



# Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology

June 2006  
Volume 2, Number 3

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## Water on Mars

• **Geomorphological Evidence**

**Orbital Search for  
Alteration Materials**

**Water at the Poles and  
in Permafrost Regions**

**Aqueous Processes Recorded  
by Martian Meteorites**

**Water at Meridiani**

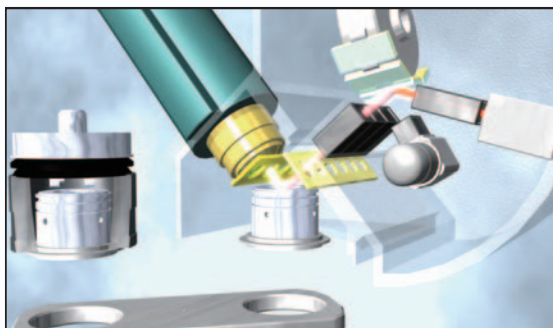
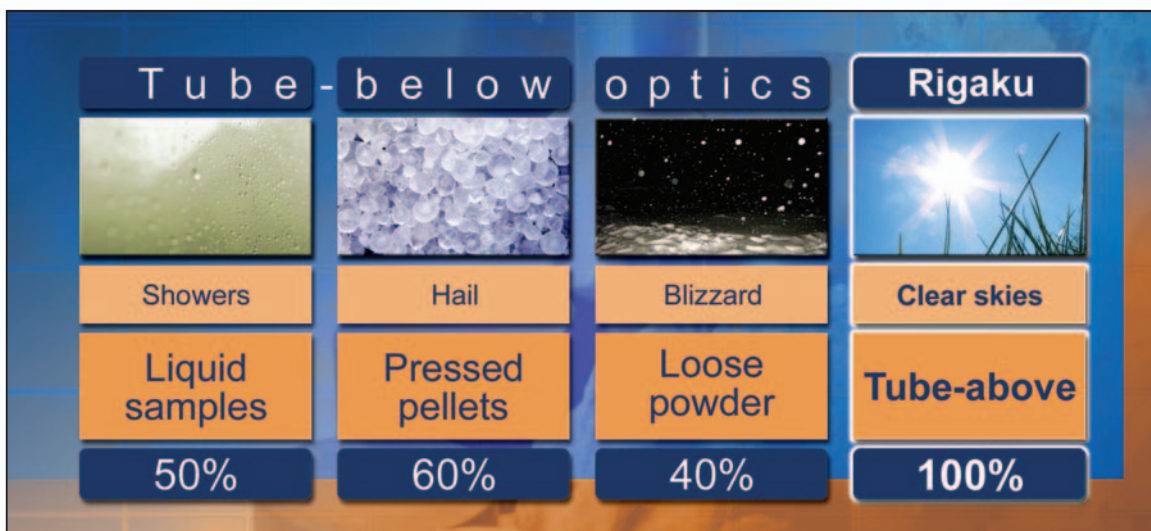
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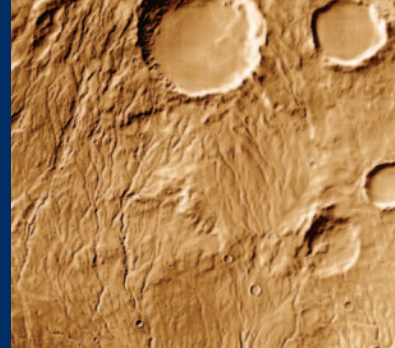
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# Elements

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ABOUT THE COVER:  
This mosaic of THEMIS daytime infrared images shows the densely dissected region of Warrego Valles, Mars, located near 43° S, 266° E. The dissection was likely caused by some form of water erosion, possibly due to surface runoff during a period of warmer climate or to subsurface runoff associated with the melting of a layer of snow or ice. This image covers an area of ~120 × 160 km at a resolution of 100 m per pixel.  
IMAGE CREDIT NASA/JPL/ARIZONA STATE UNIVERSITY

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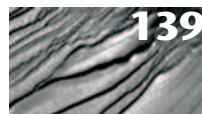
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135

## Water on Mars

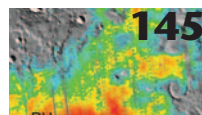
Harry Y. McSween Jr., Guest Editor



139

## Geomorphological Evidence for Water on Mars

Victor R. Baker



145

## The Orbital Search for Altered Materials on Mars

Michael B. Wyatt and Harry Y. McSween Jr.



