bay, located less than 500 meters from where she landed. This important discovery—of early Martian habitability—had been predicted based on geological maps created through the integration of orbiter observations, including thermal inertia, texture, topography, and color. Interestingly, a continuous veneer of dust across these outcrops is presumed to have prevented detection from orbit of the significant amounts of hydrated clay minerals that might otherwise have been observed using orbiter-based visible to near-infrared spectroscopic approaches. As in the exploration for mineral resources on Earth, this experience underscores the value of acquiring multiple, remotely sensed data sets for map generation and hypothesis formulation in the quest for ancient habitable environments on Mars.

After leaving Yellowknife Bay in July 2013, Curiosity drove purposefully towards the original mission objective—the foothills of Mt. Sharp (Fig. 3). Curiosity drove across the boundary defining the mission’s landing ellipse on June 27, 2014 (sol 672) and arrived at the Pahrump Hills in September 2014. This drive of roughly 8.5 km took just over one year, allowing for several stops along the way for science campaigns aimed at understanding the composition and geological context of key rock units. These waypoints (called Darwin, Cooperstown, and Kimberley) were important in that they allowed the science team to test hypotheses about the origin(s) of the Aeolis Palus (Gale Crater plains) rocks and their relationship to rocks that form the lowermost strata of Mt. Sharp. At one stop, located within the Kimberley map quadrangle, Curiosity drilled another sample (Windjana) for analysis by CheMin and SAM. In addition to the work at these waypoints, Curiosity routinely analyzed whatever rocks and soils she stopped on with both APXS and ChemCam. This protocol assured that no major compositional changes or terrain boundaries were missed that might not correlate with rock properties reflected in rover and orbiter image data.

Thus, on September 17, 2014 (sol 753), Curiosity finally crossed the geologic boundary separating the rocks of Aeolis Palus, on which she landed, from those that define the base of Mt. Sharp (Fig. 3). Initial data suggest the geological boundary relates to differences in sedimentary facies, which in turn reflect differences in grain size and/or the extent of cementation.

**ROCK TYPES OF GALE CRATER PLAINS (AEOLIS PALUS)**

Gale Crater has an age of 3.6 to 3.8 billion years, and it is inferred that Mt. Sharp developed shortly after crater formation. The mountain was perhaps the result of crater filling, followed by erosion and the creation of a “moat.” This hypothesis is supported by initial observations from the Pahrump Hills, where the Murray formation is composed of a complex assemblage of fluvial, deltaic, lacustrine, and eolian deposits. In contrast, upper Mt. Sharp strata may have originated from directed wind patterns and sediment accretion, forming a mound in the middle. In either case, sedimentation and denudation were complete by 3.2–3.4 billion years ago (Newsom et al. 2014). Curiosity landed in the plains, or lowlands, between Gale Crater’s rim and Mt. Sharp.
Gale’s larger-scale stratigraphy, mineralogy, and landforms have been well studied (Milliken et al. 2010; Grotzinger et al. 2014; Newsom et al. 2014), and Gale’s relevance to MSL’s goals has been established (Grotzinger 2009; Grotzinger et al. 2012). To fulfill the primary mission objective, Curiosity is exploring the lower foothills of Mt. Sharp, where strata containing hematite, hydrated clays, and sulfate (Milliken et al. 2012) are accessible (Fig. 2). At the time of this writing, Curiosity is analyzing the first hematite-bearing outcrops on Mt. Sharp. Geological mapping (Fig. 3) reveals several units, including the Peace Valls alluvial fan (not shown in Fig. 3, but is north of the map area displayed); an immediately adjacent and downslope bedded, fractured unit; surfaces with higher crater densities; tonally smooth but hummocky plains; light-toned, topographically variable, or rugged terrain; and light-toned striated rocks. The Murray formation is composed of rocks on the south side of the Aeolis Palus / Mt. Sharp boundary; from orbit these rocks appear to be massive, with hints of stratification, and show spectroscopic evidence for hematite, sulfate, and hydrated clay minerals. At the Pahrump Hills, the Murray formation consists of finely laminated mudstones, with interstratified cross-bedded sandstones of basaltic composition. The rocks contain abundant hematite, providing a link to orbiter-based observations and predictions. Finally, minor units of eolian fill/bedforms and ejecta blankets adjacent to larger craters are present. These diverse units represent a range of bedrock lithologies and loose, poorly consolidated mantling materials. All units except for the “alluvial fan” have now been examined by Curiosity. Nevertheless, all of the bedrock examined by Curiosity consists of alluvial deposits, with minor lacustrine and rare eolian deposits. These bedrock deposits are either down-gradient time equivalents of the Peace Valls alluvial fan or older facies equivalents that have experienced a greater degree of diagenesis and lithification.

The hummocky plains are different in that they represent mostly a surface mantle of debris, with frequent windows through which sedimentary bedrock is observed. In the vicinity of the landing site, the hummocky plains are composed dominantly of loose materials, including clasts of rock interpreted to be impact ejecta, but these plains are dominated by erosional remnants of underlying bedrock of sedimentary origin. Analyzed clasts have basaltic compositions (occasionally alkaline), and some clasts have porphyritic textures. Windows through this material in the vicinity of Bradbury Landing, including the excavations produced by Curiosity’s descent rockets, expose conglomerate bedrock of fluvial origin (Williams et al. 2013; Kah and the MSL Science Team 2015 this issue).

**PETROLOGY**

As Curiosity drove across and sampled the terrain of Aeolis Palus, it became clear that all bedrock is sedimentary and dominantly of fluvial origin (Williams et al. 2013; Grotzinger et al. 2014). Igneous rocks may occur as impact ejecta, likely derived from outside the crater, but the clearest examples we have seen are present as rounded clasts within the sedimentary conglomerates. These clasts reveal porphyritic textures (see Kah and the MSL Science Team 2015, Fig. 6d), and the phenocrysts are very likely feldspars, based on ChemCam LIBS data (Sautter et al. 2014; Wiens et al. 2015). Given that sediment transport directions for these fluvial rocks are southward (Grotzinger et al. 2014), we infer that the source area for these igneous rocks is the northern rim of Gale Crater.

Other igneous rocks of basaltic composition may also be present, but their fine-grained textures make their origins ambiguous—they could be sedimentary as well. As the mission evolved, we learned that all the sedimentary rocks are of basaltic composition, and in some cases they are indistinguishable from definitive igneous rocks observed previously on Mars (Gellert et al. 2015). These sedimentary rocks have compositions very close to the average crustal composition of Mars, indicating that they experienced little chemical weathering in their source region (Fig. 4). This similarity implies that the disintegration of primary igneous rocks to form sedimentary materials may have occurred largely by physical processes, as interpreted for the sandstones and mudstones of the Yellowknife Bay formation (McLennan et al. 2014). However, despite the absence of major element mobility (Fig. 4), mineralogical data for these rocks suggest a model of alteration in which primary mafic minerals, especially olivine, were converted into secondary Fe–Mg-smectite clay minerals (Vaniman et al. 2014). This alteration can be observed in Figure 5 by comparing mineral-abundance data from the Rocknest soil with those from the John Klein and Cumberland drill holes in the Sheepbed mudstone. The combined mineralogical and chemical data indicate that the rocks were altered and their mineralogy changed, but this occurred during diagenesis of the water-saturated sediment rather than in the sediment source region during weathering. Such isochemical diagenesis was a significant discovery by Curiosity, and the discovery was surprising because most models predicted clay mineral formation on Mars during weathering or hydrothermal fluid circulation, but not during diagenesis in sedimentary basins. This process may be a significant factor elsewhere on Mars.

![Figure 4](image-url)
The Alkaline Igneous Province of Gale Crater’s Northern Rim

One remarkable attribute of Aeolis Palus stratigraphy is the abundance of rocks with high alkali content (Fig. 6). Beginning with the Jake_M rock, the first rock measured on the mission with APXS, rocks with an alkaline composition were derived is likely the northern igneous province from which these sedimentary rocks with crater’s northern rim. The igneous province probably originated in part, as a possible cementing material. ChemCam data point to high total FeO, which is not easily related to a primary igneous composition and therefore suggests the evolution of pore fluid composition. Currently, we are exploring several hypotheses for the origin of these cements. One possible cement is clay minerals, which are abundant in the Windjana sandstone (~8%; see Downs and the MSL Science Team 2015) and very abundant in the Sheepbed mudstone (~20%; see Vaniman et al. 2014). Magnetite is also sufficiently abundant to serve, at least in part, as a possible cementing material. ChemCam data point to high total FeO, which is not easily related to a primary igneous composition and therefore suggests the possibility of iron oxide cement (Blaney et al. 2014). These data are important given that the ChemCam laser works as a type of microprobe providing ~0.5–1 mm spot size for the elemental analysis of grains and cement. By analyzing

Cementation of Sedimentary Rocks

It was a surprise to discover an extensive deposit of well-lithified, siliciclastic sedimentary rocks within the rover’s landing region. Before landing, the occurrence of broad expanses of “cratered surfaces” suggested that at least some of these rocks were hard, like lava flows; the preservation of impact craters is favored by hard target rocks, often inferred to be of igneous origin. At this point in the mission, all bedrock has been shown to be sedimentary, and the unexpected hardness of the rocks results from pervasive cementation. This bedrock is composed entirely of detrital sedimentary rocks of fluvial, lacustrine, and possibly eolian origin (Williams et al. 2013; Grotzinger et al. 2014). The rocks drilled and sampled at Yellowknife Bay (John Klein, Cumberland) and Kimberley (Windjana) were also formed by these depositional processes. The composition of these rocks indicates basaltic precursors, though substantial variations in the alkali, iron, and magnesium contents also occur (Blaney et al. 2014; McLennan et al. 2014). This variation could be due to variations in the compositions of the primary grains in the precursor rocks, which in turn might dominantly reflect the composition of their mantle source; however, it might also reflect the composition of cementing materials, as these could comprise up to 20–30% of the rock by volume, assuming minimal compaction under the reduced gravity of Mars.

The diagenesis of these sedimentary rocks has turned out to be as interesting as their primary composition. Understanding the nature and history of cementation has become a major mission focus in an attempt to decipher the evolution of pore fluid composition. Currently, we are exploring several hypotheses for the origin of these cements. One possible cement is clay minerals, which are abundant in the Windjana sandstone (~8%; see Downs and the MSL Science Team 2015) and very abundant in the Sheepbed mudstone (~20%; see Vaniman et al. 2014). Magnetite is also sufficiently abundant to serve, at least in part, as a possible cementing material. ChemCam data point to high total FeO, which is not easily related to a primary igneous composition and therefore suggests the possibility of iron oxide cement (Blaney et al. 2014). These data are important given that the ChemCam laser works as a type of microprobe providing ~0.5–1 mm spot size for the elemental analysis of grains and cement. By analyzing

and the fine-grained sandstone at Kimberley (Windjana). Minerals in gray italics are at or near detection limits. Opx = orthopyroxene.
A combination of chemical (APXS, ChemCam) and mineralogical (CheMin) data indicates that the clay minerals and magnetite in the Sheepbed mudstone are authigenic, and possibly this interpretation also applies to the Windjana sandstone, though this is uncertain at present. Other, more exotic materials, such as akaganeite or perchorlate, are possibilities, although their abundances are so small—near or below the ~1% detection limit of CheMin—that they would likely fail to produce the volumetric abundances (10–30%) required for the cementation of sandstones, siltstones, and mudstones, even if significant compaction has occurred. All other factors being equal, compaction should be less on Mars than on Earth, given the much smaller force of gravity on Mars.

Amorphous Materials

One of Curiosity’s most important capabilities arises from its being equipped for X-ray diffraction analysis, the historical tool of choice for mineralogical investigation of terrestrial geological materials. The CheMin instrument (Blake et al. 2012; Downs and the MSL Science Team 2015) has been able to analyze samples from one Martian soil deposit and four drilled rocks, providing a wealth of information on their mineral compositions. These samples all share major mineral compositions that reflect the basaltic igneous protoliths from which they were derived. The abundances of the major igneous minerals are much lower in the sedimentary rock samples due to alteration to clay minerals and minor amounts of other authigenic phases (Blake et al. 2013; Vaniman et al. 2014; Downs and the MSL Science Team 2015).

On a planet made of basalt and altered under neutral pH conditions, this outcome is perhaps not surprising. This type of alteration strongly contrasts with the alteration of the Burns formation at Meridiani Planum, where primary basaltic rocks were altered under acidic conditions, leading to extensive deposition of sulfate-rich sedimentary rocks (McLennan et al. 2005). Paradoxically, the X-ray-amorphous component of Gale Crater sedimentary rocks is substantial, despite the near elimination of olivine and a significant reduction in the amounts of other igneous minerals during the alteration to authigenic Fe–Mg-smectite and magnetite. These X-ray-amorphous materials are revealed in CheMin diffraction patterns by an elevated background at low 2-theta angles, that is, between approximately 15 and 40 degrees (Blake et al. 2013; Vaniman et al. 2014).

One possibility is that at least some of the large fraction of amorphous materials in the Sheepbed and Windjana samples (FIG. 5) could have also formed authigenically, perhaps as a silica-rich cementing material, supplementing the possible iron oxide cements discussed above. However, if such an amorphous cement did form, it is not pure silica given the abundance of other elements; instead, the composition may be a mixture of some of these components: volcanic glass, hisingerite (or silica + ferrihydrite), amorphous sulfates, and nanophase ferric oxides (Dehouck et al. 2014). It seems more likely that amorphous materials of this composition are detrital in origin and that somehow their kinetics of dissolution were less favorable than those for olivine. Alternatively, the amorphous materials might consist of multiple components that might represent distinct and separate geologic processes of formation.

VOLATILES

Volatile components that are adsorbed on and chemically bound within solid materials at Gale have been detected by several instruments. These occur in the ubiquitous dust that coats nearly every surface observed by Curiosity so far, in the soil that fills depressions and creates eolian bedforms, as well as in rock-forming particles and in the cement that binds them together. Some volatiles have been recognized within ChemCam’s plasmas, others via the structures revealed by X-ray diffraction, but most have been detected during pyrolysis of solid samples. The volatiles released during pyrolysis include H2O, SO2, CO2, O2, H2, NO, H2S, HCl, and trace hydrocarbons. Most of these are not discussed further here, and the reader is referred to Mahaffy et al. (2015) and papers referenced therein for further information. A few examples representing a range of interesting geological materials discovered by Curiosity are presented here.

Water in Dust and Soil

In the course of obtaining thousands of LIBS analyses of Gale Crater’s surface, the ChemCam instrument has had to penetrate at least some dust on every sample. A standard ChemCam analytical sequence involves 25–30 consecutive shots at the same target, resulting in ablation of the surface and penetration to a depth of about 1 mm (Wiens et al. 2015). When the laser was used for the first time on sol 19, it was recognized that the first five or so shot points were measuring the composition of the dust coating the rock or soil surface (Meslin et al. 2013); such analyses must be discarded if an uncompromised rock or soil composition is desired. These first few shot points indicated the presence of hydrogen in the dust and, in many soils, the hydrogen.
was inferred to have originated from the hydration of amorphous phases (Meslin et al. 2013; Wiens et al. 2015). This signal has been seen throughout the course of the mission, indicating the ubiquitous nature of this hydration. Independently, pyrolysis of the Rocknest soil sample and analysis by the SAM quadrupole mass spectrometer and tunable laser spectrometer have shown that the X-ray-amorphous component of soil, including dust, is hydrated and is estimated to contain 1.5–3 wt% H₂O (Leshin et al. 2013). This water is thought to be “recent,” given that its D/H isotopic value (Leshin et al. 2013) is close to that measured in the modern Martian atmosphere (Webster et al. 2013); the water is perhaps the result of adsorption onto materials such as allophane and iron (oxy)hydroxides (Meslin et al. 2013). This finding implies soil–atmosphere exchange.

**Water in Ancient Clays**

The Fe–Mg-smectite clay minerals detected by CheMin in the Sheepbed mudstone at Yellowknife Bay were studied by SAM pyrolysis. Water was released over a range of temperatures, and at low temperatures represents adsorbed water, hydrated compounds within amorphous materials, and interlayer water in the Fe–Mg-smectites (Ming et al. 2014). However, release of water in the upper range of temperatures likely represents structurally bound OH, whose origin dates back to the time of clay mineral formation in the Yellowknife Bay lake sediments. The D/H measured in this high-temperature water is ~3 times the D/H ratio in standard mean ocean water (VSMOW), in contrast to the present Martian atmosphere whose D/H ratio is ~6 times VSMOW (Mahaffy et al. 2014, 2015) and a primordial value close to 1 times VSMOW. This result shows that at the time of clay formation substantial loss of the Martian atmosphere had already occurred. However, these values allow for an approximate Global Equivalent Layer thickness of 100–150 m or more for a Martian water reservoir that could have developed after an initial detection, as a way of building confidence in earlier results. Unfortunately, it is hard to establish the source of the organics preserved at the Cumberland location in the Sheepbed mudstone. It may be that pyrolysis leads to breakdown of those initial compounds and to synthesis of new molecules that contain chlorine in their structure; this chlorine would likely be due to the presence of oxychlorine compounds in the rocks and soils. Alternatively, the cosmic radiation striking the Martian surface may facilitate reactions with inorganic chlorine, to form chlorine-containing organic compounds.

The unexpected abundance of these oxidizing compounds in ancient rocks provides a challenge for Curiosity as the mission goes forward. Nevertheless, the demonstration that

**Ancient Organic Compounds**

Measurements of the Rocknest soil, the Sheepbed mudstone, and Confidence Hills mudstone (the first sample drilled at the Pahrump Hills outcrop) indicate that, under specific conditions, organics may be preserved in ancient rocks on Mars. Simple alkanes of chlorinated hydrocarbons have been detected in all samples analyzed to date, and while greater abundances in samples relative to abundances in blanks suggest that some carbon may be indigenous to Mars, it is difficult to rule out contamination by terrestrial sources (Leshin et al. 2013; Glavin et al. 2013; Ming et al. 2014). However, C₂ to C₄ dichloralkanes were studied in further detail by Freissinet et al. (2014) and their abundances may be above the detection limit. In contrast, the abundances of more complex chlorobenzene compounds suggest a more convincing case for the presence of ancient organics preserved in rocks (Freissinet et al. 2014). Figure 7 shows samples analyzed from the Rocknest soil, the John Klein and Cumberland samples from the Sheepbed mudstone, and a sample from the Confidence Hills part of the Pahrump Hills outcrop. This last sample is a fine-grained sedimentary rock and possibly of lacustrine origin. A fourth sample of sedimentary bedrock was obtained at the Kimberley outcrop (Windjana sample), but this sample was processed in a manner to isolate heavier organic compounds and without the use of the hydrocarbon trap; thus the analysis may have missed lower-molecular-weight organic compounds if these were present.

The four samples presented in Figure 7 show that the Cumberland sample has significant quantities of chlorobenzene, above blank levels. Furthermore, samples analyzed at other drill and scoop sites show chlorobenzene levels comparable to those of the blanks (Freissinet et al. 2014). This important result underscores the value of analyzing multiple samples, including those collected after an initial detection, as a way of building confidence in earlier results. Unfortunately, it is hard to establish the source of the organics preserved at the Cumberland location in the Sheepbed mudstone. It may be that pyrolysis leads to breakdown of those initial compounds and to synthesis of new molecules that contain chlorine in their structure; this chlorine would likely be due to the presence of oxychlorine compounds in the rocks and soils. Alternatively, the cosmic radiation striking the Martian surface may facilitate reactions with inorganic chlorine, to form chlorine-containing organic compounds.

**Figure 7** Chlorobenzene abundance, measured by SAM's gas chromatograph–mass spectrometer (GCMS) in soil (Rocknest) and rocks (John Klein, Cumberland, Confidence Hills); the hydrocarbon trap was used to concentrate volatiles before analysis. The abundances in pmol are not corrected for the portion sent to the hydrocarbon trap and thus represent a lower limit. The inset represents the mass spectrum (MS) generated for the gas chromatograph peak detected in Cumberland (red), compared to the National Institute of Standards and Technology Mass Spectral Database (black). These data indicate that the Cumberland drill hole sampled an ancient environment that favored preservation of organics (see Freissinet et al. 2014). The bottom row of images shows the scoop pit the drill holes that were created during sampling.
organic compounds are likely preserved in ancient rocks on Mars represents a step forward in our understanding of how such molecules are preserved in the Martian rock record. In turn, this finding allows development of a strategy for the deliberate search for ancient biomarkers—assuming of course that life evolved on Mars. With one rover mission to Mars every decade, it’s important to have a strategy. Here’s why. On Earth, a planet teeming with microbial life, it’s difficult to identify hydrocarbons in rocks that are billions of years old. The discovery of organics depends on three processes: (1) enrichment in the primary environment, usually by reduction of background sediment, which allows any organics to preferentially accumulate; (2) minimization of the effects of oxidative diagenesis during the conversion of sediment to rock (lithification); and (3) minimization of the thermal decomposition of organic molecules during burial. On a planet without plate tectonics and with a lithosphere that is thicker than Earth’s, thus reducing geothermal gradients, Mars is a better planet for remediating the risk of degradation during burial. However, with its much thinner atmosphere, Mars poses a far greater risk of degradation by radiolysis once rocks are exposed at the surface (Farley et al. 2014; Mahaffy et al. 2015). Nevertheless, the point is that just as explorers of carbon in ancient rocks on Earth must optimize their chances of success, so must our robots on Mars.

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ACKNOWLEDGMENTS
We are indebted to the Mars Science Laboratory Project engineering and science teams for their exceptionally skilled and diligent efforts in making the mission as effective as possible and enhancing science operations. The manuscript was reviewed by Gordon Brown, Paul Mahaffy, and Dave Vaniman, and help with figures was provided by Mike Baker, Fred Calef, Caroline Freissinet, Jen Griffes Shechet, Scott McLennan, Ralph Milliken, Kirsten Siebach, and Dave Vaniman. Some of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Data presented in this paper, and in others of this issue, are archived in the Planetary Data System (pds.nasa.gov).


Elements February 2015
The surface of Mars has been sculpted by flowing water and shaped by wind. During the first two years of its exploration of Gale Crater, the Mars Science Laboratory mission’s Curiosity rover has recorded abundant geologic evidence that water once existed on Mars both within the subsurface and, as least episodically, flowed on the land surface. And now, as Curiosity presses onward toward Mount Sharp, the complexity of the Martian surface is becoming increasingly apparent. In this paper, we review the nature of the surface materials and their stories, as seen through the eyes of Curiosity.

**INTRODUCTION**

Potential preservation of a diverse geologic past led to the selection of Gale Crater as the landing site for the Mars Science Laboratory (MSL) mission (Grotzinger et al. 2012). Orbital imagery provided geomorphic evidence (Malin and Edgett 2000; Anderson and Bell 2010; Siebach and Grotzinger 2014) for a protracted history of aqueous activity in the crater, and orbitally derived geochemical data indicated a diversity of mineral components (Milliken et al. 2010; Fraeman et al. 2013) that have the potential to provide and preserve key nutrient and energy sources necessary for habitability.

Notable surficial deposits include those related to a well-defined alluvial fan, the Peace Vallis fan, that extends into the crater interior from its little-denuded rim (Palucis et al. 2014), a central mound that exposes a nearly 5 km thick section of layered rock (Malin and Edgett 2000), and a complex series of layered strata that is exposed within the topographically low region between the Peace Vallis fan and Mount Sharp (Fig. 1) (Grotzinger et al. 2014; 2015 this issue). Gale Crater also records snapshots of the broader Martian environment, such as exotic lithologies transported into the crater via impact processes and the near-ubiquitous, wind-transported fines that form a veneer on the Martian surface.

In an effort to evaluate the habitability potential of environments in Gale Crater, Curiosity’s cameras have scanned a wide range of surficial deposits to seek evidence of water, the medium for all known biochemical reactions. The presence of past water is often apparent in the depositional fabrics of surficial materials. Clues gained from the texture of surface materials can also be used to predict how persistently environments may have interacted with water, either within the shallow subsurface or at the ground surface. Curiosity’s extensive suite of analytical instruments also allow for the search for both the nutrients necessary for life (e.g. C, H, N, S, etc.) (Mahaffy et al. 2015 this issue) and for possible energy sources (e.g. disequilibrium redox pairings in minerals) that could fuel microbial metabolisms.

**THE EYES OF CURIOSITY**

The eyes of Curiosity include six engineering cameras designed to support terrain assessment, hazard avoidance, and traverse planning (Maki et al. 2012), as well as four dedicated science cameras: the Mast Cameras (Mastcam) (Bell et al. 2013), the Mars Hand Lens Imager (MAHLI) (Edgett et al. 2012), and the Remote Microscopic Imager (RMI) associated with the ChemCam instrument suite (Maurice et al. 2012). Together, these cameras provide high-resolution, black and white and RGB color images, from distances of 2.1 cm to infinity. These images aid in the interpretation of rock fabrics and, with the use of a suite of multispectral filters, permit limited detection of ferric, ferrous, and hydrated minerals.

