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Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology

Mineralogy of Mars

JOHN P. GROTZINGER, Guest Editor

Curiosity's Mission of Exploration

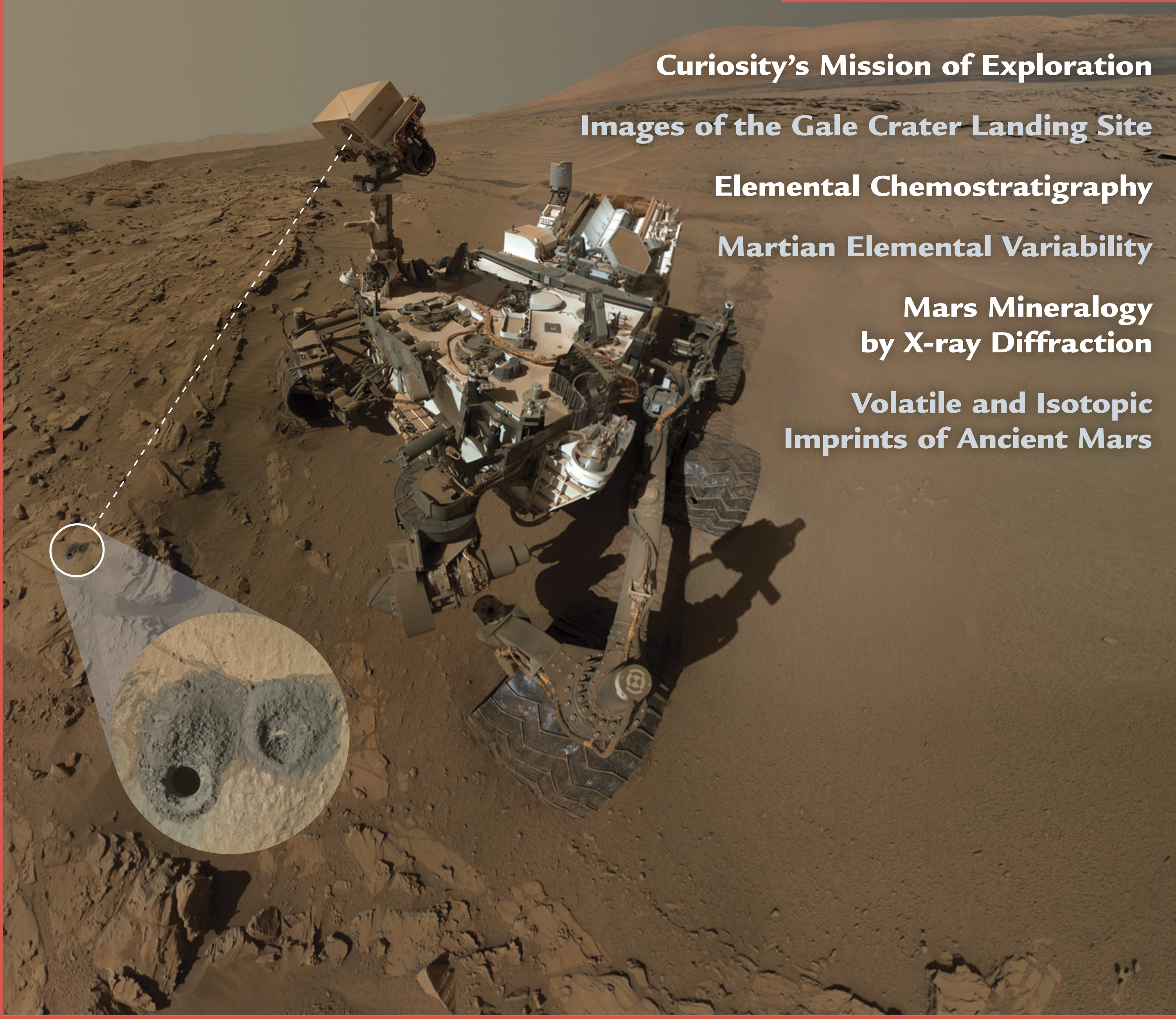
Images of the Gale Crater Landing Site

Elemental Chemostratigraphy

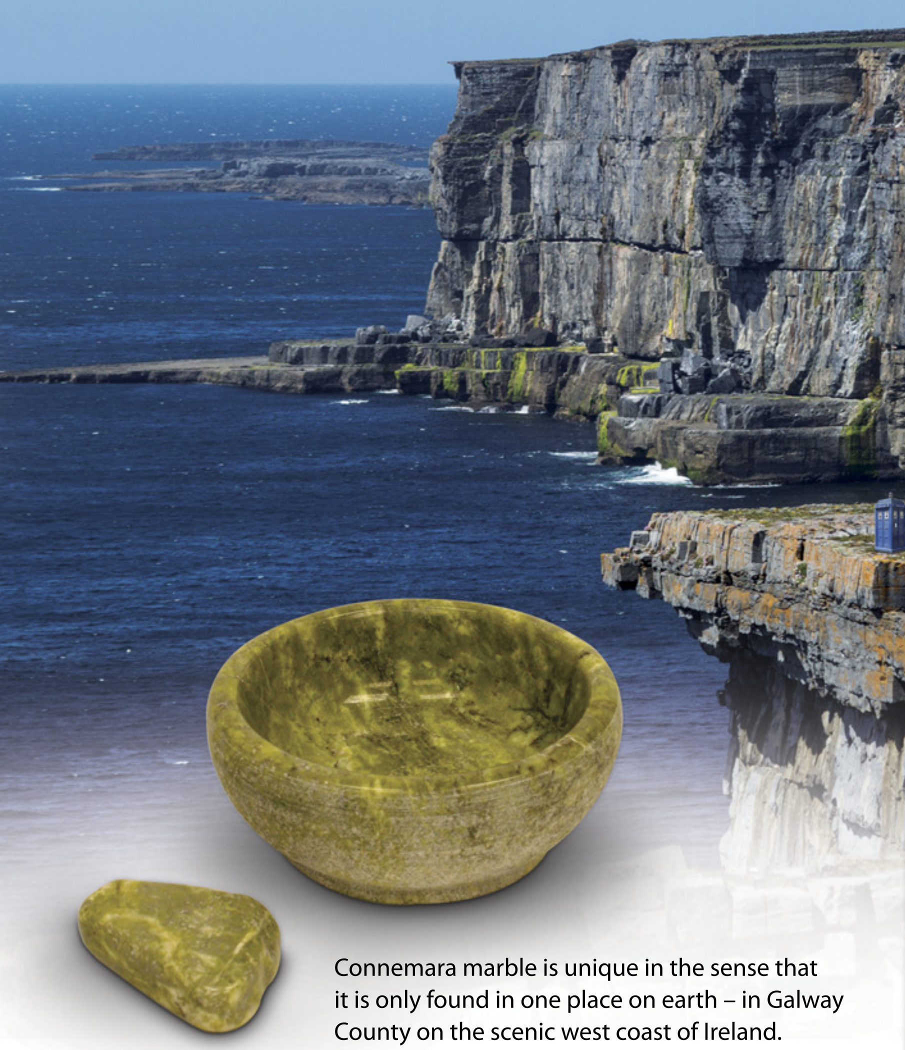
Martian Elemental Variability

Mars Mineralogy by X-ray Diffraction