151

## Water at the Poles and in Permafrost Regions of Mars

Philip R. Christensen



157

## Aqueous Processes Recorded by Martian Meteorites: Analyzing Martian Water on Earth

Laurie A. Leshin and Edward Vicenzi



163

## Evidence for Water at Meridiani

Bradley L. Jolliff, Scott M. McLennan, and the Athena Science Team



169

## Water on Mars and the Prospect of Martian Life

Andrew H. Knoll and John Grotzinger

### Departments

<b>Editorial</b> . . . . .	<b>131</b>
<b>From the Editors</b> . . . . .	<b>132</b>
<b>Triple Point</b> . . . . .	<b>133</b>
<b>Letters to the Editors</b> . . . . .	<b>134</b>
<b>Meet the Authors</b> . . . . .	<b>138</b>
<b>Society News</b>	
Mineralogical Society of Great Britain and Ireland . . .	174
The Clay Minerals Society . . . . .	176
European Association for Geochemistry . . . . .	178
Mineralogical Society of America . . . . .	180
Mineralogical Association of Canada . . . . .	182
International Association of GeoChemistry . . . . .	184
Geochemical Society . . . . .	185
Soci�t� Fran�aise de Min�ralogie et de Cristallographie .	186
International Mineralogical Association . . . . .	187
International Association for the Study of Clays . . . .	188
<b>Book Review</b> . . . . .	<b>189</b>
<b>Calendar</b> . . . . .	<b>190</b>
<b>Parting Shots</b> . . . . .	<b>192</b>
<b>Advertisers in this Issue</b> . . . . .	<b>191</b>





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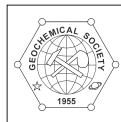
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# Two Planets – Which Future?

This issue of *Elements* presents evidence of a time when water played an important role in shaping the landscape of Mars. Deep valleys were carved, sediment was transported and

deposited, and at a smaller scale, a patina of secondary, hydrated minerals formed. Now this red planet lies desolate. The shifting polar ice caps are the only obvious remnant of a once-active hydrologic cycle. If life exists on Mars, it must be in recesses that may still harbor the right geochemical conditions and the water required to sustain primitive organisms.

In contrast to Mars, our blue planet is active at every scale. A physical dynamo drives the active tectonics that shape ocean basins and continents. Water fills the Earth's basins with oceans that circulate and in turn drive a constantly changing climate. For the Earth, we speak of cycles—tectonic, rock, hydrologic, geochemical—each with its own spatial and temporal scale. Caught among the coupled processes that drive these cycles are life forms that fill nearly every ecologic niche; even in the harshest of environments, extremophiles adapt and prosper. Despite the complexity of each of these systems, a Gaia Earth has sustained life for many hundreds of millions of years, and even catastrophic extinctions have been followed by yet another cycle of diversification and new species. However, during the past hundreds of years, the human species has become a threat to this balance, a threat to even the pattern of changing seasons as the climate warms. As professional geoscientists, we each know a particular part of this story. Among scientists from all disciplines, we are the most privileged because this story is our business, but I wonder if we are taking care of business.

There has been only one other time in history when, as the human species, we stood on the brink of massive global change, and that was with the development and proliferation of nuclear weapons. In 1945, Little Boy was dropped on Hiroshima and Fat Man on Nagasaki. Today, eight countries hold more than 27,000 nuclear and thermonuclear weapons. Thankfully, no nuclear weapon has been used by one country against another for the past sixty years. For the moment, the world has stepped back from the commitment to mutually assured destruction. I want to suggest that the geoscience community might consider the actions of physicists, facing the development of nuclear weapons, as a guide for us in the face of the looming crisis of global climate

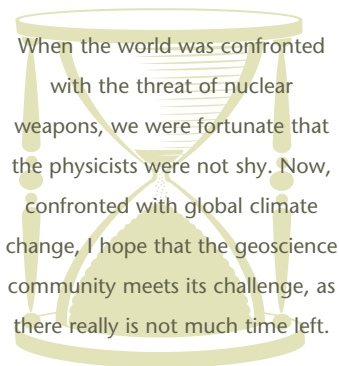
change. The first characteristic of the physics story is the very early warning at the highest levels of government of the implications of nuclear fission. From the first days in 1938 when fission was realized by Otto Hahn and Fritz Strassmann in Berlin, physicists understood that the huge amounts of energy released by fission had the makings of a powerful weapon. Albert Einstein, prodded by Leo Szilard, Eugene Wigner, and Edward Teller, wrote directly to President Roosevelt about the possibility of creating an atomic bomb. Advised by Vannevar Bush, Roosevelt launched the Manhattan Project. However, from the earliest days within the Manhattan project, there was already concern for limiting the use and spread of nuclear weapons. By 1947, the Doomsday Clock of the *Bulletin of the Atomic Scientists* marked the time to nuclear annihilation at “midnight.” In 1955, the Russell-Einstein Manifesto was issued, and this