**SURFACE MATERIALS IN GALE CRATER**

**Fluvial–Alluvial Materials**

One of the most striking features of the Mars Science Laboratory landing site is the Peace Vallis fan (Palucis et al. 2014). This landform is interpreted to be the surficial expression of a long-lived alluvial-to-fluvial system deriving from the Gale Crater rim. Curiosity’s landing site, at the distal end of this fan, allows assessment of the extent to which the region experienced inundation by fluids emanating from the fan. Some of the earliest Mastcam images from Curiosity revealed glimpses of such fluvial activity in lithified, pebble-rich conglomerates that had been exhumed from beneath the surface of Bradbury Landing by the jets of Curiosity’s landing system. Then, within the first 100 meters of Curiosity’s exploration of Gale Crater, a series of isolated outcrops revealed well-lithified deposits of rounded sand grains, granules, and pebbles with textures typical of fluvial conglomerates (Williams et al. 2013). Since these first glimpses of fluvial processes, Curiosity has investigated a number of key outcrops that confirm the widespread nature of fluvial activity in Gale Crater. The Shaler outcrop, for example, consists of interstratified pebbly sandstone and finer-grained intervals (Fig. 2a) and contains well-developed, large-scale trough cross-stratification indicative of channelized flow.
In addition to fluvial sandstones, Curiosity has encountered a broad variety of sheet sandstones (Fig. 2B and C). These sheet-like deposits occur at nearly every waypoint imaged by Curiosity (e.g., Gillespie Lake member in Yellowknife Bay, Renssalaer at the Cooperstown waypoint, and Square Top at the Kimberley waypoint), and are often interbedded with conglomeratic deposits (Fig. 2D). These beds are generally massive, although poorly defined planar lamination and cross-lamination can also be present. Most of the observed sheet sands are medium grained and contain a variety of larger pebbles. Pebbles are rounded to angular and may represent, in part, material entrained from underlying strata during periods of enhanced surface flow. Combined, the clast-supported nature of these varied facies, the presence of coarse sand grains to fine pebbles, and the occurrence of partially rounded clasts suggest that these deposits represent sediment transport by flowing water. The absence of a well-sorted fabric in the coarser-grained deposits, however, suggests that at least some of these facies may have been rapidly deposited during flood events, rather than being the result of sustained fluvial activity.

**Lacustrine Materials**

The observation of widespread fluvial material in bedrock exposures along Bradbury Rise suggests that the Peace Vallis fan is the surficial expression of a long-lived alluvial-to-fluvial system deriving from the Gale Crater rim. Detailed mapping of the toe of the Peace Vallis fan further indicates that fan deposits interdigitate with a distinctly different succession of strata located downslope from and adjacent to the fan. That these light-toned, layered rocks might represent distal alluvial or even lacustrine environments was critical in influencing the MSL team’s initial decision to detour north toward Yellowknife Bay, rather than south toward Mount Sharp.

The detour into Yellowknife Bay proved to be a superb decision, especially with regards to the investigation of the Yellowknife Bay formation (Grotzinger et al. 2014), the base of which is composed of fine-grained strata of the Sheepbed member and sheet-sands of the overlying Gillespie Lake member. Following brushing of the Sheepbed outcrop, high-resolution MAHLI images (Fig. 3) revealed an absence
of grains larger than approximately 50 μm and the presence of grooves where the Dirt Removal Tool (DRT) scraped the surface. Combined, these observations provided the first evidence of a mudstone on Mars. The tailings from the first drill hole (FIG. 3) also provided a glimpse of something rarely seen on Mars: elements in their reduced state, as suggested by the grey color. Once analyzed by Curiosity’s CheMin X-ray diffraction instrument (Bish et al. 2013; Vaniman et al. 2014), these sediments were found to contain a nonequilibrium mineral assemblage that includes primary igneous phases (primarily basaltic minerals, such as plagioclase, pyroxene, and forsteritic olivine), a substantial (>30%) X-ray-amorphous component, and a variety of secondary phases. The secondary phases included a high proportion (>20%) of trioctahedral smectite clay (including saponitic smectite and a potentially Mg-bearing smectite), calcium sulfate minerals (anhydrite and bassanite), and iron oxides (including the iron oxide–hydroxide/chloride mineral akaganeite) (Downs and the MSL Science Team 2015 this issue). The analysis of chemical trends (McLennan et al. 2014) further suggests that diagenesis of the Sheepbed mudstone took place at near-neutral pH and at water:rock ratios low enough to reflect essentially isochemical alteration conditions.

Additional information regarding the deposition and diagenesis of the Sheepbed mudstone has been obtained from a variety of preserved diagenetic features (FIG. 4). These features include spheroidal nodules (Stack et al. 2014), a dense network of mineralized fractures (Siebach et al. 2014), and calcium sulfate–filled veins (Nachon et al. 2014). Taken together, these features indicate at least two distinct diagenetic episodes.

Nodules in the Sheepbed mudstone consist of millimeter-sized spheroids that are more resistant to erosion than the host mudstone. Some nodules are solid while others have a hollow interior. This range of textures suggests a common origin, possibly as concretions or via preferential cementation around a mineral phase that has since dissolved. Alternatively, the hollow nodules may have originated via compaction and incipient lithification of the host mud at the perimeter of gas bubbles, similar to the origin of terrestrial “molar-tooth” structures (Pollock et al. 2006). Preservation of such gas-expansion features in the Sheepbed mudstone is consistent with terrestrial data that suggest retention of exsolved gas within sediment that contain sufficient (>15%) clay content to enhance cohesion. Although most gas production in terrestrial pore fluids occurs during the decomposition of organic matter, temperature- or pressure-driven exsolution of dissolved atmospheric gases could also result in such features.

Early diagenetic nodules occur in the Sheepbed mudstone along with locally dense networks of mineralized fractures, although these two features show an antithetical spatial relationships. Fracture networks consist of short (<50 cm), curvilinear to planar mineralized fractures with a range of orientations, from vertical to subhorizontal. Fractures are filled by multiphase cement consisting of two isopachous (i.e. equal thickness), erosionally resistant outer layers and a central less-resistant fill. Physical relationships suggest that the fractures may have formed both as interconnected voids and as discrete crosscutting features. The occurrence of early diagenetic concretions and fracture networks suggests a possible common origin via subaqueous exsolution of gases from the sediment–water interface (Stack et al. 2014; Siebach et al. 2014). In this scenario, gas release within weakly cohesive subsurface sediments would have driven expulsion of shallow pore waters, resulting in an increase in the cohesive strength of the sediment. Local differences in sediment strength and rate of gas production could have then resulted in the formation of either discrete spheroidal voids or fracture networks.
In addition to containing early diagenetic nodules and fracture networks, Yellowknife Bay strata also preserve evidence of later fluid flow. Planar veins containing a single phase of calcium sulfate mineral fill occur throughout the Yellowknife Bay formation and crosscut early diagenetic features. These late-stage mineralized veins penetrate up to tens of centimeters of vertical section and are characterized by a low spatial density and orientations that are predominantly vertical or horizontal (the latter following bedding planes). The light-toned veins are reminiscent of fracture networks generated when subsurface fluid pressures exceed the yield strength of the overlying rock, resulting in hydraulic fracturing. In this case, sulfur-rich fluids may have originated from burial dehydration of gypsum that was deposited prior to the Sheepbed mudstones, or from unrelated units near the base of Mount Sharp.

**Eolian Materials**

Eolian processes have played a dramatic role in transforming the materials seen in Gale Crater. Persistent wind is indicated by the polishing of depositional materials and exotic boulders, and by the ever-present veneer of dust that tends to obscure the rover’s view of the underlying geologic materials. The winds, however, were also the primary agent responsible for exposure of Gale Crater strata, providing the team with a critical cross section of depositional processes. In addition, K–Ar exposure ages (Farley et al. 2014) have focused the team’s strategy on identifying solid samples that have not experienced prolonged exposure to radiation, which could be detrimental to the preservation of organic molecules.

Early in the mission, Curiosity examined eolian materials of the Rocknest sand shadow (FIG. 5), first visually (Minitti et al. 2013) and then geochemically (Bish et al. 2013; Leshin et al. 2013). The depression left by Curiosity’s scoop shows that the bedform surface is composed of a thin veneer of 1–2 mm grains (FIG. 5A). A combination of fractures within this veneer and of displacement of rafts of this veneer during scooping indicates incipient cementation and stabilization of the bedform surface. Stabilization may also be reflected in the presence of distinct banding 12–21 mm beneath the exposed surface of the bedform. Although the origin of the banding is uncertain, the orientation of the banding parallel to the present-day surface of the bedform suggests that it may represent either a change in the relative percentage of dust deposition during bedform accumulation or chemical changes within the sediment driven by diffusion of atmospheric volatile components.

The interior of the sand shadow is composed primarily of a mixture of dark grey, red, and orange-brown lithic fragments <150 µm in diameter, with only the larger size fractions resolved in the highest-resolution images. Mineralogical analysis (Bish et al. 2013) revealed the soil to be predominantly basaltic in composition (plagioclase, forsteritic olivine, augite, and pigeonite, with minor K-feldspar, magnetite, quartz, and ilmenite), but with a relatively large percentage of iron-rich, X-ray-amorphous material. In a sieved portion delivered to Curiosity’s Observation Tray, most of the material is below the 3 pixel minimum necessary for resolving individual grains. Resolved grains, however, include three distinct morphologies (Minitti et al. 2013). The first of these consists of well-rounded and nearly equant, translucent, yellow grains with no indication of external crystal faces or internal cleavage planes. These grains are tentatively identified as quartz or olivine (FIG. 5A). A second type consists of small, opaque, angular to subangular, white grains that have distinctly flat (or faceted) sides, suggesting a mineral phase with two distinct cleavage planes, such as feldspar (FIG. 5C). Finally, near the limit of the image resolution are a small number of spheroidal grains that are distinctly symmetrical, round, and highly reflective; these may be impact spherules (FIG. 5D).

**Exotics**

It would not be a surprise to find materials generated by hypervelocity impacts in the surface materials of Gale Crater. Evidence for impact-derived materials dates to
Curiosity’s earliest days on Mars, when both Mastcam and RMI imaged a variety of exotic clasts of probable igneous origin (FIG. 6). These included a large number of grey-colored, faceted boulders with uniform, aphanitic textures and compositions consistent with alkali basalt (Wiens et al. 2015 this issue) (FIG. 6A AND B). More rarely, Mastcam and the ChemCam RMI imaged boulders that revealed hints of a porphyritic texture on dust-free surfaces (FIG. 6C AND D). The most conspicuous phenocrysts are centimeter-scale and lighter in color than the surrounding groundmass. These exotic components are distinct from other surface components in that they are irregular in their distribution, are larger and more angular than locally derived clasts, and show less evidence of abrasion, suggesting an origin potentially beyond the walls of Gale Crater, and emplacement as impact ejecta (Yingst et al. 2013).

In addition to individual exotic components, Curiosity has imaged a variety of possible impactite deposits (Newsom et al. 2015), including upturned bedrock clasts, fractured bedrock, and probable impact breccias (FIG. 7A). Impact breccias display a wide range of clast types, clast lithologies, and angularity of individual clasts. Although these characteristics alone do not uniquely define an emplacement by impact, they are broadly inconsistent with the inferred hydrological emplacement of the vast majority of coarse-grained units within Gale Crater.

The critical role of impacts in providing material to Gale Crater is also evidenced by the occurrence of impact spherules and the occasional meteorite sighting. Impact spherules result from the atmospheric condensation and solidification of impact vapor, forming small (<1 mm diameter), generally spheroidal, glassy particles (FIG. 7B). These are identifiable by their smooth and highly reflective external surface (from which dust readily falls during physical disruption). Impact spherules are observed most commonly in disturbed soils, although they also have been found in lithified materials. By contrast, potential iron
meteorites (Fig. 7c) occur as conspicuous exotic boulders on the landscape, much like those documented by the Mars Exploration Rovers (Schroder et al. 2008).

LOOKING AHEAD

Curiosity has provided us with tantalizing glimpses of a world that we are only beginning to understand. Evidence of once-abundant surface water contrasts with evidence of only minor geochemical alteration of the materials that interacted with these fluids. Geochemical evidence also reveals distinct periods of moderate salinity and near-neutral pH, as well as periods of high-salinity, with sulfate-dominated fluids and periods of migrating iron-rich groundwaters. Collectively, these observations suggest that Gale Crater was rich in potentially habitable environments.

The ultimate challenge, however, still lies ahead. Can we define the extent of these previously habitable environments, can we determine the persistence of these environments through time, and can we know whether these environments were simply habitable or were actually inhabited? The answers to these questions may lie within the flanks of Mount Sharp, and the MSL team will continue to look for clues as Curiosity traverses olivine-bearing sands and a stratigraphic succession containing Fe–Mg-smectite clay, hematite, and hydrated sulfate. There are many ideas about what we might find, but we must remember the words of Winston Churchill, who said, “It is always wise to look ahead, but difficult to look farther than you can see.”

ACKNOWLEDGMENTS

Thanks to M. Malin and K. Edgett for introducing me to Mars, and to J. Grotzinger and the Mars Science Laboratory mission for the support of an extraordinary team of scientists and engineers who work and learn together. Thoughtful reviews from team members, external reviewers A. Knoll and E. Simpson, and principal editor G. Brown helped improve this manuscript.

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The ChemCam laser-induced breakdown spectrometer on the rover Curiosity has provided more than 200,000 spectra from over 5000 different locations on Mars. This instrument is the first chemical microprobe on Mars and has an analytical footprint 0.3–0.6 mm in diameter. ChemCam has observed a measure of hydration in all the sedimentary materials encountered along the rover traverse in Gale Crater, indicating the ubiquity of phyllosilicates as a constituent of the analyzed sandstones, mudstones, and conglomerates. Diagenetic features, including calcium sulfate veins, millimeter-thick magnesium-rich diagenetic ridges, and manganese-rich rock surfaces, provide clues to water–rock interactions. Float clasts of coarse-grained igneous rocks are rich in alkali feldspars and some are enriched in fluorine, indicating greater magmatic evolution than expected on Mars. The identification of individual soil components has contributed to our understanding of the evolution of Martian soil. These observations have broadened our understanding of Mars as an active and once habitable planet.

**Introduction**

Determining geological history from the rock record requires gathering mineralogical, compositional, and textural information over a wide range of spatial scales. On Earth, thin sections of rock samples allow the study of minerals and textures, while finer scales are routinely investigated with ion probes, electron microprobes, laser-ablation inductively coupled plasma mass spectroscopy instruments, and scanning electron microscopes. This arsenal of tools is unavailable, however, when exploring another planet. With the exception of high-resolution microscopic cameras and an atomic force microscope (Pike et al. 2011), chemical and mineralogical analyses on Mars were previously done at a scale of centimeters or larger. For example, the footprint of the alpha particle X-ray spectrometers (APXSs) on the Mars Exploration Rovers (MERs) is 3.8 cm in diameter and the miniature thermal emission spectrometer (Mini-TES) had a minimum spot size of ~8 cm in diameter (Squyres et al. 2003).

We proposed a radically new concept for the Mars Science Laboratory (MSL) rover Curiosity: an active laser experiment that would probe submillimeter scales at distances of up to 7 m from the rover (Maurice et al. 2012; Wiens et al. 2012). The ChemCam instrument suite includes the first laser-induced breakdown spectrometer used on another planet. It is mounted on the rover’s mast together with a high-resolution remote microscope imager (RMI). In deploying this instrument, the size scale for the study of Mars geochemistry shrank by a factor of 100. The novel concept is to perform submillimeter-scale chemical analyses from the rover’s mast rather than at close range from the arm. ChemCam’s position on the mast enables large statistical surveys and allows access to targets outside the rover arm’s work zone. It avoids rover stability and slip issues, which prevent arm use in many instances. So far, ChemCam has returned from Mars more than 200,000 diagnostic spectra and over 3000 high-resolution panchromatic RMI images.

ChemCam’s focused laser beam is 0.3–0.6 mm in diameter, depending on target distance. When targeted grains are much larger than the beam diameter (for example, approximately 2 mm or larger), ChemCam can analyze individual mineral grains; when the grain size is much smaller than the beam, ChemCam obtains the whole-rock composition with a single observation or with only a few observations averaged together. When the grain size is at the same scale as the beam size, the mineralogy can be deduced from trends among multiple observations, and whole-rock compositions can be determined by averaging large numbers of observations.

ChemCam’s pulsed laser was designed to ablate the target material. The beam provides penetration first through the dust layer that is pervasive on the surface of Mars (Fig. 1) and then into the rock or soil, allowing studies of surface alteration. Estimates of penetration depth are based on the sizes of the craters observed in the RMI images. Sighting with the RMI allows us to locate the laser pits and to observe the spatial and textural relationships of the target locations and surrounding area at a spatial scale down to 80 µm at close range (e.g. 2 m), thus resolving grains the size of fine sand. The laser’s surface-cleaning capability reveals details that would otherwise be invisible (Fig. 1a).

Laser-induced breakdown spectroscopy (LIBS) uses laser pulses that briefly provide a power density of >10 MW/mm² to ablate target material in electronically excited states, forming a ball of plasma that lasts a few microseconds (e.g. Cremers and Radziemski 2006). The plasma emits photons at wavelengths characteristic of the electronic energy transitions of the elements present in the target material. ChemCam uses a 110 mm diameter telescope to...
focus the laser beam and to collect light from the plasma, which is recorded using spectrometers. When calibrated, the emission-line spectra provide quantitative elemental abundances. As each laser shot probes deeper into the sample, depth profiles up to 0.5 mm in rock and greater than 1 cm in soil are achieved, and the compositions returned from the successive laser shots can be investigated. ChemCam typically provides major element (Si, Ti, Al, Fe, Mg, Ca, Na, K) relative compositions to precisions in the range of 1.0–2.0 wt% for SiO$_2$ in a typical basalt with 45 wt% SiO$_2$, and in the range of 0.2–1.0 wt% for other major elements (Blaney et al. 2014) in similar sedimentary targets. In addition to probing all the major elements, the LIBS technique as used on ChemCam is sensitive to a number of minor and trace elements, including H, Li, C, F, S, Cl, Mn, Ni, Zn, Rb, Sr, and Ba.

A spectrum from a soil target, Radcliff point #4, is shown in Figure 2. This target is on the edge of a rover wheel track. Transition metal elements, such as Fe and Ti, have a large number of emission lines, while some other elements at either end of the periodic table, for example, Na, K, Si, and Cl, have relatively few emission lines. In Figure 2, all 30 spectra obtained from this observation point are shown separately to illustrate the capability to observe compositional heterogeneity within a given observation point.

ChemCam has excellent detection limits for the alkali and alkaline earth elements. Lithium, for example, can be seen in nearly all targets, at abundances down to less than ten parts per million (Fig. 2c, inset). The trace elements Li and Rb are sensitive to alteration and are concentrated in alcaline-rich rocks, as we have seen in Gale Crater (Ollila et al. 2014). Carbonates can be detected with ChemCam, but due to interference from carbon in the atmosphere, which gets excited as part of the plasma, 4–5 wt% of the target would need to be carbonate to be identified. So far ChemCam has not observed carbonates in Gale Crater. Another important feature is the sensitivity of the LIBS to hydrogen.

Elemental compositions are quantified from ChemCam LIBS data using several calibration methods. Trace elements, such as Li, Rb, and Sr, and sometimes major elements as well, are quantified by comparing the area of a strong emission peak, observed on a target of unknown composition, to the area under the same peak for a set of calibration standards (e.g. univariate analyses; Fabre et al. 2014; Ollila et al. 2014). For major elements, the presence of multiple emission lines allows the possibility of using multivariate analytical methods, such as partial least squares, in which all the spectral channels covering multiple peaks are regressed against a training set of standards. This method requires that the standards accurately cover the compositional phase space of the unknowns. ChemCam is one of the first large-scale applications of LIBS to determine the abundances of a large range of elements simultaneously, and so both of the above calibration methods are being used (Wiens et al. 2013).

The overall tactical goal of a remote-sensing rover instrument like ChemCam is to provide information about the area around the rover so that the arm-mounted and in situ instruments can be used on the most interesting samples.
The MSL landing site in Gale Crater, a 155 km wide impact basin just south of the equator, is depicted in the upper left. The landing ellipse is sandwiched between the Peace Vallis alluvial fan and a line of sand dunes bordering the base of Mt. Sharp. The location of panel A is shown in the upper-left inset map. (A) The rover’s traverse during the nominal mission. (B) The location of inset map B is shown in the top right corner of panel A and shows details from the Yellowknife Bay area. ChemCam targets mentioned in this article are indicated by yellow dots along the traverse.

In the case of ChemCam, we are also able to carry out a large amount of opportunistic science using its unique capabilities—the small analysis size, the high-resolution imaging, its sensitivity to hydrogen, and its unique ability to detect minor and trace elements. A fair amount of the science on Mars is still serendipitous because so few places have been visited.

Gale Crater was selected because, as a probable sedimentary site, it would provide greater understanding of the role of water and habitability on Mars. A number of fluvial features are observed from orbit (FIG. 3): flow channels from the crater walls and the central mound, alluvial fans, and inverted channels; in addition, some phyllisolate mineral features have also been observed (e.g. Anderson and Bell 2010). The landed mission has clearly confirmed Gale as an important sedimentary site.

Although characterization of the sedimentary rocks and diagenetic features constitutes the main mission of ChemCam, a number of discoveries have also been made about igneous rocks and about Martian soil in general. The results of some of these unique ChemCam findings are described briefly below. The Discussion section returns to the major goal of ChemCam during Curiosity’s exploration, which is to provide broad coverage of the sedimentary strata in Gale and to aid our understanding of its fluvial history.

RESULTS

First Window into the Components and Hydration of Martian Soil

On sol (Mars day) 13 of the landed mission, the first ChemCam observation was made on a small float (i.e. not outcropping) rock in front of the rover. The spectrum from the first laser shot showed a substantial hydrogen emission peak. This peak disappeared in subsequent shots, which would have been dust-free. The immediate implication was that Martian dust is hydrated, which was confirmed by the first laser shot on each rock target analyzed and by all laser shots on soil targets. The quantification of H by ChemCam is still in progress. The hydration of Martian soil and dust was also detected by the dynamic albedo of neutrons (DAN) and sample analysis at Mars (SAM) instruments: 1.5–3 wt% H2O was reported in the first soil that was sampled by SAM (Leshin et al. 2013). ChemCam observations throughout the mission have shown that soil hydration is ubiquitous, which is consistent with orbital observations that show a ubiquitous 3 μm absorption associated with H2O absorbed onto minerals and the presence of hydrated phases (e.g. Milliken et al. 2007).

ChemCam soil observations have provided the first window into the compositional makeup of individual soil grains. During each soil observation, the laser beam digs a pit several millimeters deep (e.g. inset in FIG. 2a), typically using 30 shots fired within 10 seconds. Fine grains are removed immediately, whereas several laser shots are usually required to remove coarser soil grains. Time-lapse images have shown the progression of these soil observations, and shot-to-shot variations in the spectral peaks and the total optical emission clearly distinguish between the fine and coarse soil grains (Cousin et al. 2014). Chemical results show that coarse grains have a significantly different composition from the fine grains (Meslin et al. 2013). The coarser grains are not strongly hydrated and for the most part correspond to the composition of local rocks, showing for the first time a local soil component, which is contrary to the idea that Martian soil is uniform across the planet. Probing of the finer grains showed that these are predominantly lower in SiO2 (37–43 wt%) than average Martian soil (45.4 wt%; Taylor and McLennan 2009) and are clearly hydrated (FIG. 2c, inset). The fine-grained component observed by ChemCam corresponds quite closely to the composition inferred for X-ray-amorphous soil constituents; this composition is obtained by subtracting the composition of the minerals observed by the CheMin instrument from the bulk soil composition determined by the APXS (Blake et al. 2013). Iron is an exception; it is depleted by a factor of almost two in the ChemCam observations of fine grains (Meslin et al. 2013) relative to the APXS results. Given the very different ways that ChemCam and the APXS observe these samples, it is possible that this difference is due to weathering-related iron depletions on the surfaces of these grains.

Coarse-Grained Feldspar-Rich Rocks

Imaging Observations

A number of igneous float rocks have been observed, with a variety of grain sizes. These rocks are considered igneous because of their clearly defined coarse mineral grains; some of these mineral grains correspond very well in appearance to feldspar and pyroxene grains. There is a strong correspondence between the visual and compositional identities of these grains. They also lack the hydrogen signature seen in fine-grained (presumably sedimentary) rocks and soils at Gale Crater (Schroeder et al. 2014). As more observations were made, it became clear that feldspar compositions occurred not only in float rocks but also in a majority of the clasts in some conglomerates (Williams et al. 2013). Coarse-grained, feldspar-rich float rocks were seen at Bradbury Rise in the early part of the mission (Sautter et al. 2014) and again a year later while the rover was traversing back past the landing site towards Mount Sharp. The insets in FIGURE 4 show two feldspar-rich clasts, Bindi and Horlick. Bindi, in particular, is one of a number of clasts that show a
high concentration of light-toned, elongated crystals more than 1 cm in length.

In contrast to the float rocks shown in Figure 4, the rock called Jake Matijevic (or Jake_M) (Stolper et al. 2013)—the first rock analyzed jointly by the APXS and ChemCam—did not present optically observable mineral grains despite examination at close range by the Mars hand lens instrument (MAHLL). Both the APXS and ChemCam chemical observations revealed significant compositional heterogeneity. The ChemCam observations did not correspond to known igneous mineral compositions, with the exception of one pyroxene grain (Stolper et al. 2013). Jake_M appears similar to a class of rocks observed capping local topographic highs; however, there is doubt about the igneous origin of these rocks due to an apparent lack of an igneous source, the lack of an igneous grain texture on the rock surface, and the appearance of rounded pebbles on its more weathered surface. The presence of pebbles is obvious in more recently observed rocks of similar composition and texture.