Volatile and Isotopic Imprints of Ancient Mars

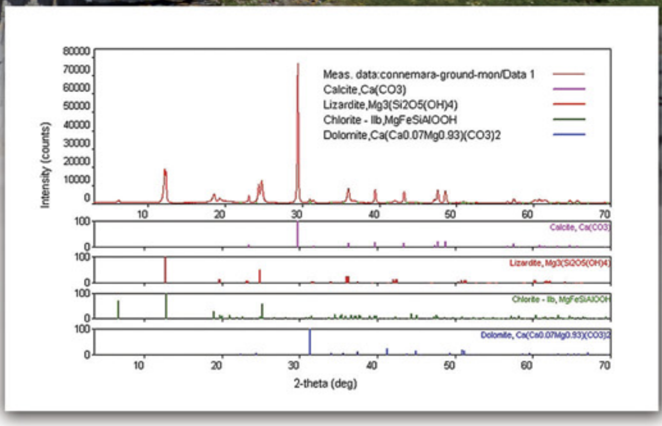


Phase identification and Rietveld refinement of Connemara marble with a benchtop X-ray diffractometer



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.



Mineral	Chemical Formula	Wt %
Lizardite	$Mg_3 (Si_2O_5(OH)_4)$	38.2
Calcite	$CaCO_3$	44.5
Chlorite IIb	MgFeSiAlOOH	15.1
Dolomite	$CaMg(CO_3)_2$	2.2

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.