call led to the first Pugwash Conference in Nova Scotia in 1957. The Pugwash Conferences on Science and World Affairs and Professor Joseph Rotblat, a founder and president of the Pugwash Council, shared the Nobel Peace Prize in 1995.

Today, we see parallel developments, as climate change is addressed with the series of meetings of the

Conference of the Parties (COP), the third of which resulted in the Kyoto Protocol of 1997. The Intergovernmental Panel on Climate Change was created in 1988, and their assessment reports, most recently in 2001, provide the scientific basis for the proposed policies for limiting greenhouse gas emissions. Global warming “stories” are now part of the daily “feed” from the media. Still, considering the scale and likely consequences of global climate change, a sense of urgency among governments, scientific societies, and individual scientists is nearly absent. There is often a reluctance to cross from our science into the political and policy arenas where important issues will be decided. With nuclear weapons, we were confronted with an instantaneous release of energy that would kill millions. With global climate change the pace of change is slower, but the results will be no less devastating. Perhaps, the value of studying other planets, such as Mars, is that they offer us good examples of the potential for dramatic changes at the global scale. When the world was confronted with the threat of nuclear weapons, we were fortunate that the physicists were not shy. Now, confronted with global climate change, I hope that the geoscience community meets its challenge, as there really is not much time left.

**Rod Ewing**, University of Michigan  
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## The Show Must Go On: Our Tribute to Rod

Rod Ewing stepped down officially as principal editor of *Elements* at the end of 2005. However, as Rod is the editor in charge of this issue, we decided to print our tribute to him here. When it was decided that the initial group of principal editors would have staggered terms, he insisted that he should have the shortest term. "I will have been involved with this project for five years by the time I step down," he said. Rod will still be involved with *Elements* in an advisory capacity to the Executive Committee. He will also be the guest editor for issue 6 of volume 2 (next December). And we know we will be able to consult him as need arises.

Rod's vision for the mineral and geochemical sciences grew out of his involvement with the Materials Research Society. Over the years, he witnessed how their flagship publication, *MRS Bulletin*, had been instrumental in raising the profile of the materials sciences. He watched the materials societies grow and prosper, and the idea of a counterpart publication for the mineral sciences germinated. When he became vice president of MSA in the fall of 2000, he undertook to bring this idea to fruition. Sorena Sorensen relates that, at the 2000 MSA fall council meeting when he introduced the idea of a magazine published by several societies, he was met with stunned silence. Could such a thing possibly be done? He left with a "OK Rod, give it a try." Being of an optimistic nature, he felt that Council had been very supportive. Over the next few months, he took his "pilgrim's stick" and systematically approached mineralogical and geochemical societies. A phone call to outline his ideas was followed by a written proposal and copies of *MRS Bulletin*.

Everyone had the same initial reactions:

"We cannot increase dues, and finances are too tight for a new project."

"Not all our members will be interested in receiving it."

"Won't we just be talking to ourselves?"

"Most of our members are members of other societies and will receive it anyway."

And if the truth be told, I was perhaps the person with the most questions and concerns! Rod respectfully and patiently answered all these questions.

Rod felt strongly about a few things: the thematic nature of the magazine, the international nature of the endeavor, and the need to make this magazine a member benefit of the participating societies. He welcomed and actively solicited input on every other aspect of the project. In early 2003, when he felt the idea had had enough time to germinate, he formed a steering committee composed of representatives of all societies that had expressed some level of interest. The group discussed the governance structure and the objectives. There was debate about defining our readership. A subcommittee, composed of Alex Speer, Kevin Murphy, and myself, formulated the first business plan. It was decided that with a substantial volunteer start-up effort, we could get going.