Spectral Observations

The main panel of Figure 4 shows molar Al/Si versus molar (Fe + Mg)/Si for observation points on the clasts Bindi and Horlick, determined using calibrated peak areas (univariate analyses; Wiens et al. 2013; Fabre et al. 2014). Overall, the Bindi spectra (not shown here) indicate strong enrichments of Si, Al, Na, K, Ca, and Nb and very weak to nonexistent Fe, Mg, and Ti peaks (cf. Fig. 2). The calibrated spectra yield compositions that are consistent with nearly pure alkali feldspar for three of the observation points and with a high fraction of alkali feldspar for the other two points. The observation points corresponding to the nearly pure feldspars are within the very light-toned mineral grains, while the other two points are near or overlapping the edges of the feldspar grains (Fig. 4, inset). In contrast, the spectra of another igneous clast, Horlick, which has finer grains, show less Si, Ca, Al, Na, and K, as well as more significant fractions of Fe and Mg, and some Ti. None of the Horlick data points lie directly on the y-axis in Figure 4, which is consistent with the smaller grain sizes in that target and the lower probability of placing the beam entirely on a single mineral grain. The Horlick data points define a trend that lies within the range of the Bindi points and extends from the alkali feldspars toward a clinopyroxene composition at a position of 0.5 on the x-axis.

Alkaline basalts were previously encountered by MER-A (Spirit rover) in the Columbia Hills in Gusev Crater. Examples of these were Backstay, Irvine, and Wishstone (e.g. McSween et al. 2006), all of which are olivine normative. In stark contrast to the inferred mineralogy from MER and that observed in a significant fraction of SNC meteorites, ChemCam has not observed individual olivine grains. Additionally, the compositions of some of the igneous float rocks in Gale are consistent with the presence of quartz and/or silica-rich glass. The overall conclusion from igneous rocks encountered along the traverse is that most are very different from those observed by MER, indicating more evolved magmas than previously encountered in surface observations on Mars. Indeed, fluorine, shown in the spectra in Figure 2, is present in these igneous rocks and in igneous clasts in conglomerates (Forni et al. 2014). Its occurrence, apparently in the form of fluorapatite, muscovite, and biotite, is also strongly suggestive of highly evolved magmas (Forni et al. 2014).

A second major difference from basalts previously encountered on Mars is the grain size and mineral occurrence. A number of the observed float rocks have centimeter-sized feldspar crystals, which are much larger than the grains observed by MER or Pathfinder. The texture of Bindi (Fig. 4, inset), in particular, is characteristic of a feldspar cumulate, never before seen on Mars, in which the density of feldspar causes it to segregate from the bulk of the magmatic material during crystallization.

Diagenetic Features and Alteration

Gale Crater is a sedimentary site, and the material along Curiosity’s traverse in the crater consists overwhelmingly of sedimentary sandstones and mudstones. Most of ChemCam’s observations have been dedicated to characterizing these materials to support our understanding of the fluvial activity that formed this site and of the setting’s potential habitability. The small size of ChemCam’s beam provides a unique capability to analyze fine-scale features within this sedimentary setting, including fine layering (Fig. 5a) and numerous diagenetic features (Fig. 5b-e). Curiosity’s first destination in pursuing its goal of determining the stratigraphy of Gale Crater’s sediments was the exposed Yellowknife Bay formation, located to the east of Bradbury Landing and several meters lower in elevation (Grotzinger et al. 2014). Upon entering the lower member, called Sheepbed (Fig. 3), images from Navcam and Mastcam indicated the presence of light-toned veins. ChemCam analyzed the first of these at a rock target named Crest and identified the light-toned material as calcium sulfate (Fig. 5a). Among the many other Ca sulfate veins and nodules, several levels of hydration were observed (Nachon et al. 2014), suggesting gypsum or bassanite—the two forms of hydrated calcium sulfate—or both. A majority of these Ca sulfate observations were in the stratigraphically lowest member (Sheepbed), which consists of mudstones, though some observations extended into the overlying coarser sandstones (referred to as the Gilbert formation; see Fig. 3). Recently, calcium sulfates have been observed more regularly along the traverse. They highlight an episode of relatively mild, low-temperature (<50°C) fluid circulation inside cracks formed after the cementation of the sediments during an earlier diagenetic period.

Gale Crater displays manifold evidence of eolian erosion: many of the rocks display exotic forms—fins, flutes, facets, and grooves—due to the carving action of the wind. It was therefore surprising to find surface alteration in one particular target using ChemCam’s depth profiling capability. Ollila et al. (2014) found that early shots at three of the five observation points at Bathurst Inlet (sol 55) indicated enrichments of mobile elements at the surface by factors of ~2 relative to the last few shots (shots 26–30) at each
location. The greatest enrichment was in Li, followed by Rb, and then by Na and K. The enrichments suggest either leaching or a deposition of mobile elements on the surface. Given the eolian erosion of most rocks, this result seems to indicate relatively recent aqueous transport of mobile elements in at least a few places in Gale Crater.

A number of locations have revealed high concentrations of manganese. The occurrence of oxidized Mn-rich minerals (indicated by abundances well above 1 wt% MnO) requires a strongly oxidizing fluid. High Mn abundances were sporadically observed in the first 1.5 years of the mission, and these observations were not generally correlated with any surface features that might help explain the production of Mn-rich minerals. One example is the target Caribou on sol 342 (Fig. 5; Lanza et al. 2014), where only one point in a line scan of LIBS observations indicated high Mn. A dark albedo around this point may suggest a Mn-rich coating, but there are no other clues. Manganese-rich surface material was also discovered by ChemCam observations on targets Stephen and Neil (sol ~615). In this case the rock surface was flat, dark, and shiny (Fig. 1), and the manganese was uniformly distributed across the surface. Numerous ChemCam depth profiles indicated that the layer is relatively thin, and other trace elements were shown by APXS to correlate with Mn, all suggesting that this material was a fluid-deposited fracture fill. The production pathway for manganese-rich minerals on Mars is at this point unclear. Although Mars is considered somewhat oxidizing, as hematite occurs in abundance, the oxygen content of the current atmosphere is low and would be insufficient to produce manganese-rich minerals, as was also the case with the early Earth prior to the great oxygenation event.

Figure 5: Fine-scale features observed by ChemCam, including (A) a transect of a target from Facies 4 of the Shaler outcrop and (B–E) diagenetic features, indicated by arrows, observed by ChemCam’s RMI. (A) Wakanbra Bay target with locations of LIBS points (sol 311). (B) Nodules in target Rae (sol 192). (C) Rised Mg-rich ridges in Rowatt (sol 133). (D) Caribou (sol 342); the black arrow indicates an observation point yielding a high (>50 wt%) MnO concentration. Two laser pits in soil can be seen above this point (dashed arrows). Panel (E) shows a calcium sulfate vein in Tukarak (sol 157); the red full arrow indicates the location of the ChemCam analysis displaying a calcium sulfate signature, as shown in the accompanying spectrum; the dashed arrow corresponds to the dashed spectrum without S and Ca enrichment. The spectrum of a typical basaltic target is shown for comparison. Images courtesy of NASA/JPL-Caltech.
upstream. Subsequently, the rover team has found even greater potassium enrichments at a more recent site named Kimberley (Fig. 3).

An important observation from Gale Crater sediments is that while the conglomerates contain clasts reflecting the compositions of the igneous float rocks (e.g. Williams et al. 2013), finer-grained sediments, including all the units at Yellowknife Bay (Grotzinger et al. 2014), are much closer in composition to Martian soil and dust (McLennan et al. 2014). CheMin results showed that >30% of the Sheepbed material was carried from a more distant source than the larger conglomerate clasts. Although the source of the fine-grained material might be farther into the source region of Peace Vallis, there is no way to confirm this idea at present, and other source regions are possible, given that Gale Crater has many inflow channels.

**Future Prospects**

As of early 2015, Curiosity has traveled more than 9 km in the direction of Mt. Sharp and is now in rough terrain upstream. Subsequently, the rover team has found even greater potassium enrichments at a more recent site named Kimberley (Fig. 3). As the rover gains elevation onto the lower flanks of the mountain, spectral features seen from orbit (e.g. Anderson and Bell 2010) are expected to be observed by the rover instruments. These include increased phyllosilicates and hematite, the latter of which has been observed from orbit along a ridge (“Hematite Ridge” in Fig. 3). Indeed, around sol 725 ChemCam’s passive spectra began showing features indicative of iron oxides and sulfates. Additionally, exploration of the Pahrump Hills outcrop (Curiosity’s current location; sols 750 to >870) shows compositions indicative of increased alteration, consistent with the hematite observed from orbit. Exploration of the regions ahead will hopefully elucidate the origins of these features and provide clues to the formation of Mt. Sharp, and possibly of the regional Medusa Fossae formation.

**ACKNOWLEDGMENTS**

This work was supported by the NASA Mars Program Office in the US and by the French Space Agency (CNES) in France. Ryan Anderson, Fred Calef, Zareh Gorjian, Stéphane Le Mouélic, Nicolas Mangold, Marion Nachon, William Rapin, Sam Clegg, Cécile Fabre, Agnes Cousin, and Violaine Sautter are thanked for their contributions to this work. The Jet Propulsion Laboratory is thanked for and congratulated on its excellent development and support of the MSL mission. This manuscript benefited from constructive reviews by R. Arvidson and G. Rosman, and from editorial support by J. Grotzinger and G. Brown.

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The Alpha Particle X-ray Spectrometer (APXS) is a soda can-sized, arm-mounted instrument that measures the chemical composition of rocks and soils using X-ray spectroscopy. It has been part of the science payload of the four rovers that NASA has landed on Mars. It uses $^{244}\text{Cm}$ sources for a combination of PIXE and XRF to quantify 16 elements. So far, about 700 Martian samples from about 50 km of combined traverses at the four landing sites have been documented. The compositions encountered range from unaltered basaltic rocks and extensive salty sandstones to nearly pure hydrated ferric sulfates and silica-rich subsurface soils. The APXS is used for geochemical reconnaissance, identification of rock and soil types, and sample triage. It provides crucial constraints for use with the mineralogical instruments. The APXS data set allows the four landing sites to be compared with each other and with Martian meteorites, and it provides ground truth measurements for comparison with orbital observations.

**Keywords:** Mars geochemistry, XRF, PIXE, APXS, MER, MSL, chemostratigraphy

**INTRODUCTION**

The alpha particle X-ray spectrometer (APXS) in the Mars Science Laboratory (MSL) is the fourth instrument of its kind that has landed on Mars. After Pathfinder (1997) and the twin Mars Exploration Rovers (MERs) Spirit (2004–2011) and Opportunity (2004–ongoing), the MSL APXS was competitively selected by NASA in 2004 to be part of the scientific payload of the rover Curiosity. It was contributed by the Canadian Space Agency (CSA). The APXS is an arm-mounted, contact instrument that measures the chemical composition of rocks and soils using X-ray spectroscopy. Bulk geochemistry is a key geological tool that complements mineralogy and imaging. It delivers crucial constraints for the interpretation of available scientific data. APXS compositional data from four landing sites, covering more than 50 km of traverse on diverse terrain, allow detailed assessment of the geology of Mars. Here we discuss the APXS method and instrument as well as some of the results from the current MER and MSL missions.

**THE APXS MEASURING METHOD AND RESULTS**

The APXS irradiates a sample with alpha particles and X-rays and measures the radiation emitted from the sample atoms. While it shares many principles with the standard X-ray fluorescence (XRF) technique used on Earth, it is a highly optimized version specifically adapted for the requirements of space exploration—light, robust, and easy to operate. Once the instrument has been deployed, the energy of each registered X-ray signal is determined and the spectrum is accumulated over a given time. The improvements and design changes in the MSL version are based on the experience gained in using the method during the development and operations of the Pathfinder and MER APXS instruments. Highlights of the instrument design, its evolution, and the basic physics principles underlying the method are summarized below.

The APXS has undergone significant changes from Pathfinder through MER to MSL. The Pathfinder instrument (Rieder et al. 1997) was mainly optimized for Rutherford backscattering (RBS) and was equipped with a thin alpha detector in the center of a ring of $^{244}\text{Cm}$ sources (Radchenko et al. 2000), which emitted 5.5 megaelectron volt alpha particles and plutonium X-rays with energies of 14.3 and 17.6 thousand electron volts onto the sample. The Si-PIN detector for X-rays was attached to the side. The MER instruments, designed and developed at the Max Planck Institute for Chemistry (Rieder et al. 2003), introduced the then new silicon drift detector (SDD), which was placed in the center of the ring of sources. However, the RBX method was found to be seriously degraded by the ~6 millibar CO$_2$ atmosphere on Mars, which resulted in a very high detection limit for carbon in the sample.

For MSL the alpha particle detectors were abandoned. This allowed a more compact geometry, resulting in a counting rate about three times higher than in the MER APXS.

The next design change concerned the $^{244}\text{Cm}$ sources. The alpha particles best excite the lower atomic number (Z) elements sodium to calcium by particle-induced X-ray emission (PIXE), while XRF excites better the higher-Z elements. The additional PIXE excitation gives the APXS a significant advantage over the pure XRF instruments on Viking, Beagle, and the Chinese lunar rover and over the CheMin XRF mode in the MSL. To essentially double the sensitivity for important high-Z trace elements, the $^{244}\text{Cm}$ sources, each emitting alpha particles and X-rays, were augmented by sealed $^{244}\text{Cm}$ sources to pass only X-rays.

With these improvements, the MSL APXS can acquire a good spectrum within 20 minutes, as shown in Figure 1; the composition extracted from this spectrum and the associated errors are shown in Table 1. A comparable analysis on MER took several hours at night. The activation of a
Peltier cooler for the SDD allows acquiring several spectra during the Martian day with centimeter-scale offsets to raster the sample. This technique reveals the degree of homogeneity of the sample and can indicate the presence of certain minerals through correlated changes of the elements measured.

Compared to terrestrial XRF analyses, there are important limitations on the surface of another planet. On Earth, samples are usually melted into borate pellets to make the compositionally homogeneous. Preparing such pellets is infeasible on Mars and would also result in the loss of many geochemically important volatiles. The APXS measures a sample about 1.7 cm across—the same as the diameter of the MSL drill—and averages over all mineral grains in its field of view. While in homogeneous glasses X-ray self-absorption can be modeled very well, the APXS samples on Mars have different absorption depending on the minerals present. This is the underlying reason for minor imperfections in accuracy in the calibration with ~100 terrestrial reference materials (Table 1). Additional details of the analysis methods can be found in Gellert et al. (2006) and Campbell et al. (2012).

On Mars the rovers do have some means of sample preparation. Besides measuring the sample as is, a brush can remove dust, soil, and unconsolidated alteration materials. MER has a rock abrasion tool (RAT) used to expose the interior; MSL also has a drill that delivers fines from an ~5 cm deep hole to the analytical instruments. Both the excavated fines and the aliquots of unused fines can be measured by the APXS. The results for drill cuttings typically agree well with results from the brushed surface. Systematic comparisons indicate that even an unbrushed spot typically shows clearly the underlying rock characteristics. For example, the unbrushed Jake_M rock in Gale Crater has 7% Na₂O, which is about three times more than the sodium content in the dust, indicating that either the dust coating is patchy or that the surface measurement is representative of the altered rock.

### APXS RESULTS FROM THE MARS ROVERS

The scientific objective of the twin MER rovers Spirit and Opportunity (Squyres et al. 2003) was to “follow the water” by finding evidence that water interacted with the rocks and soils in the past. After achieving that by identifying many different alteration products, the MSL mission (Grotzinger et al. 2012) continued to the next step of investigating the past and present habitability in detail. The fact that APXS instruments are on all rovers makes it possible to compare and interrelate all landing sites. This part of the article will discuss only the highlights of the APXS findings. Detailed mission overviews can be found in Arvidson et al. (2010, 2011), including maps and results of the overall investigations. We will refer to the samples (rocks or soils) using the names given by the mission and discuss the first encountered rock that is usually the namesake for a class of rocks with similar chemical composition. The APXS data, spectra, and extracted compositions can be found on the NASA Planetary Data System website, http://pds-geosciences.wustl.edu/.

### Spirit

Spirit landed on the plains of Gusev Crater in January 2004. APXS measurements of 6 float (non-outcrop) rocks revealed that they are all similar, primitive, olivine-bearing basalts; they are named after Adirondack, the first ever rock investigated in situ on Mars. The major elements of Adirondack basalts are somewhat similar to the global basaltic soil found at all landing sites, but they differ in many minor elements, like K, Ni, S, and Cl (Fig. 2, bcarr). Some rocks had, on their surfaces, alteration rinds or exogenous coatings with elevated soluble elements, especially Cl (Gellert et al. 2006). Finding no evidence for extensive altered sediments, Spirit drove ~2 km towards the Columbia Hills. Already outlasting the primary mission duration of 90 sols (Martian days), Spirit began around sol 200 to explore the ~100-meter-tall hills.

There, Spirit encountered an astonishing diversity of rocks and outcrops, some of which were altered to various degrees. Relative to the global basaltic soil, the Wishstone class of...
rocks and outcrops are rich in feldspars, with elevated Na, K, Al, and Ca, low Mg and Fe, and very low Cr and Ni. A peculiar trait is their high 5 wt% P_2O_5 and nearly 3 wt% TiO_2 (Gellert et al. 2006); they are interpreted as alkaline volcanic rocks with ~10% merrillite (Usui et al. 2008). One outcrop, Independence, has very high Al and Si and lower Fe, and this composition is possibly indicative of montmorillonite (Clark et al. 2007). Clovis-class outcrops are very soft and have high levels of S, Cl, and Br, even in their abraded interiors (Ming et al. 2008). The rock called Peace has high Mg, Fe, and S and extremely low alkalis within the abraded rock, and it is interpreted as being composed of mafic minerals cemented by sulfates.

Spirit then descended the opposite side of the Columbia Hills towards a structure named Home Plate, where the first in situ detection of carbonates on Mars was made with the Mössbauer spectrometer (Morris et al. 2010). The outcrop Comanche contains about one-third Fe–Mg carbonates. The APXS suggested ~10% undetected light elements (carbon, oxygen) (Campbell et al. 2008) and facilitated quantification of the carbonates.

Due to a dragged frozen wheel, two very distinct types of bright subsurface soils were serendipitously discovered. **Figure 2**, top, shows that the Dead Sea soil is very rich in S, accompanied mostly by Fe and Mg. APXS scatter peaks indicated about 20% bound water (Campbell et al. 2008). These hydrated ferric sulfate–rich soils were found at several locations. A second type of whitish subsurface soil was exposed close to Home Plate (Squyres et al. 2008). Kenosha consists of ~90% SiO_2, with all other elements diminished except Ti and Cr. Virtually all these cases of aqueous alteration point towards habitable environments. The eolian duné field sample, Eldorado, is coarse-grained, maﬁc sand and contains lower amounts of Si, Cl, and Zn. In all measurements of fine-grained soils, these elements correlate well with each other, and they are enriched in the brighter surface dust, which is interpreted to be the result of volcanic exhalations.

**Opportunity**

Opportunity landed 2 weeks after Spirit on Meridiani Planum. The landscape is dominated by a vast, fine-grained sandstone, which is partially covered by windblown soil, dust, and millimeter-sized spherical concretions (blueberries), released during the erosion of the soft, sulfate-rich bedrock in which they form. Blueberries contain the hematite that had been detected from orbit. The plains are punctuated by impact craters, which expose deeper parts of the layered sedimentary bedrock. This bedrock, dubbed the Burns formation, contains about 25 wt% SO_3 (Fig. 3). The APXS documented precisely the continuation of Burns formation material along the ~30 km long traverse. **Figure 3** is a plot of elemental ratios, relative to Martian basaltic soil, of various rocks found on Meridiani. Guadeloupe, one of ~100 APXS spots in the Burns formation measured so far, is depleted in most elements compared to soil by ~20%, simply because of dilution through the addition of SO_3. Only Mg, Ni, and possibly P have higher values, indicating that Mg sulfate could be part of the salt assemblage. As Opportunity drove downhill into the ~100 m diameter Endurance Crater, it recorded a one-third drop in Mg and S and a threefold increase in Cl in abraded samples (Fig. 4),
again indicating that Mg sulfate is present. The depletion in Mg sulfate is compensated by an increase in an Al silicate phase, which was interpreted as due to groundwater percolating through the bedrock, dissolving and depositing minerals (Grotzinger et al. 2005). This conclusion was later confirmed when the same chemosтратigraphy was found about 8 km to the south in the much larger Victoria Crater (Squyres et al. 2009).

Iron meteorites and ejected basaltic blocks are readily identified in the bland landscape on Meridiani. Bounce Rock and Marquette, likely ejected from a crater elsewhere on Mars, plot as distinct compositions in Figure 3, extending our knowledge of basaltic rocks on Mars. Bounce Rock, a pyroxene-bearing rock, was the first rock measured on Mars that resembles a Martian meteorite in composition and mineralogy, specifically EETA79001B (Zipfel et al. 2011).

Around sol 2700, the mission entered an exciting new phase when Opportunity reached the 15 km wide crater Endeavour. The rim, which predates the Burns formation bedrock, shows evidence of the presence of clays (Arvidson et al. 2014). Clay formation could indicate a changing environment, from neutral to acidic conditions. At the rim, low-sulfur rocks with compositions similar to Martian soil were found. Two kinds of white veins—a vein 3 cm thick and protruding (Homestake) and thinner fracture fills in bedrock (Ortiz) (Squyres et al. 2012)—have high Ca and S in molar proportions corresponding to Ca sulfate. Some rocks around Endeavour show signs of alteration, possibly due to hydrothermal activity. Tisdale is high in $\text{P}_2\text{O}_5$ (3 wt%), with Ni, Zn, and Br up to several thousand parts per million. Esperance shows elevated $\text{Al}_2\text{O}_3$ and $\text{SiO}_2$ mineralogy, specifically EETA79001B (Zipfel et al. 2011).

Curiouity

The MSL rover Curiosity (Grotzinger et al. 2012) landed in August 2012 in Gale Crater, where it was to search for previously habitable environments. Gale Crater was selected because clay, hematite, and sulfate deposits had been detected in the central mound, called Mount Sharp, from orbit.

Curiosity’s traverse so far is shown in Figure 5, together with the locations of samples investigated with the APXS. While the soil in Gale is very similar to the soil at all other landing sites, the first rock analyzed was a surprise. Jake_M (Fig. 6) is a feldspar-rich rock and is characteristically high in Al, Na, and K but low in Mg, Fe, Ni, and Cr; its composition resembles that of terrestrial mugearites (Stolper et al. 2013). Jake_M-like compositions were found repeatedly in float rocks, as well as in sedimentary bedrock composed of conglomerate, sandstone, and mudstone/siltstone. Overall, the Gale Crater lithologies are significantly more felsic than those from all previous landing sites (possibly excepting Pathfinder’s site), with over half of all APXS measurements recording >0.7 wt% $\text{K}_2\text{O}$. In contrast, only one-tenth of the measurements in Gusev Crater have potassium at this level, and Meridiani has even less potassium; the global soils rarely exceed 0.5 wt% $\text{K}_2\text{O}$. The rock-forming particles in the sedimentary rocks are assumed to have been derived from alkaline igneous rocks located in the Gale Crater rim (Grotzinger et al. 2014; McLennan et al. 2014). Curiosity has stopped four times at bedrock to drill samples for the SAM and CheMin instruments (see Grotzinger et al. 2015 this issue for a description of the MSL instrument package). The first two drill holes were located a few meters apart in the Sheepbed mudstone, whereas the third drill hole was located ~5 km away at Kimberley (Fig. 5). Figure 6 shows the composition of the brushed rock called Wernecke, which is part of the Sheepbed. It has one of the lowest $\text{SO}_3$ values (1%) measured on Mars, while the concentrations of major elements are soil-like. CheMin found about 20% clay in this mudstone (Vaniman et al. 2014). An analysis of early diagenetic, cement-filled cracks showed Fe, Mg, and Cl in proportions that are consistent with the mineral akaganeite, detected by CheMin.

The mudstone at Yellowknife Bay has postlithification fractures that are filled with white minerals. The APXS raster analysis for Sajunei and the ~2 cm wide white rock Mavor indicate the presence of Ca sulfate. Two examples of dark, fine-grained sandstone, a common rock in the sedimentary record in Gale, were investigated in situ. Secure and Et Then, which are ~5 km apart, have very similar characteristics: high FeO (~26 wt %) and K, but low Mg, Ca, and Al. Both share a peculiar elevated Ga content of ~70 ppm but no significant Ge, which is usually present at levels of 50–100 ppm in the sandstone.

The third drill target, named Windjana, is a sandstone that forms part of the Kimberley outcrop. As Figure 6 shows, it is distinct from Yellowknife Bay rocks, being low in Na and Al and high in Fe (~26 wt% FeO), Mg, and especially K (>3 wt% $\text{K}_2\text{O}$). Windjana is also highly enriched in Zn (~4000 ppm) and Br, and overall is similar to a class of sandstones, named Bathurst, encountered around Yellowknife Bay. ChemCam LIBS shots exposed a greyish, shiny patch on a rock named Stephen with a consistently high Mn signal (Wiens et al. 2015 this issue). An APXS raster of Stephen revealed high MnO (~4 wt%), in addition to high Mg, Cl, K, Ni, Zn, Br, Cu, Ge, and Co (~300 ppm Co). A four-spot raster of Stephen shows a good correlation of Mn with Ni, Zn, and Cu. All spots have 3–3.5% Cl, the

**Figure 4**

Compositional changes with depth in Endurance Crater; this is the first chemosтратigraphic study on Mars. The elements shown are normalized to their content at the highest elevation (Tennessee). The changes indicate a decrease in Mg sulfate in deep layers and a simultaneous threefold increase in Cl.
The similarity of the APXS data from Stephen to the trace metal enrichments in deep-sea Mn nodules is striking (Gellert et al. 2014). The APXS is used for reconnaissance, drill-site selection, and many other investigations by the MSL rover. The data from the drill fines are used for XRD Rietveld analysis and to constrain the X-ray-amorphous component (Vaniman et al. 2014); the potassium measurement can be used for K–Ar dating of the rocks (Farley et al. 2014); and the contents of volatile and soluble elements, such as P, S, Cl, and Br, allow estimates of the composition of the water from which the rocks were deposited. In the future investigation of Mount Sharp, the capability of the APXS to quantify key elements will be of great importance for testing observations made by orbiter instruments and for making new, detailed, in situ discoveries of sulfates, clays, and other evidence of aqueous activity.