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About the Cover:

Self-portrait of the rover Curiosity at the Windjana drill site in the Kimberley region, Gale Crater, Mars. With the Mars Hand Lens Imager (MAHLI), located at the end of the rover's robotic arm, Curiosity acquired 64 images that were merged to create the photomontage shown on the cover. Images were collected on sol 613 (April 27, 2014), 621, and 627. The inset shows the holes she drilled for sample analysis (test hole on right). Image courtesy of NASA/JPL-Caltech/MSSS

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

Elements is published six times a year. Individuals are encouraged to join any one of the participating societies to receive *Elements*. Institutional subscribers to any of the following journals—*American Mineralogist*, *Clay Minerals*, *Clays and Clay Minerals*, *Mineralogical Magazine*, and *The Canadian Mineralogist*—also receive one copy of *Elements* as part of their 2015 subscription. Institutional subscriptions are available for US$160 (US$175 non-US addresses) a year in 2015. Contact the executive editor (jrosso.elements@gmail.com) for information.

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Mineralogy of Mars

Guest Editor: **John P. Grotzinger**

DEPARTMENTS

The Mineralogical Society of America is composed of individuals interested in mineralogy, crystallography, petrology, and geochemistry. Founded in 1919, the Society promotes, through education and research, the understanding and application of mineralogy by industry, universities, government, and the public. Membership benefits include special subscription rates for *American Mineralogist* as well as other journals, a 25% discount on Reviews in Mineralogy & Geochemistry series and Monographs, *Elements*, reduced registration fees for MSA meetings and short courses, and participation in a society that supports the many facets of mineralogy.

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

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

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

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

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Founded in 1985, **the European Association of Geochemistry** is a non-profit organization dedicated to promoting geochemistry internationally. The society is an active and dynamic organization of over 2700 members that leads the biannual European Goldschmidt Conference organization, publishes *Geochemical Perspectives*, recognizes scientific excellence through awards, sponsors workshops and conferences in Europe and organizes a Distinguished Lecture Program.

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

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

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

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

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

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

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

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

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

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

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

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Affiliated Societies

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

HAS LIFE EVER EXISTED ON MARS?

Gordon E. Brown, Jr.

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.

Figure 1 Artist's depiction of three-legged fighting machines constructed by invading Martians in H. G. Wells' *War of the Worlds* (from http://www.waroftheworldsgame.com/images/thames-wallpaper.jpg). Ironically, the heat rays on these machines resemble the lasers used by Curiosity's ChemCam instrument to determine the elemental composition of Martian rocks.

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 organics. 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 PAHs, 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 elements, isotopes, organics, 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. Most importantly, the evidence gathered by Curiosity and interpreted by MSL Chief

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THIS ISSUE

Curiosity and her sister rovers (Sojourner, Spirit, and Opportunity) have captured our imagination since Sojourner safely landed on Mars in 1997. Although Sojourner and Spirit are no longer active, Opportunity continues to gather data and, in July 2014, NASA announced that she had set a new "off-world" distance record by having traveled over 40 km since her landing in 2004. Curiosity is the most recent NASA rover to explore Mars. As you will read in this issue, Curiosity is providing a wealth of petrological, geochemical, and mineralogical data that excite scientists and nonscientists alike.

Curiosity landed at Gale Crater on August 6, 2012, and is currently at the foot of a 5.5 km high mountain dubbed Aeolis Mons (popularly known as Mt. Sharp). The Mars Science Lab mission scientists chose Mt. Sharp as their primary target because it contains sedimentary rocks deposited over billions of years, potentially holding clues to Mars' environmental past. Curiosity's first mission, however, was to explore Yellowknife Bay, including drilling the first holes by a robot on another planet. Eleven months after landing, Curiosity pulled anchor on July 4, 2013, and began her year-long trek to Mt. Sharp, arriving in September 2014. Along the way, she mapped broad plains, rocky ridges, and sandy valleys, and sampled outcrops to search for compositional and mineralogical patterns. But, the route was not without hazards, including abundant sharp rocks that damaged the wheels (see front cover), thereby slowing the pace of exploration. On Mars, there are no emergency roadside services, and the nearest spare wheel is millions of kilometers away. Mission scientists, therefore, learned to avoid the damaging rocky ridges and to drive through the safer sandy valleys instead. Scenic overviews were traded for spectacular panoramas of layered bedrock that revealed the geologic history of the Gale Crater plains. Curiosity may not match Opportunity's distance record, but she will definitely continue to satisfy our scientific curiosity.