In the fall of 2003, the committee became very quiet: even the mock-ups of what the magazine might look like raised no discussion. I remember one phone call from a frustrated Rod. "We have a nucleation problem. If we can get two or three societies to give us a green light, I think others will



Rod looking for betafite crystals in Madagascar

come on board." This is exactly what happened. At its fall council meeting, MSA gave a green light, with the proviso that at least one other society join. MinSoc and MAC followed in short order. By the time we went to press with the first issue in November 2004, four more societies had joined. It has been heartwarming to see how readily the scientific community has accepted *Elements*.

Mike, Ian, now Bruce, and I have been involved with Rod on a quasi daily basis getting this project off the ground and running. It has been a joy working with him. In spite of a grueling schedule, he always made himself available for *Elements*. On behalf of the whole mineralogical-geochemical community and all the participating societies, we want to thank Rod. His enormous contribution is clear: without him, *Elements* would not have happened. To paraphrase Neil Armstrong's famous phrase, a small step for the societies, a giant leap for the mineral and geochemical sciences. Perhaps this is how we will view Rod's contribution years from now.

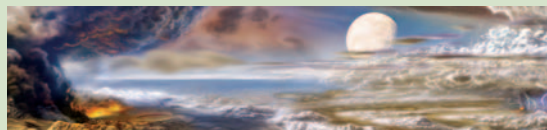
And for us, the best way to thank him is to continue the work he started, because "the show must go on."

**Pierrette Tremblay**, on behalf of  
Mike Hochella, Ian Parsons, and Bruce Watson

### IN THE NEXT ISSUE, READ ABOUT

#### Early Earth

Guest editor: John W. Valley  
(University of Wisconsin-Madison)



The earliest Earth was a strange inhospitable world, yet transitions occurred culminating in the evolution of life within the first billion years. The preservation of a sparse and ambiguous rock record has encouraged debate. Recent studies have greatly refined the nature and timing of key events. This issue will review current knowledge of the age of the Earth, massive meteorite impacts, the atmosphere and hydrosphere, the rock record, and the emergence of life.

**The Origin of the Earth: An Update**  
Alex Halliday (Oxford University)

**Impact Processes on the Early Earth**  
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**Earth's Earliest Atmosphere**  
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**The First Billion Years: When Did Life Emerge?**  
Bill Schopf (UCLA)

## Congratulations from the Common Reader

The Common Reader congratulates Professor Rodney C. Ewing on the occasion of his retirement as Principal Editor of *Elements*. Rod, as a Common Reader, I've been asked to address a tribute to you on this occasion, and also to describe the nature of your contributions to this utterly unique, inclusive, interesting, international, multisociety journal cum newsletter we all hold in our hands (or scroll on our screens!). Your editorial side will no doubt relish that I am faced with the somewhat complex literary task of praising you individually while simultaneously describing your achievements to many others. I can but try.

Even given your broad-thinking nature, Rod, it amazes me that in the year 2000 you could conceive of a (then-nameless) worldwide journal-newsletter hybrid that would unite the learned societies of those who study the mineral sciences. I well remember the Mineralogical Society of America council meeting in Reno, Nevada, when you presented your idea for the first time, with what I later learned was a characteristic combination of vision, enthusiasm, and creativity. Stunned silence ensued. (Perhaps we all thought it improbable you could achieve your goals in an ordinary human lifetime. I know I did.)

Graciously accepting MSA's collective lukewarm approval—"OK, Rod, give it a go," seems to me to have been the response—Rod began to enlist and inspire many others to give their utmost to help create *Elements*. He was clearly effective in his efforts. Today, *Elements* is an extraordinarily collaborative venture, a joint publication of the Mineralogical Society of America, the Mineralogical Society of Great Britain and Ireland, the Geochemical Society, the Mineralogical Association of Canada, The Clay Minerals Society, the International Association of GeoChemistry, the European Association for Geochemistry, and the Société Française de Minéralogie et Cristallographie. Other societies will be added, for *Elements* was born to welcome all who study minerals. We all have Rod to thank for that.