Several floats of the feldspar-rich Jake_M type were found with compositions nearly identical to the original Jake_M composition. Outcrops and conglomerates like Dismal_Lake show similar compositions, possibly indicating a mixing or common source region. Secure and Et Then are possibly part of the dark Capping unit. Wernecke is representative of the Yellowknife Bay mudstone that contains 30% clay. Note the general similarity in the rock compositions to soil composition, indicating isochemical weathering. The Windjana drill target at Kimberley is poorer in Na and Al but richer in K, Mg, and Fe. Potassium is variably enriched in Gale Crater compared to other landing sites.

The APXS is used for reconnaissance, drill-site selection, and many other investigations by the MSL rover. The data from the drill fines are used for XRD Rietveld analysis and to constrain the X-ray-amorphous component (Vaniman et al. 2014); the potassium measurement can be used for K–Ar dating of the rocks (Farley et al. 2014); and the contents of volatile and soluble elements, such as P, S, Cl, and Br, allow estimates of the composition of the water from which the rocks were deposited. In the future investigation of Mount Sharp, the capability of the APXS to quantify key elements will be of great importance for testing observations made by orbiter instruments and for making new, detailed, in situ discoveries of sulfates, clays, and other evidence of aqueous activity.
SUMMARY

The APXS has been used successfully on four NASA rovers. The compositional analyses of ~15 samples from Pathfinder, 220 samples from Spirit, 350 samples from Opportunity, and 150 samples from Curiosity have supported the rover science investigations and allowed detailed comparisons of the landing sites with the global soils investigated at the two Viking sites (Clark 1982). The capability to quantify bulk abundances of at least 16 geochemically important elements enables planetologists to relate new meteorites from Mars (e.g. Agee 2013) and orbiter data to all landing sites. APXS data are used to ground truth elemental and mineralogical measurements obtained from orbit.

ACKNOWLEDGMENTS

The APXS underwent decades of development with many key players. In particular, Rudolf Rieder, the original principal investigator for the APXS on Pathfinder, MER and Rosetta, made invaluable contributions, together with Heinrich Waenke.

The MSL APXS was financed and managed by the Canadian Space Agency, with MDA, Brampton, as prime subcontractor for the construction of the instrument. Operation of the MSL APXS is supported by the CSA contract 9F052-110786 and by NASA. The MER APXS was developed and built in the Cosmochemistry Department of the Max Planck Institute for Chemistry, Mainz, Germany, and was partly supported by the German Space Agency.

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The rover Curiosity is conducting X-ray diffraction experiments on the surface of Mars using the CheMin instrument. The analyses enable identification of the major and minor minerals, providing insight into the conditions under which the samples were formed or altered and, in turn, into past habitable environments on Mars. The CheMin instrument was developed over a twenty-year period, mainly through the efforts of scientists and engineers from NASA and DOE. Results from the first four experiments, at the Rocknest, John Klein, Cumberland, and Windjana sites, have been received and interpreted. The observed mineral assemblages are consistent with an environment hospitable to Earth-like life, if it existed on Mars.

Keywords: X-ray diffraction, Mars, Gale Crater, habitable environment, CheMin, Curiosity rover

INTRODUCTION

The Mars rover Curiosity landed in Gale Crater on August 6, 2012, and is making its way up the flanks of Mt. Sharp. One of the principal goals of the mission is to identify and characterize past habitable environments on Mars (Grotzinger et al. 2012; Meyer 2012). Determining the mineralogy and chemical compositions of Martian rocks and soils provides constraints on formation and alteration pathways, and consequently provides information on climate and habitability through time. Sample compositions are measured with the Mars Science Laboratory (MSL) in three ways: (1) ChemCam, which uses laser-induced breakdown spectroscopy to measure the composition of a spot smaller than ~550 µm from a distance of 7 m (Maurice et al. 2012); (2) Sample Analysis at Mars (SAM), which digests sieved or drilled powders in a furnace and measures their compositions by mass spectrometry (Mahaffy et al. 2012); and (3) the alpha particle X-ray spectrometer (APXS), which uses a combination of X-ray fluorescence and alpha particle induced X-ray emission (Gellert et al. 2015 this issue). X-ray diffraction on MSL is conducted with the chemistry and mineralogy instrument CheMin (Blake et al. 2012), which provides diffraction patterns of particles smaller than 150 µm and results in accurate and time-tested mineralogical identification and quantitative phase abundances. Minerals are natural crystalline materials with limited ranges of chemical composition. The century-old technique of X-ray diffraction is exquisitely sensitive to the crystal structure and secondarily sensitive to the chemical composition of minerals; as such, the CheMin instrument is used to identify the minerals and, through crystal-chemical calculations, to determine constraints on their empirical compositions.

The mineralogy of the Martian surface is dominated by the phases found in basalt and its ubiquitous weathering products. To date, the major basaltic minerals identified by CheMin include Mg–Fe-olivines, Mg–Fe–Ca-pyroxenes, and Na–Ca–K-feldspars, while minor primary minerals include magnetite and ilmenite. CheMin also identified secondary minerals formed during alteration of the basalts, such as calcium sulfates (anhydrite and bassanite), iron oxides (hematite and akaganite), pyrrhotite, clays, and quartz. These secondary minerals form and persist only in limited ranges of temperature, pressure, and ambient chemical conditions (i.e. humidity, water activity, Eh, pH, etc.), and provide clues about the habitability of Mars. A source rock, such as basalt, may be transformed into a range of different mineral assemblages depending on the physical and chemical conditions that it experiences. Thus, knowledge of the minerals in Martian environments provides insight about the conditions under which the samples were formed or altered and, in turn, about past, potentially habitable environments on Mars.

In addition to crystalline minerals, significant amounts of amorphous and poorly crystalline compounds occur on the Martian surface (Blake et al. 2013; Bish et al. 2013; Vaniman et al. 2014). These amorphous / poorly crystalline materials are not well understood, but they likely occur both as primary phases, such as volcanic and impact glasses, and as secondary phases, through the alteration of primary minerals. Their identification and characterization can lead to an understanding of how they formed. For instance, the presence of volcanic glass indicates that the glass has not undergone aqueous alteration since its formation because such glass weathers readily in the presence of water. In addition, the presence of poorly crystalline phases such as allophane and hisingerite indicates low-temperature alteration of volcanic glass and olivine, respectively. Orbital and in situ measurements of the amorphous / poorly crystalline material found globally in Martian soils suggest that it consists of at least three phases: nanophase iron oxide (Morris et al. 2008), an amorphous silicate consistent with altered volcanic glass, and amorphous sulfate (Vaniman et al. 2004; Chipera and Vaniman 2007). Along with these globally distributed amorphous components, there are local hydrated silica deposits in various places on Mars, such as Valles Marineris, western Hellas Basin, and the Nili Fossae region; their geologic settings suggest that they formed by aqueous alteration of preexisting crystalline or amorphous phases (Ehlmann et al. 2009).
THE DIFFRACTOMETER

X-ray diffraction techniques are the “gold standard” for identifying minerals, but the use of diffractometers on planetary missions has been problematic mainly because they are bulky and massive. They range from lab diffractometers that are generally the size of a double-wide refrigerator to the huge and powerful synchrotrons located in national laboratories that are from several hundred meters to several kilometers in circumference. In addition to their large size, the power requirements of X-ray sources are severe. The diffraction instruments in my lab operate at about 50,000 volts, and, before MSL, it seems that NASA had never sent a high-voltage power supply into space. Around 1990, in spite of these significant obstacles, Dave Blake, from NASA–Ames, and Dave Bish, Steve Chipera, and Dave Vaniman, from DOE–Los Alamos, independently came up with ideas to how to put a diffractometer into space. They met at a Lunar and Planetary Science Conference, where their posters were located next to each other, and decided to pool their respective talents to solve the problem. Materials scientist and engineer Philippe Sarrazin joined the team as a postdoc in 1994 to solve difficult practical problems and condense the instrument to the size of a breadbox (Fig. 1).

The instrument, described in detail by Blake et al. (2012), has a cobalt X-ray source that operates at a nominal voltage of 28 keV and a current of 100 μA. During an analysis, a collimated X-ray beam is directed through powdered or crushed sample material. An X-ray-sensitive CCD (charge-coupled device) detector is positioned on the opposite side of the sample from the source and directly detects X-rays diffracted or fluoresced by the sample (Fig. 2). The CCD detector is operated in single-photon counting mode (the detector is read out sufficiently often that most pixels contain either no charge or charge derived from a single photon). When operated in this manner, the CCD can be used to measure the amount of charge generated by each photon (and hence its energy). Diffracted characteristic X-rays strike the detector and are identified by their energy (with CheMin, CoKα X-rays with an energy of 6.929 keV are selected). Energy discrimination is important not only to reduce the sample-generated X-ray fluorescence background from a diffraction pattern but also to remove the signals from cosmic rays and high-energy protons and neutrons from Curiosity’s Radioisotope Thermal Generator power source (illustrated in Fig. 12 of Blake et al. 2012). CheMin’s angular range of 5° to 50° with <0.35° 2θ resolution is sufficient to identify and quantify virtually all minerals.

This setup is not too different from the original diffraction geometry of Bragg and von Laue, except that they used photographic film instead of a CCD detector. What truly differs, however, is the way the sample is processed. Powder diffraction studies on Earth typically utilize samples that are ground into a fine powder ideally consisting of ~5 μm diameter grains, and the grains are carefully placed into the diffraction position on the instrument. On Mars, we do not have the luxury of grinding samples into fine powders. Instead, we sieve the unconsolidated dust, sand, or drill tailings with Curiosity’s CHIMRA processing system to <150 μm (Anderson et al. 2012) and drop the sieved sample into an automated shaker, which consists of a small sample chamber with transparent, plastic windows attached to piezoelectric actuators that vibrate the sample like a tuning fork at ~2000 Hz. This shaker sends the grains into convective motions (as shown in Figs. 3 and 6–8 of Blake et al. 2012). The constant movement of grains allows the X-ray beam to sample crystals in an endless stream of random orientations that, over time, provide a two-dimensional powder diffraction pattern collected as bitmaps from the CCD (Fig. 3). The bitmaps are downloaded from Mars when transmission time and bandwidth are available, and, after 20–25 hours of collecting data, the diffraction pattern is ready to be analyzed. It is first converted into the typical one-dimensional pattern familiar to most scientists, as shown in Figure 3. In the event that the instrument gets clogged, there is a “chaos” mode of larger-amplitude vibrations. We actually found that our nominal vibration during data collection was too strong, and we were losing sample from the top of the cell. To decrease the vibration, we invented the “kumbayatic” mode, where a neighboring cell vibrates strongly enough to induce grain circulation but the sample cell itself is not being vibrated. For most samples, however, we now vibrate the cell directly, but at the lowest-possible energy.
The design and successful operation of the CheMin instrument are remarkable engineering feats! An operating diffractometer was reduced to the size of a breadbox, furthering the tradition of NASA and JPL engineering to miniaturize its instruments, making them increasingly portable. Someday we will probably use NASA-engineered devices built into our cell phones for identifying and characterizing many materials, like the fictional tricorder device used on the television show Star Trek. The development and deployment of CheMin are good examples of the process necessary to put an instrument into space. It took 22 years of work on the project to get the instrument ready to fly. I saw an eight-page list of proposal titles related to the development of CheMin, and most proposals were closed and labeled as “Failed” or “Denied.” To get an instrument into space requires not only a good idea, but more importantly, bullheaded perseverance. In recognition of the breakthroughs in technologies, the CheMin instrument and design have won several prestigious awards, including the 1999 R&D Magazine R&D 100 Award for outstanding technology developments with commercial potential; the 2009 Pittcon Gold Medal for “Best New Product” for CheMin commercial derivatives; the 2010 NASA Commercial Invention of the Year, focused on the sample-handling techniques; the 2011 FLC Far West Regional Award for outstanding commercialization success; and the 2013 Government Invention of the Year. There is a strong culture at NASA to turn its research into benefits for society, and CheMin has demonstrated success here too. The larger agencies of the federal government are required to put monies from their research budget into the Small Business Innovation Research program, which fosters technological innovation in the small business sector and the creation of commercially successful products. The CheMin instrument was commercialized by the company inXitu as a portable bench-top instrument; it is now available through Olympus Instruments and can be operated in the field without significant training (Fig. 4).

ANALYSES AT ROCKNEST

At the time of this writing, the CheMin team has analyzed the data from four samples that represent the lithologies and soils present in the Aeolis Palus region where Curiosity landed (Grotzinger et al. 2015 this issue). The first sample, unconsolidated sand from a small eolian dune called Rocknest, was fed into the instrument on sol 94 (Blake et al. 2013; Bish et al. 2013). The second and third samples were drill tailings from the Sheepbed mudstone at Yellowknife Bay (Vaniman et al. 2014) and were collected on sol 195 (John Klein sample) and sol 282 (Cumberland sample). The fourth sample was drilled on sol 621 (Windjana sample) from fine-grained sandstone at the Kimberley outcrop, as Curiosity made its final approach to Mt. Sharp. At the time of writing, a fifth sample is being processed from a location called Pahrump; this is probably Curiosity’s first opportunity to sample the Murray formation, which comprises the basal stratigraphic unit at Mt. Sharp. See Mahaffy et al. (2015 this issue) for a map of sample locations.

Mars is dusty, although not as dusty as the Moon, and there is plenty of unconsolidated “dirt” lying about (Yen et al. 2005). A fine dust layer coats every available surface. Dust devils have been recorded racing around on the surface of Mars, and dust storms encompassing the entire planet are occasionally observed. In some places the dust collects in eolian deposits of fine to coarse sands. Because these eolian deposits, dust aggregates, and dusty soils are found all over the planet, every mission has had an opportunity to sample them. They display a remarkably homogeneous chemical composition, no matter where the dust is sampled, confirming that the material is circulated and mixed through these planet-wide dust storms. The APXS chemical analyses conducted at Rocknest corroborate the earlier compositional measurements of fine-grained, wind-transported materials (Blake et al. 2013). The eolian

**Figure 3** A two-dimensional diffraction pattern collected on the CCD from the eolian soil at Rocknest is shown in the lower panel, and the fitted one-dimensional diffraction pattern is shown in the top panel. Two-dimensional data from the CCD are converted into a one-dimensional pattern that is processed using Rietveld and FULLPAT fitting routines to determine mineral phases and their cell parameters. In the one-dimensional pattern, plotted as intensity (counts) versus detection angle of the diffractometer (degrees 2-theta), the blue line is measured, the red line is fitted, and the grey line is the difference between the two.
Feldspar fragments on Mars, including several gemmy

The commercial spinoff version of CheMin, known as Rietveld refi nement (Bruker AXS 2000) and a combination of two rather recent analytical techniques were modeled as a mixture of crystalline and amorphous components. The crystalline components include feldspar (41% by weight of crystalline component), pyroxene (28%), olivine (22%), and some minor phases (as summarized in Table 1 of Bish et al. 2013). The diffraction patterns of the major phases were intense and sharp enough to allow determination of their cell parameters. In addition, the diffraction pattern appears to ride on a major hump, in the 15–40° 2θ region, which is due to the amorphous components (FIG. 3, TOP PANEL). We model its abundance as 13–40% of the total sample weight.

The cell parameters of the major phases were optimized during the Rietveld fit and were precise enough to provide meaningful constraints on the compositions of the minerals. For instance, the cell parameters of Mg–Fe-olivine form a well-deﬁned linear trend that increases with iron concentration. Morrison et al. (2013) estimated the chemical compositions of the olivine, pyroxenes, and feldspar at Rocknest. In particular, they reported that the iron content of olivine was 0.88 atoms per formula unit (apfu), which can also be expressed as (Mg0.12Fe0.88)2SiO4 or F056Fa44. On Earth, typical mantle olivine, say the well-studied material from San Carlos, Arizona, has an iron content of about 0.18 apfu, or Fo91Fa9. If the Rocknest dune represents a global average, then the average olivine on Mars is Fo056Fa44 (Morrison et al. 2013). Indeed, there is more iron on the surface of Mars than there is on the surface of Earth! The composition of pyroxene has been estimated in a similar way and shown to include a Ca component along with Mg and Fe.

Feldspar is not as simple to model as pyroxene and olivine because the crystal-chemical trends are not linear. Not only do Na, K, and Ca variations affect feldspar’s cell parameters but so does the ordering of Al and Si in feldspar’s tetrahedral sites. In spite of these variables and the large uncertainties in composition, the feldspar data yielded the formula (Ca0.52(12)Na0.48)(Al1.52Si2.48)O8, which corresponds approximately to labradorite or andesine composition. Portions of what appears to be plagioclase have also been seen in some of the photos (Edgett et al. 2013). In FIGURE 5, gemmy fragments of plagioclase can be seen lying in the sands of Mars. Coincidentally, a basaltic lava flow in the Pinacate mountains of northwestern Sonora, Mexico, also yields large gemmy fragments of labradorite, which are used to produce cut gemstones (Fig. 5). These fragments may prove to be good analogues for what is observed on Mars. After an extensive analysis of the mineralogy and composition of the Rocknest sample, the science team concluded that the sands of Mars are similar to the weathered basaltic soils of Mauna Kea, Hawaii (Bish et al. 2013).

Another important result came from the Rocknest site. The ability to estimate the chemical compositions of the crystalline components of the Rocknest eolian deposit permits us to determine the bulk composition of the crystalline materials (Morrison et al. 2013). By coupling this bulk composition with the APXS-derived composition of the entire rock (Gellert et al. 2015), we can constrain the composition of the amorphous component. While previous Martian missions measured the composition of the sand, there was no way to partition this into individual mineral phases. The best that could be done was to apply sensible mineralogical models that were consistent with the composition. With this strategy in mind, Table 4 of Blake
et al. (2013) provides an estimate of the compositions of both the crystalline component deduced from the CheMin diffraction profile and the amorphous component derived from the assumption that the overall composition from APXS is amorphous + crystalline. A limiting constraint on the amorphous composition is the assumption that it does not contain Mg. This seems reasonable because if all the Mg is present in the crystalline component, there is still an excess of every other oxide component. This constraint puts a lower limit on the amorphous component of the sand at 37 wt%, with a major-oxide composition of $\text{SO}_3 + 3\text{FeO} + 4\text{SiO}_2$.

**ANALYSIS AT YELLOWKNIFE BAY**

Based on regional mapping of the landing site, coupled with knowledge of thermal inertia mapped from orbit, the science team decided to investigate a 5 m thick sequence of sedimentary rocks exposed about 450 m east of the landing site (Grotzinger et al. 2014). Called the Yellowknife Bay formation, these rocks comprise an upper assemblage of largely fluvial sandstones and conglomerates, which overlie a basal lacustrine mudstone known as the Sheepbed member. Collectively, these rocks could represent an ancient habitable environment that lasted at least hundreds to thousands of years, and perhaps as much as millions of years. In this environment, water would have been flowing in streams, collecting in a lake, and penetrating into the subsurface via pores and fractures (Grotzinger 2014). Investigating the mineralogy of the mudstone could provide clues about the ancient environment. Accordingly, two samples from two drill sites about 3 m apart, named John Klein and Cumberland, were sent to CheMin for analysis. The analysis proceeded much as it did for the sand at Rocknest. A two-dimensional X-ray diffraction pattern, similar in appearance to that shown in Figure 3, was collected using the CCD detector. This pattern was sent to Earth, where it was processed and turned into a one-dimensional pattern similar to that also shown in Figure 3 and analyzed using the Rietveld and FULLPAT methods. Whereas the Rocknest sand analysis indicated Hawaiian-like basaltic soil, the mudstone revealed the smoking gun for demonstrating habitability (Grotzinger et al. 2014; McLennan et al. 2014; Ming et al. 2014; Vaniman et al. 2014). As a result of chemical weathering of the olivine grains in the detrital basaltic mix, the mudstones contain significant amounts of trioctahedral saponitic smectite clay along with magnetite. The pyroxene, feldspar, and olivine peak positions are the same as those measured at Rocknest, demonstrating that the compositions of the respective mineral species at the two sites are similar. Diffraction signals for minor Ca sulfate in the forms of bassanite and anhydrite were observed, along with pyrrhotite (an iron sulfide). The presence of smectite and the absence of sulfate minerals that form in acidic environments are evidence of near-neutral pH in a freshwater lake with low salinity. The mixed valence states of iron in the magnetite and sulfur in sulfide and sulfate indicate that the environment had a variable redox potential. The mineralogy of the mudstone is consistent with an environment that would have been hospitable to life as we know it. A detailed analysis of the clay and a discussion of olivine reaction pathways that could have provided energy for chemolithotrophic life (life forms, such as bacteria, that derive their energy from the oxidation of inorganic compounds of iron, nitrogen, sulfur or hydrogen) are given in Bristow et al. (in press).

**ANALYSIS AT WINDJANA**

Initial results from the Windjana sandstone demonstrate the presence of the following major components: augite (21%), monoclinic sanidine or orthoclase (15%), pigeonite (12%), magnetite (10%), clay (8%), and amorphous / poorly crystalline phases (20%). Abundant magnetite and potassium feldspar is a surprise, and more work is needed before firm conclusions are drawn. However, this sample may provide evidence that the sedimentary material came from a differentiated source area—perhaps an alkaline igneous province, first hinted at by the compositional analysis of float rocks early in this mission (Stolper et al. 2013). The presence of substantial quantities of fine-grained clay minerals in the coarser-grained sedimentary rock indicates that the sandstone may have experienced aqueous alteration.

**EARTH ANALOGUES FOR MARTIAN SAMPLES**

Until we are able to return samples from Mars for further analyses, a fruitful way to investigate Martian mineralogy and geologic processes is to work on analogue materials. What samples on Earth are similar to samples from Mars? It is well known that NASA will go to great lengths and will travel to extremely remote locations to get samples for study. So, anticipating such a field trip, it was a surprise for the CheMin team members to find out that the analogue material most similar to the clay minerals in the Sheepbed mudstone are the clays associated with the basalts at Griffith Park, Los Angeles, a 20-minute drive from the Jet Propulsion Laboratory. The Griffith Park clays are so unusual that they were originally given their own mineral name, griffithite (Larsen and Steiger 1917); however, they have since been found to be an iron-rich variety of saponite. The team conducted several field trips to collect samples of the material at Griffith Park in order to study it and understand the reaction pathways that led to its formation (Treiman et al. 2014). Figure 5 illustrates the incongruosity of studying minerals on Earth that are analogues of minerals on Mars; the sample site is located at its formation (Treiman et al. 2014). Figure 5 illustrates the incongruosity of studying minerals on Earth that are analogues of minerals on Mars; the sample site is located
near the famous Hollywood sign and next to the Bronson bat cave from the Batman TV series of the 1960s, and is home to a hundred B-grade science fiction movies about alien invasions. Considering all the places on Earth that could be similar to a habitable zone on Mars, the presence of analogue clays in Hollywood is amazing! Fortunately, the easy access to Griffith Park has helped us procure materials containing valuable information on the interactions among clays, magnetite, and olivine that may hold important clues about the habitability of the environment on Mars at the time the mudstones were being deposited and during subsequent geochemical changes.

CONCLUSIONS

The minerals and assemblages identified by the CheMin and MSL teams demonstrate that the ancient surface of Mars in Gale Crater was habitable for chemolithotrophic microbes, if such organisms ever evolved on Mars. Water pH was near neutral, freshwater ran in streams, and, if it existed, would have found the locations sampled by Curiosity to be hospitable. All the identified minerals are common on Earth. The amorphous material is not understood well enough yet, but the planet-wide Martian sand is made of the same minerals as the fertile soils of Hawaii. According to Hazen et al. (2008), the minerals of a planet should coevolve with biological activity, but none of the observations made so far in Gale Crater point to minerals whose origin and distribution require the presence of life. On Earth we have deposits of banded iron formation that some think record the global oxidation event associated with the advent of photosynthesis (Knoll et al. 2012). However, this is a far more advanced metabolic pathway than the chemolithotrophic metabolism suggested by CheMin and other MSL observations (Grotzinger et al. 2014).

ACKNOWLEDGMENTS

I thank reviewers Bob Hazen and Nick Tosca and editors John Grotzinger, Gordon Brown, and Jodi Rosso for their constructive comments. Support from the NASA Mars Science Laboratory Mission is gratefully acknowledged.