Not only are Curiosity and Opportunity studying Mars' geologic past, they are also busy documenting present-day environmental conditions. Ultimately, these robotic explorers are paving the way for manned missions to Mars; it is NASA's goal to send humans to Mars in the 2030s. Curiosity has sent several incredible "selfies" back to Earth over her 2-year mission (see front and back cover images). It is exciting to think that in 20+ years we might see "selfies" from human geoscientists on Mars instead!

CHANGING OF THE GUARD

The *Elements* editorial team is in the midst of transition. Pierrette Tremblay has "officially" retired after 10 years at the helm of *Elements*. Tom Clark, our faithful copy editor, is retiring. So, we thought it appropriate to ask Pierrette and Tom to write this issue's Parting Shots article. Dolores Durant, our dedicated proofreader, will also be retiring after this issue. We extend a huge THANK-YOU to them for 10 years of dedicated service to *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 supergene deposits.

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

EDITORIAL *Cont'd from page 3*

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

REFERENCES

Jull AJ, Courtney C, Jeffrey DA, Beck JW (1998) Isotopic evidence for a terrestrial source of organic compounds found in martian meteorites Allan Hills 84001 and Elephant Moraine 79001. Science 279: 366-369

Maniloff J, Nealson KH, Psenner R, Loferer M, Folk RL (1997) Nannobacteria: size limits and evidence. Science 276: 1776-1777

McKay DS and 8 coauthors (1996) Search for past life on Mars: possible relic biogenic activity in Martian meteorite ALH84001. Science 273: 924-930

Navarro-González R and 11 coauthors (2006) The limitations on organic detection in Mars-like soils by thermal volatilization-gas chromatography-MS and their implications for the Viking results. Proceedings of the National Academy of Sciences 103: 16089-16094

Taglieri J (2012) Quicklet on H.G. Wells' The War of the Worlds. Hyperink, Palo Alto, 30 pp

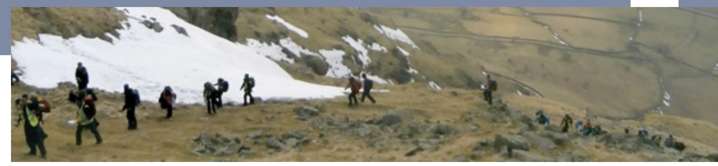
Wallace AR (1907) Is Mars Habitable? Macmillan and Co., Ltd., London, 137 pp

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

White LM, Gibson EK, Thomas-Keprta KL, Clemett SJ, McKay DS (2014) Putative indigenous carbon-bearing alteration features in Martian meteorite Yamato 000593. Astrobiology 14: 170-181

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*



Field trip to examine ignimbrites and lacustrine sediments at Scafell Pike in the Lake District (England). Photo courtesy of L. R. Pure

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

Image from anunews.net

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 life style. 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!

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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.

TIMELINE FOR AN APPLICATION

For graduate degrees in most countries, consider contacting potential supervisors as early as a year before you wish to commence your graduate degree because there is a lot to arrange (Table 1). If you submit an application late, you may not be considered for financial aid or you may need to delay your start date. The exception is mainland Europe, where many PhD positions are advertised through the supervisors or larger research programs and PhD students are employed by the supervisors on a salary rather than a scholarship. For such positions in Europe the timeline in Table 1 does not apply.

Some universities require you to submit your application online with recommendation letters included. Other universities request recommendation letters after they have received all your information. In either case, your application package is not complete until all parts, including recommendation letters, are submitted; therefore, it is important to give your recommenders plenty of time to write a letter.

Table 1 APPROXIMATE TIMING FOR GRADUATE DEGREE APPLICATIONS FOR THE START OF THE UNIVERSITY CALENDAR YEAR.

	Task	Months before enrollment
1.	Research potential advisors and topics	10–12
2.	Talk to potential advisors. Arrange a visit or Internet contact.	6–12
3.	GRE (N. America) and TOEFL	12
4.	Provide a finalized application to individuals writing your recommendation letters	8
5.	Application deadlines	4–7
6.	Announcement of acceptance of application	2–5

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:

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

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!