*Elements* began publication in 2005, with Rod, Mike Hochella, and Ian Parsons sharing the masthead, along with the brilliant, energetic Pierrette Tremblay masterminding journal production and overseeing the art work. From the first, it employed a format almost unique in the geosciences. Each issue begins with a thematic section made up of guest-edited papers. The 2005 themes were "Fluids in Planetary Systems," "Diamonds," "Genesis: Rocks, Minerals and the Geochemical Origin of Life," "Toxic Metals in the Environment: The Role of Surfaces," and "Large Igneous Provinces and Environmental Change." The first two issues for 2006 were "User Research Facilities in the Earth Sciences," and "Arsenic." The thematic content is managed by distinguished scientists in the subfield of the mineral sciences described by the issue's title. These guest editors invite papers, but each submission is rigorously peer reviewed prior to publication. Unlike a typical journal, though, these papers are broadly written yet thorough reviews of major aspects of the theme. Ideally, a reader obtains an overview and the cutting edge at the same time. This publishing strategy is not without risks.

Luckily for us, fellow readers, Rod and his co-editors have chosen their thematic editors from literally the best research groups on Earth. Happily, all these individuals have significant editorial skills, as well as impressive scientific credentials. Thanks to the excellent editing teams, *Elements* has achieved an almost impossible union of broad readability and top-flight science content, just as Rod had described to the MSA council just short of six years ago. Not surprisingly, *Elements* is now indexed in GeoRef (used for the Science Citation Index in Earth Sciences), Current Contents, the Chemistry Citation Index, and the Science Citation Index-Expanded (i.e. the Web of Science). It is already an award-winning journal (and Rod an award-winning editor!), courtesy of the Association of Earth Science Editors.



Rod Ewing surrounded by Principal Editors Ian Parsons and Mike Hochella and Managing Editor Pierrette Tremblay at the first editorial meeting in April 2004

But *Elements* is far more than an exciting new journal. The thematic section is followed by news from each member society, book reviews, conference reports, a calendar of upcoming events, news from the editors, and advertisements. These sections are presented in a modern, easy-to-read, informative format that is light years away from typical society newsletters. I've caught myself plowing through all the plans, meetings, and other doings of society after society, just because these are fun and interesting to read.

Who gets *Elements*? It is sent to more than 7600 members of the eight member societies in 92 countries. More than 1200 libraries now receive it. Think of it! In only a little more than one year of existence, a new publication has achieved global impact on a branch of science. How did it happen? Because *Elements* not only highlights exciting research directions for a broad, worldwide audience, it connects all the scientists who read it. It provides us all with the valuable commodity of open information, that essential raw material we need to truly become a community. Rod, the community spirit that is embodied in *Elements* will be needed in these increasingly challenging times for mineral sciences research—many thanks for this benefit, one I'm sure you envisioned.

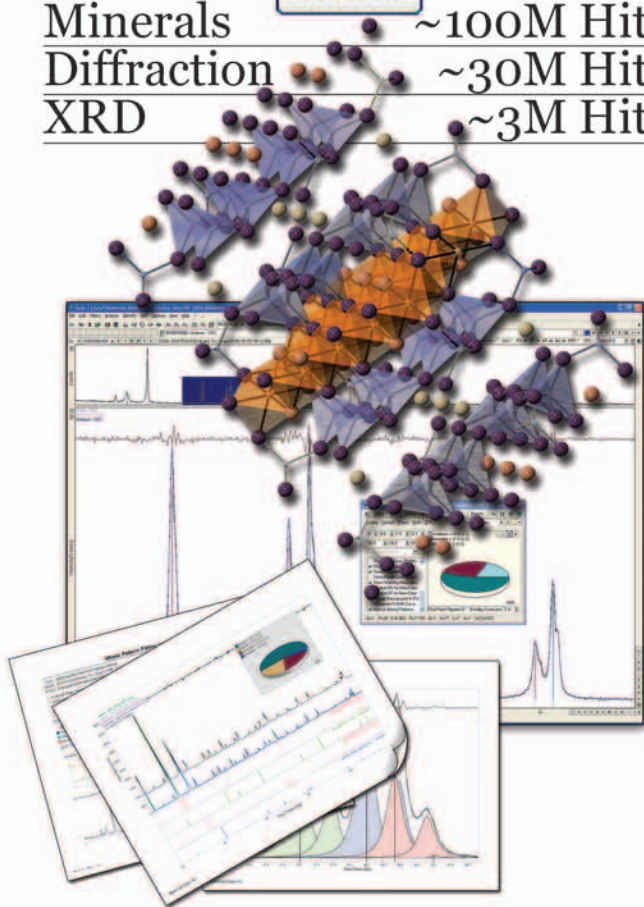
*Elements* is in every way a model for twenty-first century society publications. And although it obviously was not brought into being by one person, it is unquestionably Rod's creation. Indeed, he notes in his CV with well-justified pride that he is Founding Editor of *Elements*. For the simple reason that Rod has dedicated so much of himself to *Elements*, the magazine has already succeeded on an unprecedented scale. This is certainly owing to his vision, enthusiasm, and creativity, along with killer organizational skills—characteristics seldom united in an individual scientist, let alone one with so much drive and personal charm!