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Volatile and Isotopic Imprints of Ancient Mars

Paul R. Mahaffy¹, Pamela G. Conrad², and the MSL Science Team

The investigations by Curiosity rover as part of the Mars Science Laboratory (MSL) mission were designed to explore the geology and geochemistry in Gale Crater (Grotzinger 2009) and to determine and evaluate the habitability potential at present and in the past. The fundamental parameters of a habitable environment are the presence of liquid water and sources of energy to feed metabolism of even the simplest of prokaryotic organisms. Chemical attributes, such as the availability of elements necessary for life (e.g. C, H, O, N, etc.) and redox state, and environmental physical characteristics, such as temperature excursions and ionizing radiation, also play critical roles in determining the habitability of Martian environments. In the case of Mars, orbital characteristics (such as changes in the axial tilt, or obliquity; Touma and Wisdom 1993), the size of the planet relative to Venus and Earth, its distance from the Sun, gravitational perturbations by migrating giant planets, and impacting asteroids have profoundly influenced its evolution and have certainly had a significant impact on surface environmental conditions and habitability. Moreover, the early loss of a magnetic dynamo, as indicated by remnant crustal magnetization data (Acuna et al. 1999), and evidence for a lack of recent extensive crustal recycling through Earth-like plate tectonics (Yin 2012) are factors that caused environments on Mars to diverge dramatically from those on Earth. The prevalence or rarity of liquid water also carries consequences for habitability. There is much evidence that liquid water was abundant on the surface of early Mars, but an outstanding question is how long conditions favorable for the emergence and sustenance of early microbial life could have persisted (Fig. 1).

The ambitious investigations by Curiosity will advance our understanding of environmental evolution and habitability by making a wide range of measurements. Here we provide an overview of the volatile and isotopic measurements made by Curiosity that not only may help us to understand current surface environments but also may document milestones in the evolution of Mars. These data provide information on atmospheric loss; on the chemical composition, isotopic composition, and redox states of soils and rocks; on the clays that preserve an isotopic signature from more than 3 billion years ago; and on the signatures in surface rocks of nuclear transformations caused by cosmic radiation. The search for methane in the atmosphere and organic compounds in the rocks are also core mission objectives. Although the central mound of Gale Crater (Mt. Sharp), with its layers of clays and hydrated minerals—evident from orbital spectroscopy (e.g. Milliken et al. 2010)—is a primary exploration target,

**Keywords:** Mars, organics, Gale Crater, isotopes, habitability, Curiosity rover

**INTRODUCTION**

The investigations by Curiosity rover as part of the Mars Science Laboratory (MSL) mission were designed to explore the geology and geochemistry in Gale Crater (Grotzinger 2009) and to determine and evaluate the habitability potential at present and in the past. The fundamental parameters of a habitable environment are the presence of liquid water and sources of energy to feed metabolism of even the simplest of prokaryotic organisms. Chemical attributes, such as the availability of elements necessary for life (e.g. C, H, O, N, etc.) and redox state, and environmental physical characteristics, such as temperature excursions and ionizing radiation, also play critical roles in determining the habitability of Martian environments. In the case of Mars, orbital characteristics (such as changes in the axial tilt, or obliquity; Touma and Wisdom 1993), the size of the planet relative to Venus and Earth, its distance from the Sun, gravitational perturbations by migrating giant planets, and impacting asteroids have profoundly influenced its evolution and have certainly had a significant impact on surface environmental conditions and habitability. Moreover, the early loss of a magnetic dynamo, as indicated by remnant crustal magnetization data (Acuna et al. 1999), and evidence for a lack of recent extensive crustal recycling through Earth-like plate tectonics (Yin 2012) are factors that caused environments on Mars to diverge dramatically from those on Earth. The prevalence or rarity of liquid water also carries consequences for habitability. There is much evidence that liquid water was abundant on the surface of early Mars, but an outstanding question is how long conditions favorable for the emergence and sustenance of early microbial life could have persisted (Fig. 1).

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the landing site fortuitously provided the mission with an opportunity to meet mission goals more immediately in Yellowknife Bay (Fig. 2).

WHY SAM?
The Sample Analysis at Mars (SAM) instrument suite is a chemical laboratory (Mahaffy et al. 2012) miniaturized to the size of a microwave oven to fit in the belly of Curiosity (Fig. 3) and was selected to complement the capabilities of nine other science instruments. With 54 valves, dozens of heaters, 2 turbomolecular pumps, gas getters and scrubbers, thermoelectric cooler–driven hydrocarbon traps, pressurized helium tanks, multiple calibration samples, a sample manipulation system, and a sophisticated experiment sequencer implemented on a powerful central processing unit (CPU), it is the most complex instrument to have operated on another planetary surface. SAM’s three instruments are a tunable laser spectrometer (TLS) designed to measure carbon dioxide and water and their isotopes and to search for trace levels of methane; a quadrupole mass spectrometer (QMS) with a mass range of 2–535 daltons; and a gas chromatograph designed to work with the mass spectrometer (GCMS) mode in the search for organic compounds in surface materials. Primary measurement modes of SAM are listed in Table 1. In order to use the power resources efficiently, SAM typically operates at night when the rover is stationary and its CPU is asleep.

ATMOSPHERIC TRACERS OF LOSS TO SPACE
The isotopic composition of the noble gases and the light elements C, O, N, and H in the atmospheric gases CO₂, N₂, and H₂O reflects both the sources of these gases and the
processes that isotopically fractionate them over billions of years. Gas sources include initial outgassing of the mantle shortly after the formation of Mars (Elkins-Tanton et al. 2005), volcanic venting over most of the history of Mars, and exogenous input from meteorites and larger bodies such as asteroids and comets (Owen et al. 1992; Lunine et al. 2003). Atmospheric loss can be to surface reservoirs through weathering or precipitation and/or to space through a variety of mechanisms (e.g. Jakosky and Jones 1997). Such mechanisms include early hydrodynamic escape, thermal escape, sputtering erosion by ions picked up and accelerated into the top of the atmosphere by the fields of the solar wind, and dissociative recombination. In this latter mechanism, an electron and an ion recombine in the upper atmosphere, resulting in an atom with sufficient energy to escape the gravity of Mars. Atmospheric loss to space preferentially removes the lighter isotopes, leaving the atmosphere enriched in the heavier isotope (e.g. Bogard et al. 2001; Pepin 2006).

Previous in situ measurements of isotope ratios in a variety of gases provided by instruments on the Viking missions (Biemann et al. 1976), ground-based spectroscopy (e.g. Krasnopolsky et al. 2007), and analysis of Martian meteorites (e.g. Bogard et al. 2001) were refined during the early stages of the MSL mission using experiments carried out by SAM’s TLS (Webster et al. 2013) and QMS (Atreya et al. 2013; Mahaffy et al. 2013; Wong et al. 2013). Each of the elements studied showed the imprint of atmospheric escape (Fig. 4; Table 2). It is evident that this mechanism dominates in the case of the relevant isotopes in argon, water, nitrogen, and carbon dioxide. One ratio of particular importance is the primordial $^{36}\text{Ar}/^{38}\text{Ar}$. Argon, once released to the atmosphere, does not return to surface reservoirs; thus, it provides one of the cleanest measurements of long-term atmospheric escape. Models of the extent of atmospheric loss established by this isotope pair alone (Hutchins and Jakosky 1996) lead to an estimate of loss that is at least several times the volume of gas in the present atmosphere.

### GASES EVOLVED FROM ANCIENT LAKE BED SEDIMENTS

The first rocks drilled by Curiosity at Yellowknife Bay were found to be mudstones containing ~20% smectite clay in addition to the basaltic primary silicate minerals feldspar, pyroxene, and olivine. The presence of phyllosilicates was confirmed independently (Vaniman et al. 2014) by Curiosity’s X-ray diffractometer (CheMin), and it is consistent with the observation of a high-temperature water release in evolved gas analysis (EGA) mode by SAM (Ming et al. 2014). Nodules and lighter-tone veins observed in the rock suggest subsequent diagenesis (Grotzinger et al. 2014). Gases thermally released by heating tens of milligrams of drilled material to ~900 °C utilizing a continuous temperature increase (Fig. 5) included, in decreasing order of abundance, H$_2$O, SO$_2$, CO$_2$, O$_2$, H$_2$, NO, H$_2$S, and HCl, as well as trace hydrocarbons. The volatile sources constituted ~5% of the mass of the sample and revealed the

### Table 2  HEAVY ISOTOPES IN ATMOSPHERIC GAS DEMONSTRATE ATMOSPHERIC ESCAPE

<table>
<thead>
<tr>
<th>Isotope Pair/Gas</th>
<th>Isotope Ratio*</th>
<th>Notes**</th>
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<tr>
<td>$^{13}\text{C}/^{12}\text{C}$ in CO$_2$</td>
<td>$\delta^{13}\text{C} = 46 \pm 4%$</td>
<td>Mode ATM-D: TLS$^a$ and QMS$^b$ multiple runs</td>
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<tr>
<td>$^{18}\text{O}/^{16}\text{O}$ in CO$_2$</td>
<td>$\delta^{18}\text{O} = 48 \pm 5%$</td>
<td>Mode ATM-D: TLS$^a$ and QMS$^b$ multiple runs</td>
</tr>
<tr>
<td>$^{17}\text{O}/^{16}\text{O}$ in CO$_2$</td>
<td>$\delta^{17}\text{O} = 25 \pm 5%$</td>
<td>Mode ATM-D: TLS$^a$ and QMS$^b$ multiple runs</td>
</tr>
<tr>
<td>D/H in H$_2$O</td>
<td>$\delta D = 4950 \pm 1080%$</td>
<td>ATM-D single TLS$^a$ run / low water abundance</td>
</tr>
<tr>
<td>$^{36}\text{Ar}/^{38}\text{Ar}$</td>
<td>Ratio = 4.2 ± 0.1</td>
<td>Mode ATM-E: QMS$^c$ runs, solar value = 5.5</td>
</tr>
<tr>
<td>$^{15}\text{N}/^{14}\text{N}$</td>
<td>$\delta^{15}\text{N} = 572 \pm 82%$</td>
<td>Mode ATM-E: QMS$^d$ runs</td>
</tr>
</tbody>
</table>

* calculated as ((isotopic ratio$_\text{sample}$/isotopic ratio$_\text{standard}$) − 1) × 1000‰; error reported is two times standard error of the mean

** ATM-D designates direct atmospheric sampling; ATM-E designates atmospheric sampling with enrichment; see, for example, $^a$ Webster et al. (2013); $^b$ Mahaffy et al. (2013); $^c$ Atreya et al. (2013); $^d$ Wong et al. (2013)
**Table 3** Gases evolved from Yellowknife Bay mudstones

<table>
<thead>
<tr>
<th>Gas or Gas Pair</th>
<th>Interpretation/Significance*</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2O</td>
<td>Smectite signatures of low- and high-temperature water release</td>
</tr>
<tr>
<td>O2 plus HCl</td>
<td>Coincident release consistent with oxchloride compound</td>
</tr>
<tr>
<td>CO2 plus O2</td>
<td>Coincident release suggestive of combustion of organic compounds or degradation of nanophase carbonates</td>
</tr>
<tr>
<td>SO2 plus H2S</td>
<td>Presence of oxidized and reduced sulfur, which illustrates chemical disequilibrium</td>
</tr>
</tbody>
</table>

* After Ming et al. (2014)

following features: smectite clay signatures from characteristic low and high temperatures of water release; degradation of an oxchlorine compound; possible self-combustion of organic compounds by the oxygen released from the oxchloride compound; the presence of both reduced and oxidized sulfur compounds; and a small number of trace organic compounds that survived the self-combustion. These results are summarized in Table 3. When these results were combined with the elemental and mineralogical data obtained by other instruments on MSL and the stratigraphic context inferred from images acquired by Curiosity’s cameras, it was concluded that Curiosity had the stratigraphic context inferred from images acquired by Curiosity’s cameras, it was concluded that Curiosity had a formed scarp that started the noble gas production clock on the sample analyzed by SAM at about 78 million years ago, when the ancient rock’s scarp face was exposed. This result motivated the MSL science and operations teams to search for the most recently exposed materials near the base of an outcrop (Fig. 6); this would optimize the possibility of finding organic compounds only minimally transformed after deposition of the host sediments.

**D/H Ratio Locked into Ancient Clays**

Water released from the mudstone samples at low temperature included adsorbed water, water from hydrated compounds in the amorphous fraction of the samples, and interlayer water in the smectite clays derived from basalt alteration (Fig. 5). Water released at high temperature, on the other hand, resulted from the dehydroxylation of the OH groups in these clays. Because OH is structurally bound once the clays are formed, its thermal decomposition should reflect the deuterium/hydrogen (D/H) ratio of the water in which the clay precipitated. Multiple thermal evolved-gas analyses were carried out on samples of Yellowknife Bay mudstones, and the D/H ratio of the evolved water was measured using both the QMS and the TLS. A clear trend was observed: D/H decreased as the release temperature increased, and low-temperature released water showed a D/H value close to Mars’ atmospheric value of ~6 times that of Earth’s standard mean ocean water (SMOW). However, mixing of the low- and high-temperature components in the nominal SAM EGA experiment prevented a clean measurement of the D/H ratio in the high-temperature water release, so a special stepped-heating experiment was designed and implemented to remove the water that initially evolves over an extended time period below 550°C. The subsequent release of water gave a consistent D/H value halfway between SMOW and the current greatly enriched atmospheric value (Mahaffy et al. 2015). This experiment showed that at the time of clay formation in

**Radiogenic and Cosmogenic Noble Gas Isotopes**

By removing the chemically active gases with SAM’s scrubber and getter through the heating of ~150 mg of a powdered Yellowknife Bay sample to ~900°C, evolved volumes of 3He, 21Ne, 36Ar, and 40Ar were measured (Farley et al. 2014). With the thin Martian atmosphere, high-energy cosmic radiation penetrates only the first 2–3 meters of the surface, producing spallation products (including 3He, 21Ne, and 36Ar) and neutron-capture products (including 40Ar). A near-surface exposure age of 78 ± 30 million years was independently determined using these three noble gas measurements. 40Ar, on the other hand, is produced primarily from the radiogenic decay of potassium, and the SAM measurement of 40Ar combined with potassium measurements from the alpha particle X-ray spectrometer enabled a rock formation age of 4.21 ± 0.35 billion years to be determined. Even with uncertainties regarding the partitioning of potassium between the basaltic and amorphous portions of the sample, the measurement allowed us to conclude with 95% confidence that the materials in the Gale Crater wall that washed down to form these mudstones are older than 3.6 billion years. This is consistent with the cratering record in the source region for these materials.

The exposure-age results have important implications for the MSL mission objective to find organic compounds produced on ancient Mars because long, near-surface exposure to cosmic radiation can destroy or transform these organic compounds (e.g. Pavlov et al. 2012). The combined 3He, 21Ne, and 36Ar cosmic radiation exposure-age results were interpreted in the context of a mechanical-weathering model in which wind-driven dust and sand erosion produced a scarp that started the noble gas production

**Figure 5** The major gases (A) and minor gases (B) evolved from a Yellowknife Bay sample (from Ming et al. 2014). Used with permission.
the Yellowknife Bay aqueous environment, substantial atmospheric loss must have already taken place, if we make the reasonable assumption that the D/H ratios of early Earth and Mars were similar.

THE ONGOING SEARCH FOR MARTIAN ORGANICS

If early microbial life existed on Mars, the most direct evidence for not only an ancient habitable environment but also an occupied habitat could come from molecular fossils of microbes. On Earth, examples of these biosignatures at the chemical level include the utilization by life of a limited set of amino acids, which are the building blocks of proteins, and the ordered odd/even patterns in long-chain hydrocarbons, which make up cell walls. In addition to this molecular order imposed by life, biological activity also leaves its imprint on isotope ratios such as $^{13}$C/$^{12}$C and $^{15}$N/$^{14}$N because metabolism uses the most energetically efficient paths. The MSL mission goal is to identify and characterize a habitable environment, not to find extant or extinct life. However, if near-surface organic compounds are found in a potentially habitable environment, then the search for biosignatures can become much more focused in the future, using robotic in situ explorers or by returning samples to Earth for more detailed analysis. The organic compounds that are the target of the MSL mission could originate from indigenous geochemistry (Steele et al. 2012a, b), from life, or simply represent exogenous organic compounds that rain down on Mars at the rate of 240,000 kg per year or more (Flynn and McKay 1990) as a result of meteorite and interstellar dust infall. This deposition of micrograms of organic compounds per square meter on Mars every year could be expected to produce tens of parts per million of organics if there were no organic destruction and if mixing in the regolith over billions of years were only to a depth of tens of meters.

Many environmental factors on present-day Mars conspire to oxidize and degrade organics. Ultraviolet radiation passes readily through the thin Martian atmosphere; hydrogen peroxide is present in the atmosphere and periodically increases in the soil as a result of chemical reactions induced by dust (Atreya et al. 2006); organics are oxidized by compounds such as superoxides (e.g. Yen et al. 2000) or peroxides (e.g. Leshin et al. 2013) in the soil; and organics are transformed by high-energy solar and cosmic particles that are minimally impeded by the thin Martian atmosphere.

In the distant past, a thicker atmosphere and a less oxidizing surface environment may have limited these effects. Thus the strategy to be used in a search for ancient organic compounds must focus on locating sites where organic compounds were present in ancient times, where plausible sedimentary processes concentrated organic materials during deposition, and where rapid burial preserved and protected them from ionizing radiation until relatively recent exposure allowed their detection. The recent SAM analysis of Yellowknife Bay rocks allows some optimism that this strategy may be successful, with the determination of a cosmic radiation exposure age, the discovery of indications of possible self-combustion of organic compounds to produce CO$_2$ as the oxychloride compounds decompose, and the detection of traces of simple chlorinated organic compounds.

SUMMARY

The latest generation of tools to locate and demonstrate the existence of a habitable environment has now been successfully used by Curiosity in the Yellowknife Bay formation on the floor of Gale Crater. As a result of the volatiles investigation by Curiosity, we have provided information on carbon, chlorine, oxygen, sulfur, and nitrogen compounds in rocks, made the first in situ rock age determination on another planet; characterized the cosmic radiation that can transform organic compounds; and measured the deuterium to hydrogen ratio in clay minerals that are our tie point to an ancient environment. The clays, sulfates, and hydrated-mineral layers of Mt. Sharp have been identified as prime exploration targets for Mars Science Laboratory’s extended mission. The detailed compositional and isotopic studies of the Martian volatiles that SAM has made provide important information about the environmental conditions on early Mars. Could Mars have supported microbial life at or before the time it emerged on Earth? This intriguing question continues to motivate our current and future exploration of our neighboring terrestrial planet.
REFERENCES


POWERFUL AUTOMATED MINERALOGY SOLUTION

TIMA

Extremely fast and fully automated data acquisition process

4 fully integrated EDX detectors
THE 27th INTERNATIONAL APPLIED GEOCHEMISTRY SYMPOSIUM (APRIL 2015)

The Association of Applied Geochemists will host the 27th International Applied Geochemistry Symposium (IAGS) in Tucson, Arizona, USA, on April 20–24, 2015. This symposium is the world’s premier forum for the exchange of ideas on issues related to the use of geochemistry in the mineral resources industry, advances in geochemical analytical methods, and environmental geochemistry. The theme of the meeting will be “Applied Geochemistry: Exploration, Environmental Technologies, and Sample/Data Analysis.” A comprehensive program is planned, with multiple keynote speakers, parallel technical sessions, short courses, field trips, poster sessions, exhibits, a full day of social events, plus partner programs throughout the symposium week.

Visit the IAGS website for specific details and to register: www.27IAGS.com.

Field Trips
- Geology of the Grand Canyon: 8 days on the Colorado River with a geologist; participants will delve deep into the magnificent and extensive geology of this region.
- Colorado and New Mexico Mines: 6 days visiting former, current, and future underground or open pit gold, silver, base metal, molybdenum, and uranium mining operations. Begins in Denver, Colorado.
- Nevada and Utah Mines: 4 days visiting important gold and copper mines in the two states; participants will also examine exploration methods used to locate these deposits. Begins in Reno, Nevada.
- Miami and Carlotta Mines: 2 days visiting the major reclamation and remediation projects that have been completed or designed to meet closure requirements in advance of terminating the operations.
- Bisbee, Sierrita WWTP, and Twin Buttes: 2 days starting with a visit to historic Bisbee, from a mine-closure perspective. On the second day participants will visit Sierrita WWTP (designed to test emerging technology for sulfate reduction in groundwater and process fluids and sequential extraction of metals other than copper from process fluids), and Twin Buttes (a previously mined area that is planned for future expansion).

Workshops
- Geochronometry: An examination of geochronometry processes that affect acid waters and dissolved metal contaminants as the plume migrates from its source and interacts with the natural environment.
- Indicator Minerals: A review of the principles, methods, and developments in indicator mineral methods used in mineral exploration around the world, with presentations by highly experienced practitioners.
- Hydrothermal and Supergene Geochemistry: Presents practical applications of metals geochemistry used to characterize hydrothermal and supergene environments, including the use of activity and Eh–pH diagrams to interpret metal occurrence and distribution.
- Isotope Geochemistry: Examines how isotopes can add value to understanding the processes by which elements migrate in near-surface environments and provides new avenues to enhance learning for effective exploration and formulation of remediation strategies.

- Application of Field Portable X-ray Fluorescence in Exploration and Mining: If you use pXRF you need to attend this workshop!
- Interpretation of Geochemical Survey Data: Reviews the principles, methods, and developments in the interpretation of geochemical survey data using practical examples and case studies.
- Student Publishing Workshop: This 2-hour free workshop will focus on the philosophy and mechanics of publishing your research in the peer-reviewed literature.

Erick Weiland (Erick_Weiland@fmi.com) Freeport-McMoran Copper & Gold Inc., 27th IAGS Convener

RECENT ARTICLE PUBLISHED IN EXPLORE

Paul Morris, Joel D’Antoine, and Ann Fitton (2014) GeoVIEW.WA – an interactive software application for mineral exploration in Western Australia. EXPLORE 165 (December 2014)

Mineral production is the cornerstone of the Western Australia economy, and there is accordingly a high level of mineral exploration activity in the State, carried out by a range of junior to international mineral exploration companies. The only source of comprehensive geoscience data is from the Geological Survey of Western Australia (GSWA), which has compiled a software application as a front end to these data. Access to more than 100 layers of digital information of interest to mineral explorers is afforded by the GSWA’s GeoVIEW.WA application. The application and related data are freely available from the website www.dmp.wa.gov.au. The available data include seven geochronometry datasets, drawn from GSWA mapping and mineralization programs, exploration company reports, and other private sector compilations. In total, these data comprise more than 100,000 analyses in digital form, and the locations of more than 4,500,000 assays from which mineral exploration surface geochemistry can be accessed. GeoVIEW.WA allows the searching of digital data both spatially and textually. The latter includes searching on host rock lithology, exploration tenement etc., as well as filtering and querying data based on geochemical composition. Data can be downloaded as comma-separated files and in GIS format, and the software allows for printing of user-generated maps. Data available through GeoVIEW.WA are refreshed daily.

Paul Morris (paul.morris@dmp.wa.gov.au) Geological Survey of Western Australia, Australia

SOCIETY NEWS

Elements
THE PRESIDENT’S CORNER

The CMS had a good year in 2014! We held a highly successful meeting at Texas A&M. We created several new e-vehicles for pushing our knowledge outward: a CMS E-newsletter and Wikipedia and Facebook pages. The impact factor of Clays and Clay Minerals has gone up. We now look forward with great anticipation to our 2015 Annual Meeting in Edinburgh, Scotland, highlighted below. Steve Hillier (James Hutton Institute) and his troops are planning a wonderful meeting. In addition to its outstanding scientific program and field trips, the meeting will honor Dr. Blair F. Jones (USGS-Reston), whose loss is felt in many areas of the geosciences. Blair held many roles in the CMS, including a term as president in 2002.

Having held this post for a year, I am impressed by the broad range of science undertaken by our members and by the international scope of our membership and Council. I am inspired by our ability to support clay science through a number of initiatives, including the biennial Reynolds Cup (a terrific competition featured in a previous CMS news page), our Annual Meeting, our journal, and our Student Travel and Research Grants. In particular, I would like to highlight our CMS Source Clays program, a repository of reference materials operated by the CMS. Thorough mineral and chemical characterizations of the Source Clays, carried out by our members, are published in Clays and Clay Minerals. Portions of these well-characterized clays are sold at nominal cost to researchers and industry groups. The demand for our Source Clays is high. We are refreshing some of our standard lines with new materials. We are always on the lookout for sources of the more unusual clays.

In sum, we shoulder the kinds of activities found in major scientific societies. We are able to do this through a membership whose dedication to clay science and the CMS is very high. Many individuals contribute greatly to these efforts. I am personally grateful for these contributions on behalf of the CMS.

Sincerely,

W. Crawford Elliott, CMS President wcelliott@gsu.edu

NOMINATIONS SOUGHT FOR CMS AWARDS

The CMS gives four awards at its annual meetings. See the CMS website for a description of the awards and an overview of the nomination process, www.clays.org. Nomination deadline for the 2016 awards is March 31, 2015.

STUDENT RESEARCH GRANTS AND TRAVEL AWARDS

The research grant program is designed to provide partial financial support (up to $3000) of master’s and doctoral research to graduate students of clay science and technology. The travel grant program is designed to provide partial financial support to graduate students to allow them to attend the annual meeting of the Clay Minerals Society to present results of their research. All student members of the Clay Minerals Society are eligible for the Travel Grant Program. See the CMS website for more information, www.clays.org. Application deadline is March 31, 2015.

STUDENT RESEARCH SPOTLIGHT

Congratulations to Sayako Inoue (The University of Tokyo) for winning a CMS Student Travel Award!

Sayako Inoue’s research aims to understand why random interstratification of serpentine–chlorite (Srp–Chl) is common in Fe-rich chlorite. Sayako examined chlorite with various Fe contents using high-resolution (scanning) transmission electron microscopy (HR(S)TEM) and discovered that Srp–Chl interstratification is ubiquitous in Fe-rich chlorite even though its presence is not clear in the powder XRD pattern. Her HR(S)TEM observations of Srp–Chl show that the stacking structure is a random mixture of different polytypic groups. Moreover, Srp–Chl interstratification is not a simple mixture of 7 Å serpentine and 14 Å chlorite layers, but involves frequent changes in the polarity of the serpentine layer and a transition between the 1:1 and 2:1 layers by the inversion of the tetrahedral sheets. Sayako's studies provide new insight into the relationship between serpentine, Srp–Chl, and chlorite with Fe-rich compositions.