ADDITIONAL RESOURCES

Canadian Association of Graduate Studies, http://www.cags.ca/documents/publications/best_practices/CAGSHandbook05.pdf

THE STUDY OF EXOGENIC ROCKS ON MARS—AN EVOLVING SUBDISCIPLINE IN METEORITICS

James W. Ashley*

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). 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 irons 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
Kasos	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
Oileán Ruaidh	Opportunity	2368	iron	PancamNavcam
Ireland	Opportunity	2374	iron	PancamNavcam
Bingag Cave	Opportunity	2642	iron	PancamNavcam
Dia Island	Opportunity	2642	iron	PancamNavcam
Canegrass	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

* Official name: Meridiani Planum (Connolly et al. 2006)

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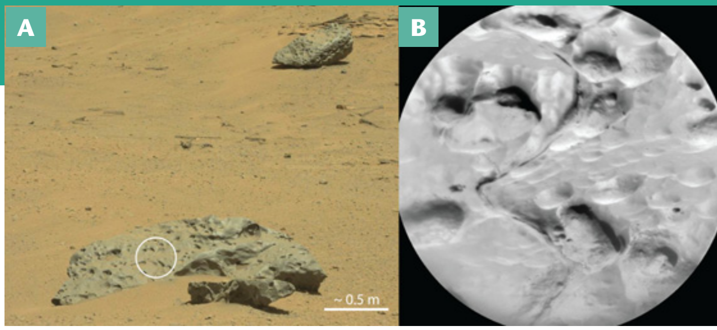

Figure 1 (**A**) Released images of Lebanon, Lebanon B, and Littleton taken by Curiosity's Mastcam on MSL sol 640 in Gale Crater. (**B**) A ChemCam Remote Micro-Imager view of the circled area in (A). Note the deep incision, the scalloped and polished surface, and the enlarged hollows. Images courtesy of NASA/JPL/LANL

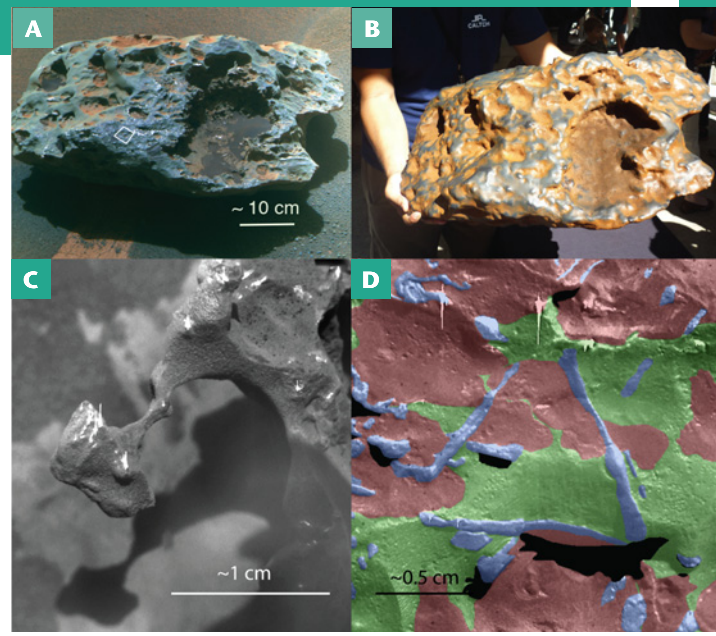

Figure 2 The Block Island meteorite found by Opportunity on Meridiani Planum on sol 1961. (**A**) The outline shows the Microscopic Imager (MI) mosaic area shown in D; north is toward the lower left. (**B**) A full-scale, resin 3-D print of Block Island prepared by Kris Capraro of JPL from a geometric model using Pancam images collected at six circumferential rover standoff positions around the meteorite. (**C**) A hammerhead-shaped metal protrusion together with its shadow along the rim of Block Island's conspicuous pit. (**D**) Map of the MI mosaic area in (A). Blue indicates Widmanstätten pattern (may be taenite or schreibersite lamellae), red is iron oxide/oxyhydroxide coating, green is bare metal, and black is shadow. Images courtesy of NASA/JPL/MIPL/Pancam/MI

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.