In summary, Rod, as a Common Reader of *Elements*, I have taken great pleasure in describing your achievements to my fellow readers. Congratulations upon your retirement from the editorial board of *Elements*. I can't wait to see what wonderful new things you will accomplish with all your free time!

**Sorena Sorensen**  
Smithsonian Institution

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### ABOUT VOLUME 2, ISSUE 1

I am writing to see how one may obtain a few extra copies of the February issue of *Elements*. I am a subscriber (through my membership in the Mineralogical Society of America) and thoroughly enjoy this publication. As for my interest in February's issue—this is an excellent issue for a number of reasons. First, a wonderful overview of the capabilities of national facilities is given and as such serves as an excellent reference. Primarily, however (and here is my motive!), this issue is fantastic ammunition for promoting research at such facilities to people such as my Dean, VP for research, etc. I would be grateful if I could wave a copy or two under the noses of these individuals, especially since many of my colleagues are featured in this issue, as well as facilities at which I am a regular user. Is there a way to purchase five extra copies?

**Chris Cahill,**

George Washington University

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I read every new issue of *Elements* as soon as it reaches my desk. The Journal is so informative and well produced. The congratulations and awards that it receives are well deserved. In volume 2, issue 1, Michael Hochella mentioned a few questions in his editorial that prompt me to take up two issues. The first is about the intelligent design hypothesis. I am convinced of the fact of evolution, but I see a great logical gap in the traditional explanation for the development of morphologies or processes that need many generations to become advantageous to the species: many mutations are needed, but, oddly, selection seems to operate only at the end of the development ... I would not be surprised if some biologists find these gaps too large and indicative of some fundamental flaw, leading them to explore different avenues. In my view, the intelligent design concept contains an exploitable core for science. Design is ever-present in nature. Every law of nature is a design, in that it brings about certain phenomena in a consistent and permanent way. Design, in this sense, is opposed to chaos and lack of pattern. Is evolution produced by a design or law of this type? Is there a biological law operating at molecular or genetic level that encourages organic changes in certain directions? I would like to see this avenue explored.

The second issue is global warming. Since the first cries of alarm were heard, I have come across of a number of articles based on geological and ice records that point in the opposite direction. In other words, the present temperature increase may be just a small cycle within a more general trend. Even if we are in a long-cycle global warming period, is it produced by human activity? Again, there are data that seem not to match this interpretation. My favourite one is this. The temperature has been increasing constantly since 1910 except in the period from 1940 to the late 1970s. It is precisely in that period that CO<sub>2</sub> emission experienced one of its greatest jumps. The two hardest pieces of evidence that we have, actual CO<sub>2</sub> emission and temperature, appear to be loosely linked. There are other factors. How much of this extra man-produced CO<sub>2</sub> is actually remaining in the atmosphere? How much is being dissolved in the oceans?...

**Javier Cuadros**

Natural History Museum

We welcome letters to the editors. We reserve the right to edit them for clarity and brevity. By writing a letter to the editors, you give *Elements* the permission to reproduce it.

**The editors**



# Water on Mars

Harry Y. McSween Jr.<sup>1</sup>

**Water on Mars exists at the poles and in the subsurface. It has interacted with crustal rocks, providing geomorphological, geochemical, and mineralogical insights into Mars' geological history and inferences about its biological potential. The roles of water are revealed through studies of altered materials using orbiting-spacecraft imagery and spectroscopy, instruments mounted on rovers, and laboratory measurements on Martian meteorites.**

KEYWORDS: water, aqueous alteration, spacecraft, rovers, meteorites

The eroded valley networks pictured on the cover of this *Elements* issue demonstrate that flowing water once shaped the face of Mars. Borrowing from an old adage, we might say that water on Mars “can run, but it can’t hide.” But hide it does. Although frozen water covers the Martian poles, liquid water is not stable anywhere on the planet’s surface under present environmental conditions. Finding where this elusive substance hides and understanding its role in the geological (and possibly even biological) history of Mars require innovative approaches—as revealed in this collection of articles.