52nd CMS ANNUAL MEETING

The 52nd CMS Annual Meeting will be held at Edinburgh University, July 5–10, 2015, jointly with the Euroclay2015 meeting of the European Clay Groups Association (ECGA) and in association with the International Natural Zeolite Association (INZA) and the Geological Society. The CMS Annual Meeting program includes sessions on natural zeolites, halloysite, chlorite, and bentonite; on bioreactive clay minerals; on clays in the critical zone, in the hydrocarbon industry, and in geothermal studies; on the computational chemistry of clays; and on the structural characterization and quantitative analysis of clayey materials. There will also be a session by the Asian Clay Minerals Group and a workshop on the properties of shales.
FROM THE PRESIDENT

Dear members of the DMG,

The German Mineralogical Society (DMG) has completed its 105th year of existence. The society is in good shape with an approximately constant number of members, around 1650, and an increasing number of student members (including PhDs), indicating that the society remains young and dynamic. The financial situation is still healthy, but the very low interest on investments is problematic and our financial reserve for awards is shrinking.

On behalf of the members, I would like to thank the outgoing officers who served the society with high efficiency and enthusiasm. The work of Astrid Holzheid, who served for the last two years as president, is highly appreciated by the Board. Thank you Astrid, especially for managing the establishment of the umbrella association of five solid-Earth geosocieties (DVGeo, associating geophysical, geological, paleontological, and mineralogical societies). M. Meyer, who served for 7 years as secretary, retires at the end of March and hands over the job to K.-D. Grevel. J. Hoefs took care of the finances for 6 years and was replaced by G. Franz last year. Finally, two new councilors, C. M. P. De Campos and I. T. Derrey, will join the team, and we say good-bye and thanks to resigning officers M. Koch-Müller and C. Giehl.

The next two years will be marked by two DMG meetings with a strong international character.

- The GeoBerlin meeting on 4–7 October 2015 will be devoted to Alfred Wegener, who at the time of the meeting will have formulated the hypothesis of plate tectonics exactly 100 years before, as set out in his book Die Entstehung der Ozeane und der Kontinente (“The Origin of Continents and Oceans”). This event will be jointly organized by the new geological society DGGV, established in September 2014 in Frankfurt, and the German Mineralogical Society. The topics of the planned sessions will be of interest to a large national and international community, including DMG members of all sections (visit www.geoberlin2015.de).

- The DMG annual meeting in 2016 will be held on 11–15 September in Rimini, Italy, concurrently with the 2nd European Mineralogical Conference (EMC2016). The latter is coordinated by the Italian mineralogical society (SIMP), with the contribution of ten European mineralogical associations (visit emc2016.socminpet.it).

Last year, the DMG developed a memorandum of understanding with the European Association of Geochemistry (EAG) that promotes geochemistry in Europe and internationally. A direct benefit for DMG members is participation in the EAG-led V.M. Goldschmidt ConferenceTM in Rimini, Italy, concurrently with the 2nd European Mineralogical Conference (EMC2016). The latter is coordinated by the Italian mineralogical society (SIMP), with the contribution of ten European mineralogical associations (visit emc2016.socminpet.it).

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DMG AWARDS 2015 – CALL FOR NOMINATIONS

The Abraham Gottlob Werner Medal is the highest award of the German Mineralogical Society. It recognizes outstanding original research in mineralogy (silver medal) or distinguished service for the advancement of the mineralogical sciences (gold medal). The Georg Agricola Medal recognizes outstanding achievements in the field of technical and applied mineralogy. The Victor Moritz Goldschmidt Prize is given to young researchers for outstanding contributions to the mineralogical sciences.

Every DMG member is eligible to submit nominations for the DMG awards. Nominations should include the CV and publication list of the candidate as well as a cover letter outlining the candidate’s qualifications. Please submit your nominations to: Prof. François Holtz, Leibniz University Hannover, Institut f. Mineralogy, Callinstr. 3, 30167 Hannover, Germany; e-mail: f.holtz@mineralogie.uni-hannover.de.

In memory of the late petrologist and geochemist Beate Mocek, the Beate Mocek Prize of the German Mineralogical Society was created by her family to encourage young female scientists in petrology and geochemistry. Female undergraduate and PhD student members of the DMG are eligible to apply for this prize. Please submit your application by June 30 to François Holtz.

The Paul Ramdohr Award is given for the best oral presentation by a student at the annual meeting of the DMG. In 2015 the meeting will take place in Berlin (GeoBerlin 2015). DMG student members may apply when submitting an abstract for the meeting.

Further information on the DMG awards is available in our bylaws: http://dmg-home.de/pdf/Satzung%20DMG2013.pdf.

DIFFUSION MODELING – JOINT DMG SHORT COURSE AND MSA WORKSHOP

Application of Diffusion Studies to the Determination of Timescales in Geochemistry and Petrology – Institute for Geology, Mineralogy, and Geophysics, Ruhr University Bochum; Prof. Sumit Chakraborty, Dr. Ralf Dohmen, and others; 24–28 August 2015.

The course is directed at petrologists, geochemists, and planetary scientists interested in retrieving information on the timescales of processes from their rocks. Such information might include the residence times of magmas in their reservoirs, the cooling or exhumation rates of rocks, the duration of terrestrial or extraterrestrial (e.g. parent bodies of meteorites) metamorphism, the duration of fluid flow (e.g. metasomatism by fluids/melts in the crust or mantle), and the evaluation and application of closure temperatures. Our focus will be high-temperature processes. Therefore “high-temperature thermochronometry” and “geospeedometry” are related keywords that describe the course contents.

Previous experience with numerical modeling and programming is not required, but an interest in learning the rudiments of these tools is necessary. One of the objectives of the course is to demonstrate that...
much can be accomplished with little or no programming experience. The basic information on diffusion that is required for carrying out such calculations will be provided, but this is not a course designed to cover all aspects of diffusion in minerals and melts. In addition to lectures, a major component of the course will be hands-on training in small groups to enable participants to “do their own” modeling. Participants will be expected to bring their own laptop computers. All instruction and exercises will be in English. The course material will be designed for graduate students and postdocs starting off in the fields mentioned above, but participants with all levels of experience and expertise are welcome. To maintain the hands-on nature of the course, we expect to restrict the number of participants to around 30, to be admitted on a first-come first-served basis. Student members of DMG and MSA will be given priority for registration if the demand for a slot becomes a concern. Interested persons can express their intention to register by sending an e-mail containing a brief paragraph describing their background and reasons for wanting to participate to Ralf.Dohmen@rub.de.

For more information see http://www.minsocam.org/msa/sc/DFFSN_descriptn.pdf.

**OBITUARY**

**Günther Friedrich, 1929–2014**

After a protracted illness, Prof. Günther Friedrich (RWTH Aachen University) passed away on November 24, 2014. Born in Stuttgart on April 15, 1929, he studied mineralogy and geology at his home university and obtained his PhD at the University of Heidelberg in 1954 under the guidance of “Erzvater” Paul Ramdohr. Subsequently, he joined the RWTH Aachen University as assistant professor, where he earned his Habilitation in 1962. Günther Friedrich dedicated his life to bringing a standard of excellence to the profession of economic geology, and his distinguished career reflects the diversity and impact of the subject.

After spending two years as a visiting scientist at the University of Missouri–Rolla and the University of California–Berkeley and at the U.S. Geological Survey in Denver and the Geological Survey of Canada in Ottawa, he returned to Aachen where he accepted the position of professor and head of the Division of Applied Ore Deposit Research. Recognizing a gem, RWTH Aachen University appointed him in 1975 as the chair of mineralogy and economic geology and director of the institute. In August 1994, he became “actively retired” from the university and was awarded the title of Professor Emeritus for more than 30 years of dedicated service.

Günther Friedrich’s tenure was distinguished by extensive service to the Earth science community, including membership on the Earth Science Committee of the Deutsche Forschungsgemeinschaft and several offices in the Society of Geology Applied to Mineral Deposits, including the presidency in 1982–1984. He was also instrumental in the inauguration of the German Forschungskollegium Lagerstätten in 1988. He served for many years on the council of the German National Committee for the Geological Sciences to the IUGS, was president and vice-president of the Deutsche Mineralogische Gesellschaft in 1990–1993, and was editor of the Monograph Series on Mineral Deposits. In the process he has forged important international ties through his active participation in international Earth science committees and collaborative research projects in Europe, Canada, the Philippines, Brazil, and southern Africa.

Günther Friedrich’s knowledge of ore deposits was extensive, and his remarkable ability to home in on fundamental problems in the field of economic geology has resulted over the years in a wide range of research interests. For many years, he focused on the development of methods for geochemical exploration, including the use of mercury as a pathfinder element in the search for various types of sulfide ore deposits. In recent years, this method has been applied by environmental geochemists to detect and map areas contaminated by mercury. Much of his scientific life, however, was dedicated to the study of marine mineral deposits, and Günther Friedrich was a pioneer in manganese nodule research. Numerous cruises to the manganese nodule areas of the Pacific Ocean, including the Central Pacific Nodule Belt, the Southwest Pacific, and the Peru Basin, were planned and carried out under his scientific guidance. His research topics also included the mineralogy and geochemistry of the Kupferschiefer deposits; laterite deposits and their gold, chromium, and nickel potential; the formation of alkaline rocks and associated ore deposits; and the genesis of epithermal gold deposits.

Within the German Continental Deep Drilling Project, Günther Friedrich took an active role in the study of ore mineralogy and in developing models for ore formation in metamorphic rocks. The formation of ore deposits by intraformational processes was the subject of a long-term priority research program coordinated by him and funded by the Deutsche Forschungsgemeinschaft. In close cooperation with the Bundesanstalt für Geowissenschaften und Rohstoffe, Günther Friedrich and his students participated in the “Gold metallogenesis in Africa” program, during which an economic, currently exploited gold deposit was discovered as a result of systematic research.

The results of Günther Friedrich’s scientific achievements are summarized in more than 200 publications and 70 conference abstracts, which reflect his broad scientific interests in the fields of mineralogy, geochemistry, ore microscopy, and economic geology. His enthusiasm and his almost endless energy have been a driving force not only for him but also for his many students, some of whom are now leading professionals in various parts of the world.

Those of us who were privileged to work with Günther Friedrich remember him for his modesty, his generosity, and his dedication to his science, students, and colleagues.

**Franz Michael Meyer** (RWTH Aachen University)
I am a scientist and a geochemist – I am one of you. Since January, I just happen to also be the president of the EAG. Holding this position is a great privilege and an honour, and it comes with responsibilities that I am still learning about. I am stepping into the huge leadership footsteps left by Chris Ballentine. This in itself is a daunting task, not just because of his innumerable contributions while a Council member and Goldschmidt officer but also because the EAG is what it is today largely because of his calm, steady leadership. This led to a step change in the way the European and international geochemical communities collaborate and interact, and I learned from him diplomacy and how to strive for inclusiveness. Thanks Chris.

The council of an organization such as the EAG is not a one-person show. It relies on the common effort of a team of geochemists who together develop new initiatives. We are grateful to outgoing EAG Council members Bernard Bourdon, Bernie Wood, Christa Göpel, Amaele Landais and Michael Bau for their contributions to the society and past European Goldschmidt meetings. Special thanks go to Christa Göpel for her long service as our treasurer. From her early years, when our financial situation was shaky to say the least, she has helped us develop a solid base, which is now paying dividends through a number of funded activities. Christa is passing the bank box to Karim Benzerara. We also have new members on the Council. These include two new officer councillors: Bernard Marty, who was elected as our next vice president, and Antje Boetius, who has agreed to serve as Goldschmidt officer for the 2017 meeting. In October 2014, you also elected 3 new EAG councillors, Sigurður Gíslason, Andreas Pack and Dominik Weiss. With the new role of early career councillor filled by Stefanie Lutz, we also aim to improve our response to the needs of young geochemists.

There was some consternation about our recent councillor election roster, which listed only 6 white males. EAG policy is to elect Council members who are the best at what they do and who are willing to contribute to our geochemical community efforts, regardless of gender, nationality or age. Members who looked at the current make-up of our Council may have noticed that we actually have an approximately 1:1 gender balance; electing 3 males (and 2 females) in this round does not change that ratio (see www.eag.eu.com/about/council/). However, it is good to know that our members took notice and commented on this issue. I would like to thank all those who voted and I am looking forward to working with our new Council members over the next 2 years.

The EAG is your society, and Council members are just temporary gate masters acting in your interest. We look forward to your opinions and offers to help make our society more effective. We are developing several new initiatives for you in 2015. One that is currently very exciting is the launch of a new EAG publication: Geochemical Perspectives Letters (www.geochemicalperspectivesletters.org). You can find our first GPL paper as a free online download. The first printed volume, in the well-known AS format of Geochemical Perspectives, will be distributed at the Goldschmidt Conference in Prague. The editors of GPL are looking forward to many more exciting geochemical contributions, also from YOU. Only with your engagement, in GPL and the spectrum of EAG activities, can the community effort gain the success it deserves. I truly hope to see you at the 2015 Goldschmidt in August in Prague.

Liane G. Benning, EAG President

Bernard Marty is a professor of geochemistry at the CRPG in Nancy. His main research interests include the origin of isotopic variations in the Solar System, the geochemistry of volatile elements (C, N, water, noble gases), early-Earth geodynamics and environments, mantle geodynamics and fluid circulation in the crust. Bernard has been elected as EAG vice president.

Antje Boetius is a deep-sea and polar researcher, with a focus on biogeochemistry, geomicrobiology and ecology. She leads a Joint Research Group of the Alfred Wegener Institute, the Helmholtz Centre for Polar and Marine Research and the Max Planck Institute for Marine Microbiology. She is also engaged in the MARUM Excellence Cluster for Marine Environmental Sciences of the University of Bremen, Germany. Antje has been elected as Goldschmidt officer for the 2017 meeting.

Sigurður (Siggi) Reynir Gíslason is a research professor at the Institute of Earth Sciences, University of Iceland, and chairman of CarbFix (carbfix.com), an initiative to store carbon in basaltic rocks. Sigurður has been elected as EAG councillor.

Stefanie Lutz is a PhD student in the Cohen Geochemistry Group in the School of Earth & Environment at the University of Leeds and is currently working on the biogeochemistry of glacial surfaces. Stefanie has been elected as our first early career councillor.

Andreas Pack is a professor of isotope geology at the University of Göttingen and works on topics in geo- and cosmochemistry, atmospheric science, experimental petrology and applied mineralogy. Andreas has been elected as EAG councillor.

Dominik Weiss is a reader in environmental geochemistry at Imperial College London. His main research interests centre on the role and chemistry of metals in the environment. Dominik has been elected as EAG councillor.
25TH ANNIVERSARY

Goldschmidt (2015)

PRAGUE, CZ
AUGUST 16 - 21
2015

ABSTRACT DEADLINE:
APRIL 2ND, 2015

Hold your society events at Goldschmidt:
- Editorial and Board Meetings
- Short Courses and Workshops
- Ceremonies and Medal Presentations
- Exhibition Booths and Social Events

For more information:
helpdesk@goldschmidt.info
goldschmidt.info/2015

For more information:
http://goldschmidt.info/2015/societies
Thank You

As is often the case when making major life decisions, it was with conflicting emotions that I submitted my resignation to GS President Barbara Sherwood Lollar on November 18, 2014. My last day with GS will be Tuesday, June 30, 2015.

When this issue releases, I will have served as your business manager and chief operating officer for 15 remarkable years. In this same year, 2015, Goldschmidt18 will be held in Prague. Society membership has grown substantially, from 1497 when I arrived in February 2000 to over 4000—with 4718 ballots sent to members for the recent election of the Board of Directors. Society finances are solid, publication activities are sound, and GS’s partnerships could not be better.

Although I have helped in creating and maintaining these achievements, I can by no means take all the credit for them. Society volunteers and the geochemical community have served critical roles. A group of individuals whom I wish to thank publicly right now are the GS presidents. The true workhorses of GS, their time, energy, and expertise have been vital. Each has brought his or her own flavor and life to the organization and all are deserving of this recognition. In order from 2000, they are Michael Hochella, Judith McKenzie, Tim Drever, Sue Brantley, Marty Goldhaber, Sam Mukasa, Rick Carlson, and Barbara Sherwood Lollar. Thank you all for your contributions.

Two other individuals I need to thank for their service are Frank Podosek, who while editor of Geochemica et Cosmochimica Acta supervised the business office, and Rich Heuermann, the administrative head of the Earth and Planetary Sciences Department at Washington University in St. Louis (WUSTL). Both provided unwavering support in housing the business office at WUSTL. Finally, I thank my administrative assistant, Kathryn Hall, with whom I have worked closely for the last seven years.

A search is currently underway to relocate the business office and hire staff members to take over critical functions. A new chief operating officer should be in place by April or May, providing a few months of overlap to ensure a smooth transition.

It has been a joy to serve the geochemical community and I wish all of you and GS the very best in the future.

Seth Davis, GS Chief Operating Officer

Goldschmidt2018 Boston and Upcoming Conference Venues

We are pleased to announce that the Hynes Convention Center in Boston, Massachusetts, USA, has been selected as the 2018 venue of the Goldschmidt Conference. Boston was selected as the strongest of several proposed sites. Boston’s accessibility, state-of-the-art facilities, and amenities will make it an excellent host for our international geochemical community. The conference dates are August 12–17, 2018.

Goldschmidt2015 Prague, Czech Republic 16–21 August
Goldschmidt2016 Yokohama, Japan 26 June–1 July
Goldschmidt2017 Paris, France 13–18 August
Goldschmidt2018 Boston, USA 12–17 August

For more information on past and future Goldschmidt conferences, visit the archive at www.goldschmidt.info.
FROM THE PRESIDENT

It is a great honor to have been appointed to the presidency of the Japan Association of Mineralogical Sciences. I will do my best to develop the mineralogical sciences and build the influence of JAMS in the field of Japanese Earth and planetary science during my two-year term, which began in September 2014.

Today, the mineralogical sciences are not restricted to the study of substances that make up the Earth and the other planets, but provide essential research results for investigations in the materials, environmental, and life sciences.

Current collaborations include projects in disaster science, archeology, and forensic geological science, all of which greatly contribute to the development of interdisciplinary academic fields. It is, of course, necessary to maintain close academic links with the fields of geology, geophysics, geochemistry, and planetary science. I hope that every member of the Japan Association of Mineralogical Sciences will take full advantage of his or her expertise to contribute not only to the development of the mineralogical sciences but also to a variety of other academic fields, industries, and technologies. At the same time, many scientific specialties are deepening and expanding to focus on specific questions in particular areas. This is true not only in the mineralogical sciences, but in many other scientific fields. While scientists must provide the broad expertise that society demands, I hope that such pressures will not lead to the diffusion of each field, but will further strengthen the mineralogical sciences through “harmonious diversity.”

JAMS was created in September 2007 through the merger of the Mineralogical Society of Japan and the Japanese Association of Mineralogists, Petrologists and Economic Geologists; it was launched at a “JAMS Establishment Meeting” held at Tokyo University. Initially, JAMS had more than 1000 members and this number has dropped only a fraction after seven years. This success, relative to other Japanese Earth and planetary science organizations, testifies to the long-term vision of the JAM’s senior managers. Both former president Eiji Ohtani and ex-president Takashi Murakami took concrete steps to achieve an attractive future vision for JAMS. Their plans included the following goals:

- Managing the organization to increase younger membership through the support of the Young Mineralists’ Organization
- Reducing the withdrawal rate by introducing a senior membership system
- Subscribing to the international journal Elements to enhance the attractiveness of JAMS
- Introducing Japanese mineralogical science to the world through Elements
- Reducing running costs by transferring academic journals to electronic media

I aim to continue this tradition: promoting the mineralogical sciences both inside and outside Japan, while building up the organization, in particular by increasing the number of younger members.

JAMS is currently working toward becoming an incorporated association. At present, it is a private association, not an organization governed by Japanese laws. Becoming an incorporated association will improve the social and academic reputation of JAMS, clarify responsibilities, and protect properties that belong to the association. By becoming an association recognized for high compliance, JAMS will also enhance its credibility among academic associations in Japan. We will begin detailed discussions with Vice-President Akira Tsuchiyama and the other council members about a range of issues, including targets in the mineralogical sciences, challenges facing JAMS, and the process of becoming an incorporated association. Although none of these issues can be resolved easily, we will find the best direction for the association and all of its members.

Three-and-a-half years have passed since the megquake, tsunami disaster, and Fukushima nuclear accident of March 2011. Although Japan is on the road to recovery, we have experienced several other large-scale volcanic explosions and mudslides caused by heavy rain, in which many lives have been lost. Mineralogical science not only contributes to the development of scientific research but also helps to significantly reduce and prevent such natural disasters. The Japan Association of Mineralogical Sciences, as a member of the Elements family, aims to extend the field by building links with mineralogy, geochemistry, and petrology groups around the world.

Yasuhiro Osanai, JAMS President

INVITATION TO THE JAPAN GEOSCIENCE UNION MEETING 2015

We are delighted to announce that the annual Japan Geoscience Union Meeting 2015 will be held from May 24 to May 28, 2015, at Makuhari Messe, Chiba, Japan. More than 50 international sessions will be held. You are encouraged to submit a paper; the deadline for abstracts is February 18, 2015. More information is available at the following address: http://www.jpigu.org/meeting_e/

JOURNAL OF MINERALOGICAL AND PETROLOGICAL SCIENCES

Vol. 109, No. 6, December 2014

Original articles

- Geochemical and Sr-Nd-Pb isotopic compositions of lithospheric mantle: Spinel lherzolites in alkaline basalts from the northwestern Ethiopian plateau
  Daniel MESHESHA, Ryuichi SHINJO and Yuji ORIHASHI

- White mica K-Ar ages from lawsonite-blueschist facies Hakoishi sub-unit and from prehnite-pumpellyite facies Tobiishi sub-unit of the Kurosegawa belt, Kyushu, Japan
  Eitaro SATO, Takao HIRAJIMA, Kenichiro KAMIMURA and Yoshikazu FUJIMOTO

- Millimeter-to decimeter-scale compositional mapping using a scanning X-ray analytical microscope and its application to a reaction zone in high-grade metamorphic rock
  Masaoki UNO, Atsushi OKAMOTO and Noriyoshi TSUCHIYA

Technical note

- Testing for robustness on estimation of graphitization degree by Raman spectroscopy
  Hayato UMEDA and Masaki ENAMI

Letters

- Cathodoluminescence of calcite decomposed from dolomite in high-temperature skarn
  Nobuhiro KUSANO, Hirotugu NISHIDO and Kouich INOUE
URANIUM–THORIUM SHORT COURSE

The Geology and Geochemistry of Uranium and Thorium Deposits

COORDINATORS AND SPEAKERS:
Michel Cuney (CNRS) and Kurtis Kyser (Queen’s University)

SPONSORS: Mineralogical Association of Canada and Society for Geology Applied to Ore Deposits

DATE: Fri. and Sat., May 1–2, 2015, prior to the AGU-GAC-MAC-CGU Joint Assembly 2015

DURATION: 1.5 days

LOCATION: Palais des Congrès de Montréal

CONTACT: Kurtis Kyser; e-mail: kyser@geol.queensu.ca

REGISTRATION: Via the Joint Assembly–Montreal 2015 website, ja.agu.org/2015/

Overview

Despite the lack of interest in uranium as a commodity during the past few years and the loss of expertise during the past downturn beginning 30 years ago, new ideas and technologies developed over the past 7 years have resulted in an enhanced understanding of the formation of uranium deposits. These have allowed researchers to quantify models for all types of deposits and, thus, to reclassify deposits in relation to their occurrence and probable genesis. The purposes of this short course are to highlight the research being integrated into refining exploration strategies for uranium and to discuss new developments in thorium deposits. The future of uranium and thorium as energy resources is increasingly important by-product of REE mining. The short course will consider geotectonic contexts and models of different types of uranium deposits and the mechanisms that control their genesis; the course will relate source, transport, and the forces driving deposition and preservation, and will consider how these factors can be used in more efficient uranium exploration and remediation. Two coffee breaks and lunches are provided. Costs are $500 for professionals and $100 for students.