REFERENCES

Ashley JW, Wright SP (2004) Iron oxidation products in Martian ordinary chondrite finds as possible indicators of water exposure at Mars Exploration Rover landing sites. 35th Lunar and Planetary Science Conference, abstract 1750

Ashley JW and 16 coauthors (2011a) The scientific rationale for studying meteorites found on other worlds. In: Visions and Voyages for Planetary Science in the Decade 2013-2022. National Academies Press, 400 pp

Ashley JW and 9 coauthors (2011b) Evidence for mechanical and chemical alteration of iron-nickel meteorites on Mars: Process insights for Meridiani Planum. Journal of Geophysical Research 116: E00F20, doi: 10.1029/2010JE003672

Ashley JW, Velbel MA, Golombek MP (2015) Weathering-induced fragmentation as a possible contributor to anomalous stony meteorite scarcity on Mars — Insights from Antarctica and MER. 46th Lunar and Planetary Science Conference, abstract 2881

Buchwald VF (1975) Handbook of Iron Meteorites. University of California Press, Oakland, 1418 pp

Chappelow JE, Golombek MP (2010) Entry and landing conditions that produced Block Island. Journal of Geophysical Research, Planets 115: E00F07, doi: 10.1029/2010JE003666

Chappelow JE, Sharpton VL (2006) Atmospheric variations and meteorite production on Mars. Icarus 184: 424-435

Connolly HC and 11 coauthors (2006) The Meteoritical Bulletin No. 90, 2006 September. Meteoritics and Planetary Science 41: 1383-1418

Fleischer I and 6 coauthors (2011) New insights into the mineralogy and weathering of the Meridiani Planum meteorite, Mars. Meteoritics and Planetary Science 46: 21-34

Johnson JR and 6 coauthors (2010) Pancam visible/near-infrared spectra of large Fe-Ni meteorites at Meridiani Planum, Mars. 41st Lunar and Planetary Science Conference, abstract 1974

Kraft MD, Smith RJ, Christensen PR (2014) Perspectives on Amazonian weathering on Mars. Geological Society of America Meeting, abstract 111-10

Schröder C and 22 coauthors (2008) Meteorites on Mars observed with the Mars Exploration Rovers. Journal of Geophysical Research 113: E06S22, doi: 10.1029/2007JE002990

Schröder C and 14 coauthors (2010) Properties and distribution of paired candidate stony meteorites at Meridiani Planum. Journal of Geophysical Research 115: E00F09, doi: 10.1029/2010JE003616

Velbel MA (2014) Terrestrial weathering of ordinary chondrites in nature and continuing during laboratory storage and processing: review and implications for Hayabusa sample integrity. Meteoritics and Planetary Science 49: 154-171

Yen AS and 7 coauthors (2005) Subsurface weathering of rocks and soils at Gusev Crater. 46th Lunar and Planetary Science Conference, abstract 1571

Yen AS and 18 coauthors (2006) Nickel on Mars: Constraints on meteoritic material at the surface. Journal of Geophysical Research 111: E12S11, doi: 10.1029/2006JE002797

ROVING ACROSS MARS: SEARCHING FOR EVIDENCE OF FORMER HABITABLE ENVIRONMENTS

Michael H. Carr*

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.

FIGURE 1 Mars rovers showing their evolution from 1996 to the present day. In the foreground is the tethered rover, Sojourner, launched in 1996. On the left is a model of the rovers Spirit and Opportunity, launched in 2004. On the right is Curiosity, launched in 2011. IMAGE CREDIT: NASA/JPL-CALTECH

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–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

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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 isochemical 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 acid pH under which the sulfate-rich deposits at the Opportunity site in Meridiani accumulated and implies significantly more habitable conditions.

A major issue—hotly debated over the last few decades—is how warm and wet early Mars was at the end of the Noachian when most of the valley networks formed. One view is that the valleys were eroded by streams that resulted from rainfall fed by evaporation from transient oceans (e.g. Baker 2001; Craddock and Howard 2002). Warm, wet, Earth-like conditions are implied, enabling both evaporation and rainfall. An opposing view is that the valleys were formed by flowing water resulting from the melting of surface ice by impacts or volcanic events or under cold climatic conditions that enabled melting only a few days a year (Wordsworth et al. 2013). The Curiosity findings so far do not require the persistent, warm, wet surface conditions that are needed for surface weathering and the development of soils and so may favor the colder models, but it will be interesting to see what the Mt. Sharp deposits reveal.

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.