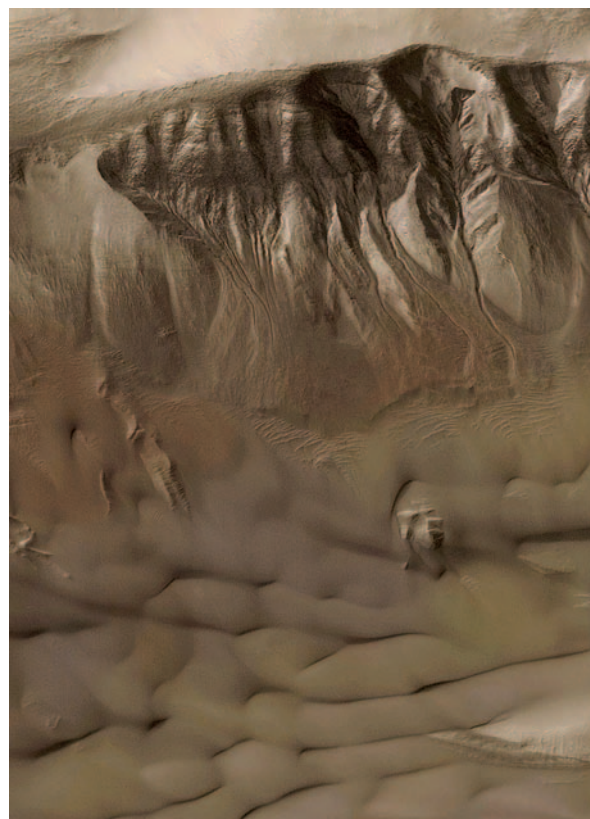
The history of water on Mars is recorded by its chemical interactions with rocks. Most of the Martian crust consists of basaltic lavas (McSween et al. 2003). On Earth, basalts are readily altered to clays and other hydrated minerals, and they experience profound geochemical and isotopic changes when exposed to water. However, remote sensing of Mars by spectroscopic methods has not yet found clays in abundance, and geochemical changes in texturally altered rocks seem to be of limited extent. One spectral feature that is commonly noted, the ferric absorption edge, indicates that fine-grained ferric oxides (thought to be weathering products) are abundant everywhere in soils and rock coatings (Bell et al. 2000), as are sulfates, chlorides, and other salts formed by evaporation (Squyres et al. 2004). These oxides and salts are unambiguous indications of aqueous alteration, but even so, the extent to which Martian rocks have interacted with water remains controversial.

Water’s hiding places are revealed by an orbiting spacecraft carrying an instrument that probes the ground for hydrogen. Mineral-bound H<sub>2</sub>O occurs in areas near the equator, and subsurface ice is thought to be widespread at higher latitudes. Rovers dig trenches and explore craters, both of which expose salts once carried by groundwater. Enrichments of the heavy isotopes of hydrogen and oxygen measured in Martian meteorites disclose a cycle that moves water from the crust to the atmosphere and back again.

The papers in this issue of *Elements* summarize some of the most recent and intriguing discoveries about water on Mars. The investigations described utilize imagery and remote sensing measurements from orbiting spacecraft, analyses from rovers scurrying across the surface, and laboratory studies of Martian meteorites to try to unravel the mystery of when water ran and where it hides. This is not

a comprehensive catalog of research on the topic, but it should allow an appreciation of the diversity of scientific approaches and a glimpse into the excitement of planetary geological exploration.

In his paper, Baker describes geomorphological features that were carved by running water. He also postulates that the huge basin that forms the northern hemisphere of Mars was once filled with an ocean. Orbiting spacecraft carry the Thermal Emission Spectrometer (TES) and Thermal Emission