Topics

- Nuclear fuel cycles and the economics of uranium and thorium fuels
- New classifications of deposit types
- Distribution and evaluation of global resources and mining techniques
- Geochemistry and mineralogy of uranium and thorium
- Heat production and flux; radiation and natural reactors
- Magmatic processes involved in deposit formation
- Metasomatism and metamorphism in the production of uranium deposits
- Basins and uranium deposits
- Deposits related to low-temperature processes
- New ideas about controls on grade and size of deposits
- Exploration strategies and techniques—what works and what doesn’t
- The future of uranium and thorium as energy resources

BERRY SUMMER SCHOOL

Applications of TEM-FIB-SEM Methods to Geomaterials

ORGANIZERS: Hojatollah Vali and Robert F. Martin (McGill University), and Luiz Morales and Richard Wirth (GFZ German Research Centre for Geosciences)

SPONSOR: Mineralogical Association of Canada

DATE: May 1–3, 2015, prior to the AGU-GAC-MAC-CGU Joint Assembly 2015

DURATION: Three days

(location: 3 ½ hours in the morning and 1 hour in the afternoon) + FIB-SEM and TEM demonstrations in the afternoon

LOCATION: McGill University, Faculty for Electron Microscopy Research, 3640 University Street, Montreal, QC H3A 0C7

CONTACT: S. Kelly Sears; e-mail: femr@mcgill.ca

REGISTRATION: Via the Joint Assembly–Montreal 2015 website, ja.agu.org/2015/

Overview

The latest generation of the focused ion beam–extreme high-resolution scanning electron microscope (FIB-SEM) and the transmission electron microscope (TEM) are the ideal tools to study geomaterials at the micro-and nanoscale in 2-D and 3-D, including chemical composition and crystal structure. The Berry Summer School will provide an overview of the theory and practical applications of FIB-SEM and TEM in the geosciences using state-of-the-art electron microscopes available at the McGill University Facility for Electron Microscopy Research (FEMR). Participants will have the opportunity to discover the latest techniques in sample preparation and imaging relevant to the Canadian geoscience community. The workshop content includes:

- High-resolution SEM imaging using the in-column detector (ICD)
- Serial SEM imaging of FIB-prepared cross-sections of soft and hard materials
- 3-D FIB tomography and reconstruction of materials
- 3-D energy-dispersive spectroscopy
- Direct detection device (DDD) and phase plate (contrast) technology in TEM

Instructors and Contributors

Alan Anderson (St. Francis Xavier University, Nova Scotia, Canada); Luiz Morales (GFZ German Research Centre for Geosciences, Potsdam, Germany); Richard Wirth (GFZ German Research Centre for Geosciences, Potsdam, Germany); Hojatollah Vali, McGill University, Montreal, Quebec, Canada)

Audience, Capacity, and Requirements

The primary audience will be graduate students, postdoctoral fellows, and senior researchers. We expect students to come mainly from the geosciences and mineral sciences, but students from other disciplines, such as materials science, bioscience, engineering, and other disciplines are welcome to attend. Enrollment is limited to 30 participants. Participants should have a general understanding of electron microscopy. Basic knowledge of crystallography, crystal symmetry, the chemistry of minerals in general, and the interaction between electrons and crystalline matter would also be an asset.
Mineralogical Society of Poland

www.ptmin.agh.edu.pl

WORKSHOP ON ACCESSORY MINERALS

A Workshop on Accessory Minerals, organized by Bogusław Bagiński and Ray Macdonald and held at the Institute of Geochemistry, Mineralogy and Petrology of the University of Warsaw on September 25–26, 2014, was attended by invited participants from 11 countries. Papers covered the geological occurrence, paragenesis, structure, composition, and alteration products of a wide range of accessories, stressing the need for multitechnique approaches to such studies. The abstract volume of the workshop may be found at http://www.geo.uw.edu.pl/tl_files/publikacje/Tom_abstraktow_6b-ost_ver_publ.pdf.

Participants in the Workshop on Accessory Minerals (left to right): Petras Jokubauskas, Pavel Uher, Tom Andersen, Bogusław Bagiński, Grzegorz Zielirski, Robert F. Martin, Silvio R. F. Vlach, Fernando Camara, Lutz Nasdala, Daniel E. Harlov, Marcin Stachowicz, Igor Broska, Ray Macdonald, Anne-Magali Seydoux-Guillaume, Krzysztof Woźniak, Harvey E. Belkin, Michał Ruszkowski, Stanisław Mikulska, Marta M. Michalska

Visits were made to the new analytical facilities in the Faculty of Geology, including the electron microprobe laboratory with field-emission equipment and the SEM lab with a dual-beam Auriga machine equipped with FIB, Cryo-SEM, STEM, and EBSD. Participants also visited the X-ray laboratories in the Department of Chemistry and the new SHRIMP IIe facility in the Polish Geological Institute. A desired outcome of the workshop will be new international research collaborations, some of which were outlined during the meeting.

THE 21ST ANNUAL PETROLOGY SESSION OF THE POLISH MINERALOGICAL SOCIETY

The Petrology Session, organized by the Institute of Geochemistry, Mineralogy and Petrology of the University of Warsaw and held in Boguszyn near Kłodzko (Sudetes) on 16–19 October 2014, was attended by invited participants from 11 countries. Papers ranged broadly over the fields of petrology, mineralogy, and geochemistry, the main theme being “From Magma Genesis to Ore Formation: Evidence from Macro- to Nanoscales.” During the conference 25 lectures were presented, including talks by invited speakers Chris Hawkesworth (University of St. Andrews), Peter Kokelaar (University of Liverpool), and Vojtěch Janousěk (Czech Geological Survey). Forty-four posters were displayed. The meeting concluded with a field trip to localities in the Kłodzko-Złoty Stok granitoid intrusion, where the strong heterogeneity of the rocks in the body was demonstrated. The abstract volume of the session is available at http://www.ptmin.agh.edu.pl/mpsp30/Vol42_2014.pdf.

Bogusław Bagiński (University of Warsaw)

THE SFMC AT THE FRENCH EARTH SCIENCE MEETING (RST 2014)

The Réunion des Sciences de la Terre 2014 (“Earth Sciences Meeting 2014”) was held on October 27–31. It was well organized by the UPPA (Université de Pau et des Pays de l’Adour) and held in the Palais Beaumont in Pau. The SFMC convened sessions on several themes: mafic and ultramafic rocks, the continent-ocean transition, hydrogen, monazite, and technological and analytical advances on very large instruments. At the SFMC booth, we presented our society to the participants and showed them how the SFMC serves the community through (1) organizing scientific workshops, meetings and short courses, (2) awarding the Hauty-Bravais PhD thesis prize every year, (3) sponsoring PhD students and (4) providing miscellaneous information. Members of the SFMC Council volunteered to take care of the booth. For this meeting, the SFMC selected and sponsored four PhD students to present their ongoing thesis work.

President Bruno Goffé and Treasurer Stéphanie Rossano manning the SFMC booth

A meeting of the Groupe de Pétrologie Endogène (“Endogenous Petrology Group”) took place during RST 2014. This is a thematic group supported by the SFMC. The activities of the group include bringing together researchers working in igneous and metamorphic petrology and engaged in the igneous, metamorphic and associated structural petrology of natural or synthetic samples, field study, and so on. The group provides information to its members by means of a mailing list, a website and biennial scientific meetings. The third scientific meeting of the group is already planned for the University of Rennes in 2015. All are welcome!

MINTEM 2014: TEM IN MINERALOGY

The third edition of the MINTEM school, organized by the SFMC and the Société Française de Microscopie (http://www.sfmu.fr/) and held at the UMET (http://umet.univ-lille1.fr/) laboratory, was held on November 3–7, 2014, at Lille 1 University. Fifteen graduate students from France, Germany, Hungary and Spain attended the school. Alternating with lectures, practical sessions were held at the Centre Commun de Microscopie de Lille (http://umet.univ-lille1.fr/CCM/) and the Centre Commun de Mesures Imagerie Cellulaire (CCMIC, http://ccmic.univ-lille1.fr/). The next edition of the school is planned for 2016. The website of the school is http://umet.univ-lille1.fr/Animation/MinTem/.

Students who attended MINTEM 2014

The four PhD students sponsored by the SFMC: Gáëlle Lamarque (Saint-Étienne), Gáëlle Mollex (Nancy), Hugo Bourque (Orléans) and Alexis Grand’Homme (Grenoble)

A core and a piece of granitic rocks in a granite quarry near Kłodzko, Poland, that was a field trip destination of the workshop on Accessory Minerals, organized by Bogusław Bagiński and Ray Macdonald at the Institute of Geochemistry, Mineralogy and Petrology of the University of Warsaw in September 25-26, 2014. Participants included (left to right): Petras Jokubauskas, Pavel Uher, Tom Andersen, Bogusław Bagiński, Grzegorz Zielirski, Robert F. Martin, Silvio R. F. Vlach, Fernando Camara, Lutz Nasdala, Daniel E. Harlov, Marcin Stachowicz, Igor Broska, Ray Macdonald, Anne-Magali Seydoux-Guillaume, Krzysztof Woźniak, Harvey E. Belkin, Michał Ruszkowski, Stanisław Mikulska, Marta M. Michalska.
INCOMING PRESIDENT’S ADDRESS

Michael Zolensky

It is with great pleasure that I take over as president of the Meteoritical Society. I thank Professor Monica Grady, CBE, for her wise presidency over the past two years, which successfully led our Society to new levels of prosperity. I will endeavor to not screw this up.

I attended my first Met Soc annual meeting in 1985 as a new postdoc, coming from the field of nuclear waste disposal and containment. I note that nearly all my best friends in grad school were working on meteorite geochemistry, ore deposits research, igneous and metamorphic petrology, and other fascinating topics. I was fantastically lucky to transition to meteoritics, and I found that all my old grad school buddies went in the opposite direction and are now working on nuclear waste disposal and containment. At that 1985 Met Soc meeting, I was amazed at how combative the meteoriticists were, compared to what I had experienced at, say, GSA and rad waste meetings. It took some time to realize that the fierce arguments I saw masked great friendships (though not always, of course). Several of the scientists who told me in no uncertain terms that my talk was really stupid later became great friends of mine. Over the succeeding 30 years I have collaborated with a great many Met Soc members, and the Society has always been an extended family for me. Met Soc is still small enough to be intimate, which means that even new members can have a major, positive impact. I look forward to my two years as president of the Society, and I especially look forward to meeting the many students who attend Society meetings and usually give the very best presentations.

There are a few initiatives I would especially like to foster. There is a great future in using radar data to quickly locate new meteorite falls—to complement the new camera networks that are being implemented—and it should be possible for Met Soc to help make this a worldwide effort. The Society is financially healthy, and we invite proposals for how some of our funds could be usefully utilized. In addition, there should be a database of meteorite sample images (BSE mosaics, element maps, etc.) that all could contribute to and draw from. Please don’t be shy about telling us how to make the Society work better for you.

Michael Zolensky, President 2015–2016
NASA Johnson Space Center
michael.e.zolensky@nasa.gov

THE BARRINGER FAMILY FUND FOR METEORITE IMPACT RESEARCH

The Barringer Crater Company has established a special fund to support field work by eligible students interested in the study of impact cratering processes. The Barringer Family Fund for Meteorite Impact Research will provide a number of competitive grants in the range of $2500 to $5000 in support of field research at known or suspected impact sites worldwide. Grant funds may be used to assist with travel and subsistence costs, as well as the costs of laboratory and computer analysis of research samples and findings. Master’s, doctoral, and postdoctoral students enrolled in formal university programs are eligible. Application to the Fund will be due by April 3, 2015, and awardees will be notified by June 5, 2015. Additional details about the Fund and the application process can be found at http://www.lpi.usra.edu/science/kring/Awards/Barringer_Fund.

OFFICERS AND COUNCIL MEMBERS

The Meteoritical Society will welcome a number of new officers this year. Mike Zolensky (see above) will be transitioning from vice president to president, and Trevor Ireland (Australian National University) will be the incoming vice president. Mike Weisberg (City University of New York, USA) will be our new secretary, and Candace Kohl (University of California–San Diego, USA) will be the treasurer. Monica Grady (Open University, UK) will continue to serve, albeit in her new capacity as past president. We thank these new officers in advance for their efforts to lead the Meteoritical Society through the next two years.

Michael Zolensky, President 2015–2016
NASA Johnson Space Center
michael.e.zolensky@nasa.gov

Trevor Ireland
Mike Weisberg
Candace Kohl
Monica Grady

The Meteoritical Society Council will consist of Jay Melosh (Purdue University, West Lafayette, USA), Larry Nittler (Carnegie Institution, Washington, DC, USA), Maria Schönbächler (ETH, Zürich, Switzerland), Kevin Righter (NASA Johnson Space Center, Houston, USA), Hisayoshi Yurimoto (Hokkaido University, Sapporo, Japan), Alexander Krot (Hawai’i Institute of Geophysics and Planetology, USA), Keiko Nakamura-Messenger (NASA Johnson Space Center, Houston, USA), François Robert (Muséum National d’Histoire Naturelle, Paris, France), and Caroline Smith (Natural History Museum, London, UK).

We would like to sincerely thank Greg Herzog (secretary), Rhian Jones (treasurer), and Ed Scott (president / past president) for their years of dedicated service devoted to keeping the Meteoritical Society operating smoothly!

Cont’d on page 69
2014 SOCIETY FELLOWS
The Meteoritical Society congratulates its new Fellows. Gretchen Benedix (Curtin University, Perth, Australia), Fred Ciesla (University of Chicago, Chicago, USA), Harold Connolly (City University of New York / American Museum of Natural History, New York, USA), Matthieu Gounelle (Muséum National d’Histoire Naturelle, Paris, France), Munir Humayun (Florida State University, Tallahassee, USA), Dante Lauretta (University of Arizona, Tucson, USA), Marc Norman (Australian National University, Canberra, Australia), Ian Sanders (Trinity College, Dublin, Ireland), Rhonda Stroud (Naval Research Laboratory, Washington, DC, USA), and Andrew Westphal (University of California at Berkeley, Berkeley, USA).

ANNUAL MEETING SCHEDULE
2015 – Berkeley, California, USA, July 27–31
2016 – Berlin, Germany, August 7–12
2017 – New Mexico, USA, dates to be determined
2018 – Moscow, Russia, dates to be determined

RENEW YOUR MEMBERSHIP NOW!
Please renew by March 31, 2015; after that date, a $15 late fee will be assessed. You can renew online at http://metsoc.meteoriticalsociety.net.

OUR FLAGSHIP JOURNAL – APPLIED GEOCHEMISTRY
Just about every president of every society has, at one time or another, written an opinion piece about the importance of reviewing in the publication process. However, this is a special appeal to our members, from three current officers of the IAGC and our executive editor.

We are sure you are all aware that Applied Geochemistry is the flagship journal of IAGC and is published by Elsevier. Our relationship with Elsevier gives Applied Geochemistry good exposure via online publication alongside related journals. In turn, IAGC agrees to support Applied Geochemistry by encouraging its members to publish high-quality papers in the journal and to provide reviews in a timely manner. What you may not know is that Elsevier supports IAGC financially through this contract by means of an annual payment to IAGC, and that these royalties represent the financial backbone of our Society. IAGC uses this money to support our working groups and to fund the Elsevier Student Research Grant Program.

Thus, we as IAGC members should have a keen interest in the success of Applied Geochemistry, and we should do all that we can to advance its standing among geochemical journals. One of the most important ways we support our journal is by providing colleague reviews. While many of us feel a sense of dread when we receive tons of e-mails asking for reviews of manuscripts from a whole range of journals, we would like to point out the positive aspects of reviewing for Applied Geochemistry:

- Reviewing gives us an in-advance look at new research in the field of applied geochemistry before it is published.
- Having to look critically at the work of others forces us to look critically at our own work, thus improving the quality of both.
- New collaborative opportunities sometimes arise from the review process by establishing new connections within our Society.
- The review process is a learning process: both reviewers and authors learn by exchanging ideas and providing feedback.
- Reviewing is our way of recognizing the importance of our journal: by agreeing to provide a colleague review, we ensure and maintain the high standards of our journal.
- By agreeing to do a review for our journal, we acknowledge our obligation to our scientific association. Each paper that we publish requires two or three reviewers, so it stands to reason that we should do two or three reviews for each AG paper that bears our name.

Therefore, the next time you receive an e-mail from Applied Geochemistry offering you the opportunity to do a review, please make all possible effort to accept the review, and then, of course, complete it in a timely manner! Though this is a demanding, unpaid, extra job, please remember that when you do a review for our society journal, Applied Geochemistry, you in fact make an in-kind donation to your association! The IAGC lives off the royalties we receive for our journal. We would need to increase the membership fees several times over if we lost these royalties. And then, of course, please also submit your excellent papers to our journal!

Rich Wanty, IAGC Past-President
Ian Cartwright, IAGC President
Michael Kersten, Applied Geochemistry Executive Editor
Clemens Reimann, IAGC Outgoing Past-President
Membership Dues

Please note: your membership fees for 2015 are due now. The sooner you pay, the less time/money we spend on sending reminders. We look forward to hearing from you! Go to www.minersoc.org and click on ‘Member login’. Go to www.minersoc.org and click on ‘Member login’.

Annual Report

The Society’s annual report for 2013–2014 is now available for viewing on the Society’s website (www.minersoc.org/annual-reports.html). Members are encouraged to read the report and to send comments or queries to Executive Director, Kevin Murphy (kevin@minersoc.org). The Society’s Annual General Meeting will be held on 12 March 2015 at 11.00 AM at the Natural History Museum.

Mineralogical Society ‘Best Paper Award’ in Honour of R. A. Howie


Geochemistry Group, Research in Progress Meeting 2015

23–24 March 2015
NATIONAL OCEANOGRAPHY CENTRE, SOUTHAMPTON

Further information about this annual meeting of the Geochemistry Group is available at http://www.minersoc.org/geochem.html. Register online at http://www.go.soton.ac.uk/68a.

Chartered Scientist (C.Sci.) Status

WHAT IS CHARTERED STATUS?

Almost all professions have a professional/chartered membership that conveys and assures professional qualifications, a professional attitude to work, keeping up to date with best practice, and abiding by the code of conduct of a professional society. It is an ongoing qualification that shows you are an active practitioner.

This designation is very different from any academic qualifications you may already have, such as a bachelor’s, master’s or PhD degree gained by fixed-time courses and ‘one off’ examinations. It is also very different from Higher Education Academy qualifications that apply only to university teaching. None of these conveys that you are a professional and practising scientist.

WHY BECOME CHARTERED?

That rather depends on whom you ask and in what field you work. The engineering world maintains a high level of respect for Chartered Engineers, and the majority of senior engineers in the UK are chartered. In some countries, only people with a similar status have the legal authority to sign for the completion of certain projects, but that stricture seems unlikely to be adopted here. In science, however, the requirements are much more varied as the prevalence of higher degrees is relatively high. It is more common at present to see a job advertisement requiring applicants to have a PhD than to see a specification for someone registered as C.Sci., C.Chem. or C.Geol., for example. Things are changing, however. A look through the piles of magazines on our desks shows several job adverts with just those requirements, and it seems likely that as the number of chartered scientists in senior positions increases, then so too will their demand for similarly qualified applicants. To quote the Science Council: “Being chartered is the mark of professional recognition” and “allows all scientists working at the full professional level to be recognised on an equal footing. It gives an assurance of current competence through annual CPD monitoring, and encapsulates the interdisciplinary nature of science in the 21st century. By benchmarking professional scientists at the same high level, C.Sci. aims to re-engage public trust and confidence in science and scientists.”

As mineralogists, should we not seek to equate our professionalism with that of colleagues who achieve C.Geol., C.Chem. or C.Eng. status?

Metamorphic Studies Group, Research in Progress Meeting

The MSG-RIP meeting will be held on 15 March 2015 at the University of Leeds. Further details to follow.
IS IT REALLY WORTH IT?
The imperative to become chartered is no doubt pressing at the back of many of our minds but not at the top of the ‘must do today’ list.
For university academics and others, if you want to promote your profession and show your industry and wider contacts that you work to international professional standards, chartered status is certainly for you.

HOW DO I BECOME CHARTERED?
The ‘best’ route to chartership is different for different people. The Mineralogical Society C.Sci. scheme requires applicants to have a certain amount of professional experience and to maintain a regular Continuing Professional Development (‘CPD’) record (see http://www.minersoc.org/chartered-requirements.html). There are two drivers for this: keeping up to date with evolving methods, regulations, standards and practice and also adding new skills which will broaden their experience.

BUT IT IS SO MUCH WORK!
The first thing to do is check the requirements to see if you meet the criteria. All this might sound a bit daunting, but remember, it is in the interests of the Mineralogical Society to see our most able members chartered. We offer guidance through the application procedure and will appoint a mentor to advise you on how best to present your application. No awarding body wants applications to fail, and if you are at an early stage in your career, your mentor will recommend that you make the final stage of the application only when you have a strong case for registration.

FIRST STEPS AND ADVICE
If you are considering applying for membership, the first port of call should be the Mineralogical Society web pages at http://www.minersoc.org/chartered.html. Contact Executive Director Kevin Murphy at kevin@minersoc.org. Kevin will team you up with someone who has experience in scrutinising applications to help make your application as straightforward and efficient as possible. You should not put off making those first important steps! Two examples follow:

• Mark Tyrer is a fellow of three institutions and was regularly making those first important steps! Two examples follow.
• Frances Wall is an academic at the University of Exeter, a fellow of the Mineralogical Society and the Geological Society and has also recently become C.Sci. through the Mineralogical Society. She is keen to encourage the view that ‘even’ university academics are professionals.

Anniversary

The Society’s Executive Director, Kevin Murphy, has reached a significant milestone, 25 years as an employee of the Mineralogical Society. Kevin joined the Society in early 1990: there was a typewriter on his desk, multipart invoices for book sales, very expensive typesetting and printing costs and just a mere hint of the Internet in the air (!). Well, things have moved on. The mineralogical world is much smaller and faster moving. We have lots of wonderful collaboration between the societies and associations involved in our subject, and Kevin has many mineralogical friends all around the world. Here’s to the next 25!

Student Bursary 2014 to Adam Jeffery

Funding by the Society enabled Adam Jeffery of Keele University to attend the 1st International Workshop on Volcano Geology, held in Funchal, Madeira, in July 2014. The conference provided a forum for the discussion of state-of-the-art research topics, including volcanology, volcanic hazards and the impacts of volcanoes on society and the environment, and it attracted a wide variety of experts in physical volcanology, igneous petrology and geophysics. It represented a superb opportunity for Adam to disseminate some of his PhD research findings to an audience of leading academics and specialists. This was achieved via two oral presentations:


Adam also took part in a very informative two-day field excursion detailed the extraordinary volcanic geology of Madeira Island, led by Prof. António Brum da Silveira of the University of Lisbon, Portugal.

Introduction to the Rock-Forming Minerals III

The third edition of this iconic textbook was published by the Mineralogical Society in May 2013 and is now available for sale. The volume has been completely updated, is printed in full colour at A4 size and includes over 200 colour images, including those from the Atlas of Rock-forming Minerals (with the permission of Pearson, UK) and from CrystalMaker. A CD including interactive images of crystal structures of many of the minerals listed in the book is also included.

Pricing

• List price: £35
• Non-member price: £40
For posts to the UK, add £4 per book by sign-up for digital membership (if you do not already have a digital membership).

ORDERING

Order the book online at www.minersoc.org

For students, join the Society today (free of charge for students) and get a discount on the cost of this book.

For further information please contact the Mineralogical Society (info@minersoc.org).
Mineralogical Society of America

www.minsocam.org

PRESIDENT’S LETTER

Minerals Matter—Ways You Can Help MSA to Promote Mineral Awareness

You’re probably reading this because you are an MSA member. And if you are an MSA member, it is because you love minerals for their beauty, you love what minerals tell us about the Earth, or you make your living teaching about or selling minerals. In an era of flashy science and short attention spans, most of us would agree that mineralogy could benefit from an increase in visibility in the physical sciences and more specifically in the geosciences. In this newsletter, I would like to suggest ways you can take a leadership role in promoting mineral science through MSA, ways that are fun and important especially if you are in early- or mid-career.

MSA is typical of most scientific societies in that it is run by individuals well along in their careers. Early- and mid-career scientists usually play a lesser role at the top for a number of reasons. They may be starting families, obtaining tenure, developing courses, advising grad students, honing their research focus, or not be as well known. If they are involved, they are perhaps on an MSA committee—an opportunity available only by invitation and perhaps not the first thing that would go on a to-do list.

There are three simple ways in which any motivated MSA member, especially members in early- or mid-career, can get directly involved: (1) by developing an MSA session at a national meeting, (2) by organizing an MSA topical workshop, and (3) by writing a Minerals Matter Geoscience Sheet.

1. MSA Sessions If you have been to a national or international meeting and lamented the lack of talks in an area of mineralogy that is of deep interest to you, now is the time to take charge. MSA has technical session sponsorship arrangements with GSA, AGU, and the Goldschmidt conferences. You can respond to calls for sessions from these societies or contact the scientific program committee for the meeting directly. Propose a session with several colleagues. Contact the scientists you want to see in your session to remind them to submit an abstract. Structure the order of talks in the session for maximum impact. There are few things more enjoyable than attending a meeting where you have been the key organiser of a packed, exciting session. Besides, it is great for your professional visibility. Deadlines for proposing sessions: (1) February 2015 for the GSA 2015 Annual Meeting, Baltimore, USA; (2) for the Fall AGU 2015, San Francisco, USA; and (3) November 2015 for Goldschmidt 2016, Yokohama, Japan.

2. MSA Topical Workshops MSA has instituted topical workshops that are held at the GSA annual meetings and Goldschmidt conferences. These workshops are the brainchild of MSA Past President David Vaughan. They are a one-day-only series of lectures given by experts to small groups of students, teachers, and professionals that highlight the state of the art in a research area. They are given either the day before or the day after a national/international meeting, and there can be more than one at a meeting. They are exciting because they can be organized with less lead time than a short course and tailored to a hot, current, or important topic. In scope they are the meeting equivalent of an issue of Elements except that there is no publication associated with them. The first of these, entitled Deep Data through Deep Time, was held at the 2014 GSA meeting in Vancouver and organized by Bob Hazen. New topical workshops are being planned, such as Diffusion and Mars Mineralogy. Please think about organizing one of these workshops and contact David Vaughan, University of Manchester (david.vaughan@manchester.ac.uk), MSA Workshop Coordinator, if you are interested.