REFERENCES

Baker VR (2001) Water and the Martian landscape. Nature 412: 228-236

Bibring J-P and 52 coauthors (2006) Global mineralogical and aqueous Mars history derived from OMEGA/Mars Express data. Science 312: 400-404

Carr MH (2006) The Surface of Mars. Cambridge University Press, New York, 322 pp

Craddock RA, Howard AD (2002) The case for rainfall on a warm, wet early Mars. Journal of Geophysical Research 107: 5111, doi: 10.1029/2001JE001505

Grotzinger JP and 19 coauthors (2005) Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns formation, Meridiani Planum, Mars. Earth and Planetary Science Letters 240: 11-72

Hartmann WK, Neukum G (2001) Cratering chronology and the evolution of Mars. Space Science Reviews 96: 165-194

Klein HP (1979) The Viking mission and the search for life on Mars. Reviews of Geophysics 17: 1655-1662

NASA (1995) An exobiology strategy for Mars exploration. NASA SP-530, NASA, Washington, D.C., 56 pp, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19960000318.pdf

Scott DH, Carr MH (1978) Geologic map of Mars. USGS Numbered Series IMAP-1083, U.S. Geological Survey, http://pubs.er.usgs.gov/publication/i1083

Squyres SW and 15 coauthors (2006) The rocks of the Columbia Hills. Journal of Geophysical Research 111: E02S11, doi: 10.1029/2005JR002562

Wordsworth R and 5 coauthors (2013) Global modelling of the early martian climate under a denser CO_2 atmosphere: Water cycle and ice evolution. Icarus 222: 1-19

THE QUEST FOR A SECOND ORIGIN OF LIFE

Malcolm R. Walter*

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 precise exploration targets, and more and more we have highly effective instruments with which to equip our spacecraft and rovers. The early results from measurements by some of these instruments on Curiosity are described in the articles in this issue.

From the beginning of the exploration for life on Mars, we have used techniques first developed for comparable searches on Earth. This approach is known as the use of "Earth analogues." These can be places where there are living microbes or places where their fossilized remains can be found. Two such places – Shark Bay and the Pilbara – I know well because I and my colleagues and students have studied them for decades.

Shark Bay is on the coast of Western Australia (Playford et al. 2013). This is a vast area with several large embayments. One of these is Hamelin Pool, which is a misnomer because the "pool" is 55 km north–south by up to 25 km east–west. It is now part of a marine national park and a World Heritage Site. The high salinity of the area keeps out many metazoans, so it has become a haven for microbes that otherwise would be grazed upon. The result is an ecosystem that resembles that of early Earth.

Visually, the ecosystem is dominated by cyanobacteria, the organisms responsible for oxygenating the Earth as a result of their photosynthesis. They are responsible for much of the architecture of stromatolites (Fig. 1), sedimentary structures that can be found in abundance in rocks as old as 3.49 billion years. However, when this ecosystem is analysed by modern genomic techniques, it turns out to be extremely complex (Goh et al. 2009; Fig. 2), with many different kinds of microbes. If there were ever life on Mars, this is the sort of community we could expect, possibly without oxygenic photosynthesisers but still with some organisms that reacted to light (this seems to be an important component of stromatolite-building communities).

Figure 1 Subtidal stromatolites offshore from Carbla Point, Hamelin Pool, Shark Bay, Western Australia. The complexity of the microbial communities that inhabit and construct these and other stromatolites in this area is shown in Figure 2. Photo: David Flannery

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

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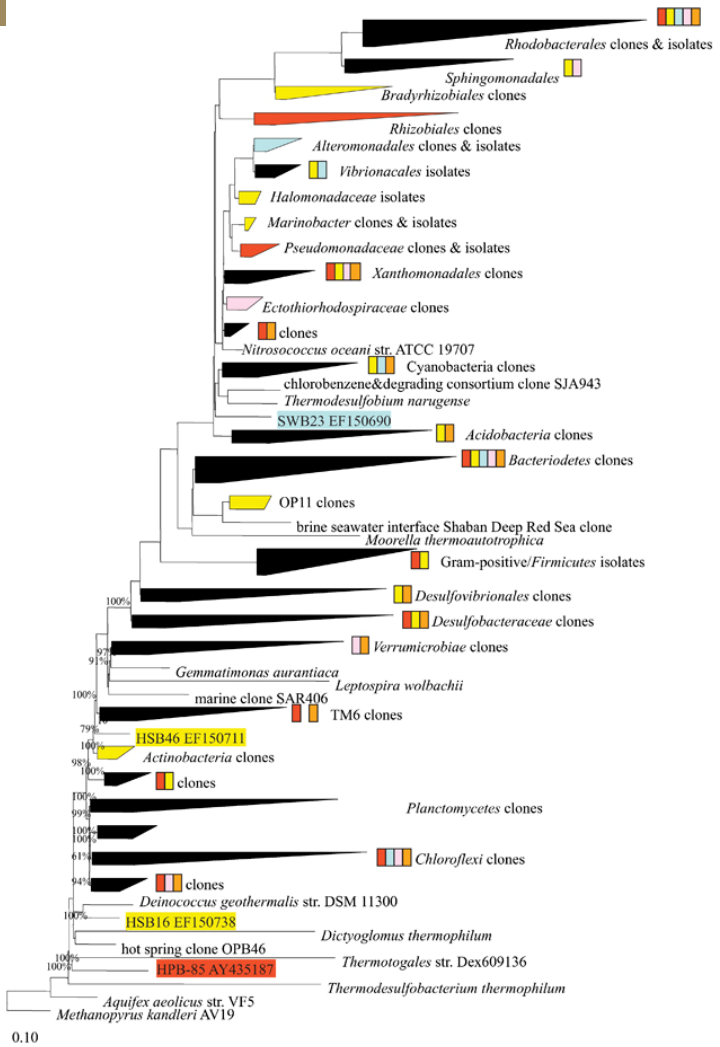


FIGURE 2 Phylogenetic relationships of total bacteria genomically sequenced from Shark Bay intertidal stromatolites. In addition to bacteria there are diverse archaea and eukaryotes, not included here. The scale bar represents 0.1 nucleotide changes per nucleotide position (this is a measure of the genetic disparity between related organisms). The colours represent different studies summarized here. Details are in Goh et al. (2009), from which this figure is reproduced with permission.

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 significant is Yellowstone National Park in Wyoming, USA. It was there that research first revealed the high temperature tolerance of some microbes (FIG. 4). Scientific 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 define. 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 identified (e.g. Brown et al. 2010).

MSL has confirmed 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

FIGURE 3 Martin Van Kranendonk discussing 3.43-billion-year-old stromatolites in the Strelley Pool Formation, "Trendall locality," Shaw River, Pilbara Craton, Western Australia. PHOTO: CAROL OLIVER

FIGURE 4 A thermal spring in Sentinal Meadow, Yellowstone National Park, USA. Even the boiling, 96 °C water contains living "extremophilic" microbes. Some of the colours on the white SiO_2 sinter are due to differing microbial communities distributed according to their temperature tolerances. PHOTO: GEOFFREY BRUCE

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.

REFERENCES

Allwood AC, Walter MR, Kamber BS, Marshall CP, Burch IW (2006) Stromatolite reef from the early Archaean era of Australia. Nature 441: 714-718

Brock TD (1978) Thermophilic Microorganisms and Life at High Temperatures. Springer-Verlag, New York, 465 pp

Brown AJ and 8 coauthors (2010) Hydrothermal formation of clay-carbonate alteration assemblages in the Nili Fossae region of Mars. Earth and Planetary Science Letters 297: 174-182

Goh FI and 6 coauthors (2009) Determining the specific microbial populations and their spatial distribution within the stromatolite ecosystem of Shark Bay. International Society for Microbial Ecology Journal 3: 383-396

Playford and 5 coauthors (2013) The Geology of Shark Bay. Geological Survey of Western Australia, Bulletin 146, 281 pp

Van Kranendonk MJ, Smithies RH, Hickman AH, Champion DC (2007) Review: secular tectonic evolution of Archaean continental crust: interplay between horizontal and vertical processes in the formation of the Pilbara Craton, Australia. Terra Nova 19: 1-38

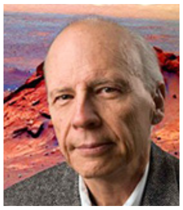
Van Kranendonk MJ, Philippot P, Lepot K, Bodorkos S, Pirajno F (2008) Geological setting of Earth's oldest fossils in the c. 3.5 Ga Dresser Formation, Pilbara Craton, Western Australia. Precambrian Research 167: 93-124

Walter MR (1999) The Search for Life on Mars. Perseus Books (US), Allen & Unwin (Australia), 170 pp

Walter MR, Des Marais D (1993) Preservation of biological information in thermal spring deposits: Developing a strategy for the search for fossil life on Mars. Icarus 101: 129-143

Weed WH (1889) Formation of travertine and siliceous sinter by vegetation of hot springs. US Geological Survey 9th Annual Report 1887-1888, p 613-676

Meet the Authors



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.

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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.