3. Minerals Matter Geoscience Sheets This is a new idea introduced in 2014. We are starting a series of informational publications entitled Minerals Matter Geoscience Sheets (MMGS). These little papers are one page in length with no more than two figures and five references and are devoted to one mineral per Sheet. Authorship will be limited to MSA members. They will describe a microscale property of a mineral or rock and relate it to some large-scale geologic process or finding. The purpose is to link the scale on which we actually study minerals to the scale we study planetary geologic processes in a short document that captures the scale idea in a straightforward way. MMGSs should be designed to be scientifically accurate but not complicated for the reader. Geologic processes operate on the scale of minerals and are controlled by mineral properties, but outside our scientific community this fact is poorly understood and underestimated.

For example, MMGSs could be written that describe the relationship between dislocation in olivine and mantle convection, inclusions in diamond and recycling, microcracks in shale and natural gas extraction, OH storage in minerals and the existence of an ocean, shock lamellae in quartz and meteorite impact, SiC grains and stellar nuclear processes, and zircon and continental growth.

MMGSs will be written for the high school level in a “News and Views” style so that they can be used by students in beginners’ classes, be understandable to nonscientists and policy makers, and, with their five references, act as a springboard for further enquiry. They will be published in American Mineralogist and so will be citable, and they will be archived on the MSA website and be available for on-demand printing for classroom use.

We are working on the first two MMGSs and seek ideas for others. Please contact me with your thoughts, suggestions, and ideas.

Steven B. Shirey (sshirey@carnegiescience.edu) 2015 MSA President

NOTES FROM CHANTILLY

- MSA will have electronic balloting for its 2015 election of MSA officers and councilors. The slate of candidates is as follows. President: Rebecca A. Lange, University of Michigan. Vice president (one to be selected): Mickey E. Gunter, University of Idaho, and George E. Harlow, American Museum of Natural History. Secretary: Brian Chakoumakos and Jacob Lowenstern. Councilors (two to be selected): Aaron Celestian, Rasdeep Dasgupta, Francis McCubbin, and Peter Nabelek. Howard Day continues in office as treasurer. Continuing councilors will be Edward S. Grew, Wendy Panero, Abby Kavner, and Matthew J. Kohn.

- All 2013 and 2014 MSA members have been contacted by mail, electronically, or both about renewing their membership for 2015. 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 any time.

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

IN MEMORIAM

Stefan S. Hafner – Senior Fellow
Hans Wondratschek – Senior Fellow
MSA & GS SHORT COURSE ANNOUNCEMENTS

Pore-Scale Geochemical Processes
Organizers: Carl Steefel, Simon Emmanuel, and Larry Anovitz
14–15 August 2015, Design Elephant Hotel, Prague, Czech Republic

This short course will review recent research on the pore-size dependence of reaction rates; thermodynamic and kinetic factors that influence geochemistry in nano-confined pores; and the experimental, characterization, and modeling advances in our understanding of pore-scale geochemical processes. Characterization approaches include X-ray synchrotron techniques, small-angle neutron scattering (SANS), backscattered electron (BSE) mapping, and FIB-SEM mapping of pore structure. Experimental studies include those making use of micromodel and/or microfluidic approaches that quantify geochemical or coupled geochemical transport processes. Several of the most important pore-scale modeling approaches, including direct numerical simulation and lattice Boltzmann methods, as well as the coarser-grained approaches based on pore network methods and microcontinuum models, will be reviewed.

Siderophile and Chalcophile Elements
Organizers: Jason Harvey and James Day
14–18 December 2015, Scripps Institution of Oceanography, San Diego, USA

The strongly chalcophile (sulfur-loving) elements include Se and Te, while the highly siderophile (iron-loving) elements are the platinum-group elements (PGEs: Ir, Os, Pt, Pd, Rh, Ru), Re, and Au, and include the long-lived isotope systems based on the decay of Re and Pt to isotopes of Os ($^{187}\text{Re}-^{187}\text{Os}$ and $^{190}\text{Pt}-^{190}\text{Os}$, respectively). These elements and their isotopes have received less attention than the more familiar lithophile elements and their associated isotope systems. As a result of the strong partitioning of siderophile and chalcophile elements into metals, alloys, and sulfides, study of the distribution and behavior of the siderophile and chalcophile elements and the phases that host them has the opportunity to provide unique perspectives on how the major geochemical reservoirs of the Earth and other rocky planets formed and have developed over time; these subjects include tracing core–mantle interaction, determining the history of melt depletion within the mantle of the rocky planets, the mobilization and concentration of precious metals with siderophile/chalcophile behavior during the formation of ore deposits, and the geochronology of diamonds and their role in tracing the formation of Earth’s ancient lithosphere.

DMG & MSA SHORT COURSE / WORKSHOP ANNOUNCEMENT

Application of Diffusion Studies to the Determination of Timescales in Geochemistry and Petrology
Organizers: Sumit Chakraborty and Ralf Dohmen
24–28 August 2015, Ruhr Universität Bochum, Germany

This workshop is aimed at petrologists, geochemists, and planetary scientists interested in retrieving information on the timescales of high-temperature processes from their rocks. Such information might include the residence times of magmas in their reservoirs, the cooling or exhumation rates of rocks, the duration of terrestrial and extraterrestrial (e.g. parent bodies of meteorites) metamorphism, the duration of fluid flow (e.g. metasomatism by fluids/melts in the crust or mantle), and the evaluation and application of closure temperatures. For further description and online registration, go to www.minsocam.org or contact the Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110, USA; phone: +1 (703) 652-9950; fax: +1 (703) 652-9951.

APPLY FOR STUDENT RESEARCH GRANTS

The Mineralogical Society of America 2016 Grants for Research in Crystallography from the Edward H. Kraus Crystallographic Research Fund with contributions from MSA membership and friends

Student Research in Mineralogy and Petrology from an endowment created by MSA members

Selection is based on the qualifications of the applicant and the quality, innovativeness, and scientific significance of the research as judged from a written proposal and the likelihood of success of the project. There will be up to three US$5000 grants with the restriction that the money be used in support of research. Application instructions and online submission are available on the MSA website, http://www.minsocam.org. Completed applications must be submitted by June 1, 2015.

NOMINATIONS SOUGHT FOR 2016/2017 AWARDS

NOMINATIONS MUST BE RECEIVED BY JUNE 1, 2015

The Roebling Medal (2016) is MSA’s highest award and is given for eminence as represented by outstanding published original research in mineralogy.

The Dana Medal (2017) recognizes continued outstanding scientific contributions through original research in the mineralogical sciences by an individual in the midst of their career.

The Mineralogical Society of America Award (2016) is given for outstanding published contribution(s) prior to the 35th birthday or within 7 years of the PhD.

The Distinguished Public Service Medal (2017) is presented to an individual who has provided outstanding contributions to public policy and the awareness of mineralogical topics through science.

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

MINERALOGICAL SOCIETY OF AMERICA

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

For further description and online registration, go to www.minsocam.org or contact the Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110, USA; phone: +1 (703) 652-9950; fax: +1 (703) 652-9951.
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For more information please visit www.bruker.com/elements
MICADAS: NEW INSTRUMENTATION FOR CARBON-14 DATING

I recently had the pleasure of visiting the Ion Beam Physics Group at ETH-Zürich, a place well known for innovative analytical instrumentation. Even before my trip I was eager to learn about Zürich’s new “mini” accelerator mass spectrometer, which was specifically designed for high-throughput ¹⁴C dating applications. MICADAS—an acronym for Mini Carbon Dating System—came into existence in the mid-2000s (Synal et al. 2004, 2007), and since then it has undergone further design improvements. What is novel about this mass spectrometer is that it shrinks the overall dimensions of such instrumentation from the tens of meters of a “traditional” ion accelerator down to a size small enough to fit into a mere 30 m² of laboratory space. No longer must such analytical tools be kept under the watchful gaze of physicists and engineers: accelerator mass spectrometry is entering the arena of geochemical instrumentation that can be supported by a geoscience department at a well-equipped university. An important aspect of the MICADAS system has been the focus on automation and high sample throughput, allowing up to 40 high-precision determinations per day with virtually no operator intervention and minimal instrument tuning.

What distinguishes MICADAS from its larger cousins is the use of a relatively modest acceleration voltage of “only” 200 kV, allowing for a much simplified design of the instrument’s acceleration unit and smaller overall dimensions. Negative carbon ions from the sample, generated in the cesium sputter ion source, are initially accelerated by a ~38 kV potential that injects the ions into the instrument (Fig. 1). An initial sector field magnet deflects the ion beam by 90°, feeding a mass-separated beam to the accelerator segment of the instrument. An added advantage of the low-energy sector magnet is that it permits direct measurement of the ¹³C⁻ peak intensity when the low-energy magnet is set for m/e = 14; this ¹³C⁻ signal can be used to monitor the ion beam’s intensity and stability. Farther downstream the ions enter the spectrometer’s accelerator segment, where a high electric field gradient accelerates the ions into a gas-filled stripper tube. This tube, in a recent modification, is filled with helium gas (at a mean pressure of about 20 Pa) that interacts with the ion beam; multiple collisions between the high-energy ions and the stripper-gas atoms cause the ions to undergo a charge-state conversion, from their initial −1 to a +1 charge state. The now positively charged ions are accelerated a second time back to ground potential—hence the term “tandem” accelerator. Crucially, this collision process is nearly 100% efficient at destroying molecular ions that might be present in the ion beam (e.g. ¹³C¹H on the m/e = 14 mass station) while transmitting nearly half of the atomic C⁺ ions to the exit of the high-voltage segment. These atomic C⁺ ions, now with a total energy of 438 keV and m/e = 12, 13, or 14 (depending on which species is being transmitted by the low-energy magnet at a given point in time), are projected into a second magnetic field sector. This so-called high-energy magnet provides a static magnetic field that steers a given mass to a dedicated ion detector: Faraday cups for ¹²C⁺ and ¹³C⁺ or, in the case of much less abundant ¹⁴C⁺, a gas ionization detector farther downstream after an energy filter (electrostatic analyzer). Put all together, this system has a machine background ¹³C/¹²C value on the order of 3 × 10⁻¹⁶ and is able to measure ratios with a total uncertainty of ±2‰ or better on contemporary (so-called “modern”) samples, while requiring a total analysis time of around 40 minutes per result. In other words, ¹⁴C dating of samples with ages up to 50 thousand years has now become possible on what one could (somewhat euphemistically) describe as a bench-top system. This raises the topics of sample preparation and how a laboratory is to cope with providing the many thousands of samples needed for daily operation throughout a year. In this our colleagues in Zürich have also been active. The ion source of the MICADAS system has been optimized for maximum flexibility, accepting graphitized material or CO₂ gas (Fig. 2). Graphitized material can be directly sputtered using a Cs ion source. Alternatively, when CO₂ is to be used, the sample material can be combusted by an elemental analyzer system, after which the sample is transported by helium entrainment to a zeolite trap (Ruff et al. 2010), allowing subsequent injection of the CO₂ sample gas directly into the mass spectrometer. In other setups, sample CO₂ is fed into the MICADAS ion source from sealed glass ampoules or, alternatively, from an automated system for acid digestion of carbonate samples (see Fahnri et al. 2013; Wacker et al. 2013). All the above methods are automated, and the MICADAS’s sensitivity allows for sample amounts as small as 10 µg of total carbon. Despite the somewhat reduced precision of such measurements, the ability to operate the MICADAS in conjunction with a gas ion source (Fig. 3) may well prove key for the adoption of this technology. Such flexibility in terms of sample type, combined with good overall sensitivity, means that the analysis of, for example, single foraminifera tests can become quasi-routine. With nine MICADAS systems already in operation across Europe and in the USA, it is reasonable to expect a rapid increase in the number of scientific publications making use of ¹⁴C age determinations produced by MICADAS instruments. With the upcoming full commercialization

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**Figure 1** (Top) Photo of the MICADAS instrument, with a total flight tube length of 8 m. The sample introduction and ion source is at the lower left of the picture and the high-voltage segment are at the top center. The gas bottle shows the scale. (Bottom) Simplified diagram of the ion optics of the MICADAS system. The high-voltage segment is shown in green. Diagram courtesy of the ETH Ion Beam Physics Group. Photo courtesy of S. M. Fahnri

**Figure 2** Examples of graphitized ampoule (top) and gas ampoule (bottom) sample formats, both of which the MICADAS can run in an automated mode. Courtesy of S. M. Fahnri
of the MICADAS system, through the ETH spin-off Ionplus, one may expect the number of systems to continue to grow at a healthy rate well into the future. For me, this field looks ripe for a genuine revolution over the coming few years.

I want to thank Max Döbeli for hosting my visit to ETH-Zürich, as well as his helpful colleagues who were eager to explain their research. I would like to close by expressing my special thanks to Simon Fahrni for his assistance in explaining the many details of the MICADAS technology.

Best regards from Potsdam,

Michael Wiedenbeck
(michael.wiedenbeck@gfz-potsdam.de)

REFERENCES
Nuclear Instruments and Methods in Physics Research B 223-224: 339-345

FIGURE 3 Schematic layout of the MICADAS gas ion source, which allows the direct injection of CO2 sample gas entrained in a helium gas flow. Cesium gas injected into the source undergoes thermal ionization (yellow); the resulting Cs+ ions are then accelerated onto a titanium target (red), where the (partially neutralized) Cs interacts with the sample gas, producing C+ ions, which are fed into the mass spectrometer via the extraction lens (green). Courtesy of S. M. Fahrni; see also Fahrni et al. (2013).

Compact AMS Systems
National Electrostatics Corp. offers a wide variety of compact, low voltage AMS systems for radio isotope ratio measurement through the actinides. NEC also provides complete AMS systems up to 25MV. All NEC systems provide high precision and low background. They can be equipped with a high throughput, multi-sample ion source or dual ion source injector for added versatility.

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<th>Model</th>
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NEW ADDRESS
**2015**

**March 15–19**  TMS Annual Meeting & Exhibition, Orlando, FL, USA.  
Web page: www.tms.org/meetings/annual-15/AM15home.aspx

**March 16–20**  46th Lunar and Planetary Science Conference, The Woodlands, TX, USA.  
Web page: www.hou.usra.edu/meetings/lpsc2015

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

**April 6–10**  MRS Spring Meeting & Exhibit, San Francisco, CA, USA.  
Web page: www.mrs.org/spring-meetings

**April 12–17**  European Geosciences Union General Assembly, Vienna, Austria.  
Web page: www.eGU2015.eu

**April 20–24**  27th International Applied Geochemistry Symposium (AGS), Tucson, AZ, USA.  
Website: www.27ags.org

**May 3–7**  AGU-GAC-MGU-CGU Joint Assembly, Montreal, Canada.  
Web page: http://ja.agu.org/2015

**May 21–22**  The Institute on Lake Superior Geology 2015 Annual Meeting, Dryden, ON, Canada.  
Website: lakesuperiorgeo.com

Details forthcoming

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

**June 7–12**  Gordon Research Conference: Interior of the Earth, South Hadley, MA, USA.  
Web page: www.grc.org/programs.aspx?id=12344

**June 7–13**  Applied Mineralogy & Advanced Materials - International Conference AMAM 2015, Castellana Marina, Taranto, Italy.  
Website: www.amam2015.org

Website: www_icam2015.org

**June 14–19**  Gordon Research Conference: Catchment Science: Interactions of Hydrology, Biology & Geochemistry, Andover, NH, USA.  
Website: www.grc.org/programs.aspx?id=12330

**June 15–19**  Astrobiology Science Conference 2015, Chicago, IL, USA.  
Web page: www.hou.usra.edu/meetings/abscicon2015

**June 17–21**  7th international Symposium on Granitic Pegmatites (PEG 2015), Kazol, Pakistan.  
Details forthcoming

**June 21–26**  Isotopes 2015, Jerusalem, Israel.  

**June 22–29**  Extensional Reactivation of Thrust Faults, Coseismic Surface Rupture, and Crustal Evolution in the Eastern Basin and Range Transition Zone, Evanston, WY, USA.  
Web page: www.geosociety.org/penrose

**June 22–July 2**  XXVI General Assembly of the International Union of Geodesy and Geophysics (IUGG), Prague, Czech Republic.  
Web page: www.iugg2015prague.com

**June 26–28**  ECROF23 – The Sorby Conference on Fluid and Melt Inclusions, University of Leeds, UK.  
Web page: www.see.leeds.ac.uk/ecrof

Website: www.zmpc.org

**July 5–10**  52nd CMS Annual Meeting, Edinburgh, Scotland.  
Website: www.clay.org

**July 5–10**  Euroclay 2015, University of Edinburgh, UK.  
E-mail: stephen.hiller@hutton.ac.uk;  
Web page: www.minersoc.org/euroclay.html

**July 25–29**  Annual Meeting of the Geoanalysis Crystallographic Association, Philadelphia, PA, USA.  
Website: www.americalastasrin.org/content/pages/main-annual-meetings

**July 26–29**  Granulites and Granulites 2015, Windhoek, Namibia.  
Web page: wurtz.ca.de/depz/geolci/GGq_2015_1_circular.pdf

**July 27–31**  78th Annual Meeting of the Meteoritical Society, Berkeley, CA, USA.  
Website: www.meteoriticalsociety.org

**August 2–6**  Microscopy & Microanalysis 2015, Portland, OR, USA.  
Web page: www.microprobe.org/events/microscopy-microanalysis-2015

**August 2–7**  The 20th American Conference on Crystal Growth and Epitaxy (ACCGE-20), Big Sky, MT, USA.  
Web page: www.cystalgrowth.org

**August 8–14**  Geoanalysis Conference, Leoben, Austria.  
Website: http://2015.geoanalysis.info

**August 10–12**  ICAM 2015 (International Congress on Applied Mineralogy), Istanbul, Turkey.  
Web page: http://icam2015.org

**August 16–20**  250th ACS National Meeting & Exposition, Boston, MA, USA.  
Web page: www.acs.org

**August 16–21**  2015 Goldschmidt Conference, Prague, Czech Republic.  
Website: http://goldschmidt2015.info

**August 23–28**  29th Meeting of European Crystallographic Association (ECM29), Rovinj, Croatia.  
Website: ec29.ecanews.org

**August 24–27**  SGA 13th Biennial Meeting, Nancy, France.  
E-mail: stam.2015@univ-lorraine.fr;  

**August 24–28**  Joint DMG / MSA Workshop: Application of diffusion studies to the determination of timescales in geochemistry and petrology, Bochum, Germany.  
Website: www.minsocam.org/msa/SC/#open_sc

**September 9–11**  8th European Conference on Mineralogy and Spectroscopy (ECMS 2015), Rome, Italy.  
Details forthcoming

**September 20–25**  8th Hutton Symposium on Granites and Related Rocks, Florianopolis, Brazil.  
Web page: www.hutton.com.br

**September 21–25**  11th meeting on Applied Isotope Geochemistry (AIG-11), Orleans, France.  

Website: www.seg2015.org

**September 28–October 2**  22nd International Symposium for Environmental Biogeochemistry, Portoroz, Slovenia.  
Web page: www.iseb22.ijs.si

**October 4–8**  MS&T’15: Materials Science & Technology Conference and Exhibition, combined with ACerS 117th Annual Meeting, Columbus, OH, USA.  

**November 1–5**  Geological Society of America Annual Meeting, Baltimore, MD, USA.  
E-mail: meetings@geosociety.org;  
Website: www.geosociety.org/meetings

**November 9–13**  Short Course "Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences," Potsdam, Germany.  
Website: www.git-potsdam.de/3M3/short-course

**November 29–December 4**  MRS Fall Meeting & Exhibit, Boston, MA, USA.  
Web page: www.mrs.org/fall-meetings

**2016**

**January 18–22**  10th International Symposium on Environmental Geochemistry (ISEG10), Perth, Western Australia.  
Website: www.iseg10.com

**January 24–29**  40th International Conference and Expo on Advanced Ceramics and Composites (ICACC’16), Daytona Beach, FL, USA.  
Details forthcoming

**February 26–March 2**  TMS Annual Meeting & Exhibition, San Diego, CA, USA.  
Web page: www.tms.org/meetings/annual-17/AM17home.aspx

**April 2–6**  253rd ACS National Meeting & Exposition, San Francisco, CA, USA.  
Web page: www.acs.org

**May 8–June 17**  International Kimberlite Conference (111RC), Gabrone, Botswana.  
Details forthcoming

**August 20–24**  254th ACS National Meeting & Exposition, Washington, DC, USA.  
Web page: www.acs.org

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

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 http://homepages.udayton.edu/~akoziol/meetings.html). To get meeting information listed, please contact her at Andrea.Koziol@notes.udayton.edu.
PARTING SHOTS

PARTING WAYS

Pierrette Tremblay and Tom Clark, who have been an integral part of Elements over the past 10 years, were invited to write this issue’s Parting Shots. I hope you enjoy reading their parting words as they embark on their next adventure, retirement.

Jodi Rosso

As I write this, I am in the second week of my “official” retirement. I am discovering the art of slowing down... taking my time to enjoy my coffee in the morning, doing the crossword puzzle, picking up my knitting for a few minutes, etc.


Tom Clark and I met while in graduate school at Queen’s University, Kingston. We married in January 1974 and moved to Quebec City in the fall of 1975 to take jobs with the Quebec government. Ironically, my first job was as editor of geological reports, and I hated it. I longed to do field work, and one year later, I got an opportunity to work as a mineral deposits geologist with the government. In 1979, our son David was born. I was lucky to have a one-year maternity leave, but when the year was up, I could not tear myself away from this beautiful toddler and I quit my secure job to be at home. Both Tom and I believe that our greatest life accomplishment has been the raising of our three children, now grown up. We derive so much pleasure from watching them chart their own lives.

In 1998, I took over the editorship of the Mineralogical Association of Canada (MAC) Newsletter and I enlisted Tom’s help to edit the texts. Issue 58, the first issue under my editorship, had 12 pages; by October 2004, the Newsletter had grown to 24 pages and 3 issues a year, and I had introduced some color. I enjoyed planning the layout, encouraging people to write for it, and of course, getting feedback from members saying how much they enjoyed reading it. I was very proud of it, and only something as exciting as Elements could induce me to leave it.


Elements has become a big beast: from 320 pages in 2005, it has grown to 480 pages. One day, when the first issue was being planned, Tom told me, “You will need a copy editor; I could do it.” Oops! There was no line item for a copy editor in the budget. So Tom copyedited Elements as a volunteer for seven years.

Over the past ten years, working with more than 100 guest editors, I pride myself in the fact that it has been a positive experience for all of them, and in fact, many have written to say how much they appreciated the care taken in handling their manuscripts. Even though our lineup is firmed up years in advance and we have no backup plans if an issue goes awry, somehow, almost magically, just about everyone has come through.

Since copyediting is a rather solitary endeavor that does not lend itself to interesting photographs, I’ve included a field photo of me in my other life, that of a (now part-time, “retired”) geologist for Quebec’s department of energy and natural resources. A few weeks before the photo was taken in 2011, it had dawned on me that the layered “ultramafic” rocks in the field area, like those in the picture, were actually banded silicate iron formation metamorphosed to granulite facies. Sharp-eyed readers will notice in the photo a bilaterally symmetrical pattern in the banding and some very tight fold hinges in the white metachert layers. Interpreting this isoclinally folded outcrop was, for me, a thrilling moment, one that I wanted to share.

The photo exemplifies why I like field geology—it’s fun, and every new outcrop holds promise of an exciting discovery. A similar feeling of excitement for their subject is surely why, for ten years now, some of geology’s best scientists have been sharing their stories and discoveries with readers of Elements. It’s been a joy for me to read their articles, and I trust they will continue to inform and inspire us in the magazine for many years to come.

Tom Clark

Tom beside an isoclinal fold in meta–iron formation in the Grenville province, Quebec, in 2011.

To learn more about Elements:

Ewing RC (2014) Presentation of the Distinguished Public Service Award for 2013 of the Mineralogical Society of America to Pierrette Tremblay. American Mineralogist 99: 1185
Parsons I (2009) Five years on. Elements 5: 408

many excellent ones to choose from—it would be Mike Hochella’s manuscript on nanoparticles (volume 1, number 4, pages 199–203). After reading it, I was so excited: I understood it all! I am also a big fan of Peter Heaney’s writing—I loved reading his intricately woven stories in his Triple Point articles—and of Ian Parsons’ marvelously entertaining and personal Parting Shots.

What gives grey hairs to an editor/copy editor? Capitals, commas, and typos. No matter how careful you are, typos can be introduced at all stages of working with a manuscript. My biggest worry has been a typo in a title. Well, it happened in my final issue: the Travelogue has a typo in the title. All proofs were fine; the graphic artist thinks he introduced the typo when making the final pdfs. *Telle est la vie d’un éditeur!*

The joys have been many, and far outweighed the frustrations: joys such as the times someone wrote to say thank you or say that they enjoyed reading *Elements*, the times interacting with advertisers, the positive interactions with the larger community, watching *Elements*’ impact factor grow, etc.

**AFTER ELEMENTS**

My plans for the coming year include: learning traditional Nova Scotia rug hooking, getting my weaving loom in working order (it has been abandoned since 1979), brushing up on my Italian, learning Spanish, and spending more time with my lovely granddaughter. Tom and I are looking forward to traveling: our next adventure is an upcoming one-month holiday on our favorite Caribbean island, Barbados.

Tom and I enjoy many of the same activities: spending time at our summer home in Nova Scotia, traveling, going to the movies, trying out the fine restaurants in Québec City, and cross-country skiing. Between our shared interests and individual hobbies (I enjoy cooking and knitting; Tom likes drawing, pastels, and biking), there should be enough to keep us busy in the years to come.

Thanks for all the memories and the support over these 10 years! It has been great. And good luck Jodi!

*Pierrette Tremblay*
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