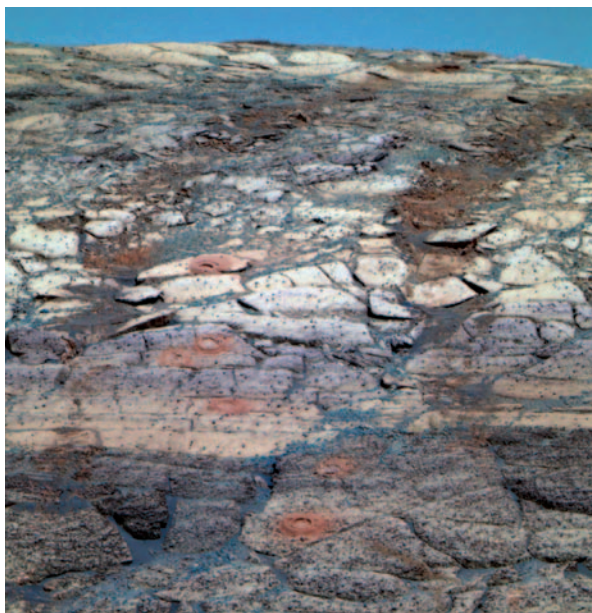


**FIGURE 1** Gullies in a Martian crater, image width ~3 km. MGS MOC Release No. MOC2-1182

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Imaging System (THEMIS), which measure the heat emitted from the planet's surface. These instruments can identify minerals and map their distributions. The OMEGA spectrometer records light reflected at visible and near-infrared wavelengths, which provides complementary information on mineralogy. Wyatt and McSween describe how spectrometers on orbiting spacecraft can be used to search for evidence of aqueous alteration. The Gamma Ray Spectrometer (GRS) reveals the extent of icy permafrost in the subsurface over large areas of the planet. Christensen reports how new imagery from THEMIS and the Mars Orbiting Camera (MOC) shows the complicated history of ice at the poles, and high-resolution images of gulleys on the sides of large craters (FIG. 1) suggest that water has existed, at least fleetingly, during modern times.

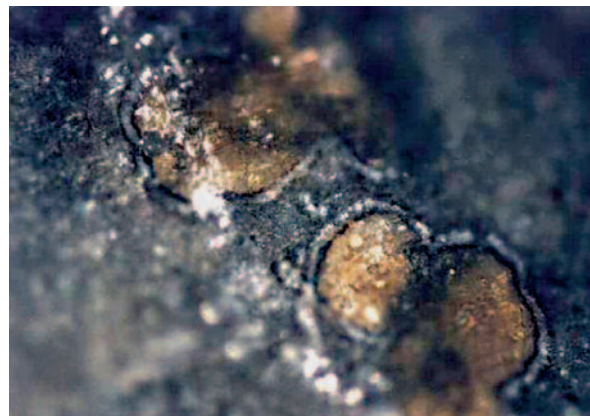
A variety of geochemical and mineralogical tools on the Mars Exploration Rovers (MER) provide a wealth of new discoveries at two locations. Jolliff and McLennan note that the Opportunity landing site, in Terra Meridiani, shows unmistakable evidence for evaporation of a salt-laden sea and flushing with groundwater during diagenesis (FIG. 2). A handful of Martian meteorites, thought to be igneous rocks ejected during impacts, contain minor amounts of alteration minerals (FIG. 3) and have unusual isotopic anomalies in hydrogen, oxygen, and sulfur. Leshin and Vicenzi describe the evidence for interaction with water in these meteorites.



**FIGURE 2** Evaporitic rocks in Endurance crater at the Opportunity landing site. Tracks formed when the rover descended are visible at the top, and (silver dollar-sized) holes formed by grinding of the Rock Abrasion Tool (RAT) are seen at various levels.

Life, as we know it or can imagine it, requires water, so it is not surprising that the exploration of Mars focuses on a search for water, both past and present. A final paper, by Knoll and Grotzinger, describes emerging ideas and constraints on possible Martian organisms and their dependence on water.

The story of the search for Martian water, which began decades ago with images of water-carved landforms, has become in large part a geochemical and mineralogical investigation. Much of this research involves remote sensing measurements that differ from the conventional laboratory techniques used in these disciplines, but they are in reality extensions of Earth-based research, and interpretations of these data are informed by terrestrial studies. Mars is a



**FIGURE 3** ALH84001 Martian meteorite, showing mm-size secondary carbonate globules

grand petrological, geochemical, and possibly biological experiment, complete with water, and its study deepens our understanding of how our own world works. ■

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## GLOSSARY OF MARS TERMS

### Remote sensing instruments

*on current spacecraft* (see FIG. 4)

**Alpha Particle X-ray Spectrometer (APXS)** – Instrument on Mars Exploration Rovers that measure bulk rock chemistry using interactions of alpha particles with the target

**Gamma Ray Spectrometer (GRS)** – Spectrometer on Mars Odyssey that measures abundances of H and other elements by their interactions with neutrons

**Mars Orbiter Laser Altimeter (MOLA)** – Instrument on Mars Global Surveyor that measures topography using laser reflections from the planet's surface

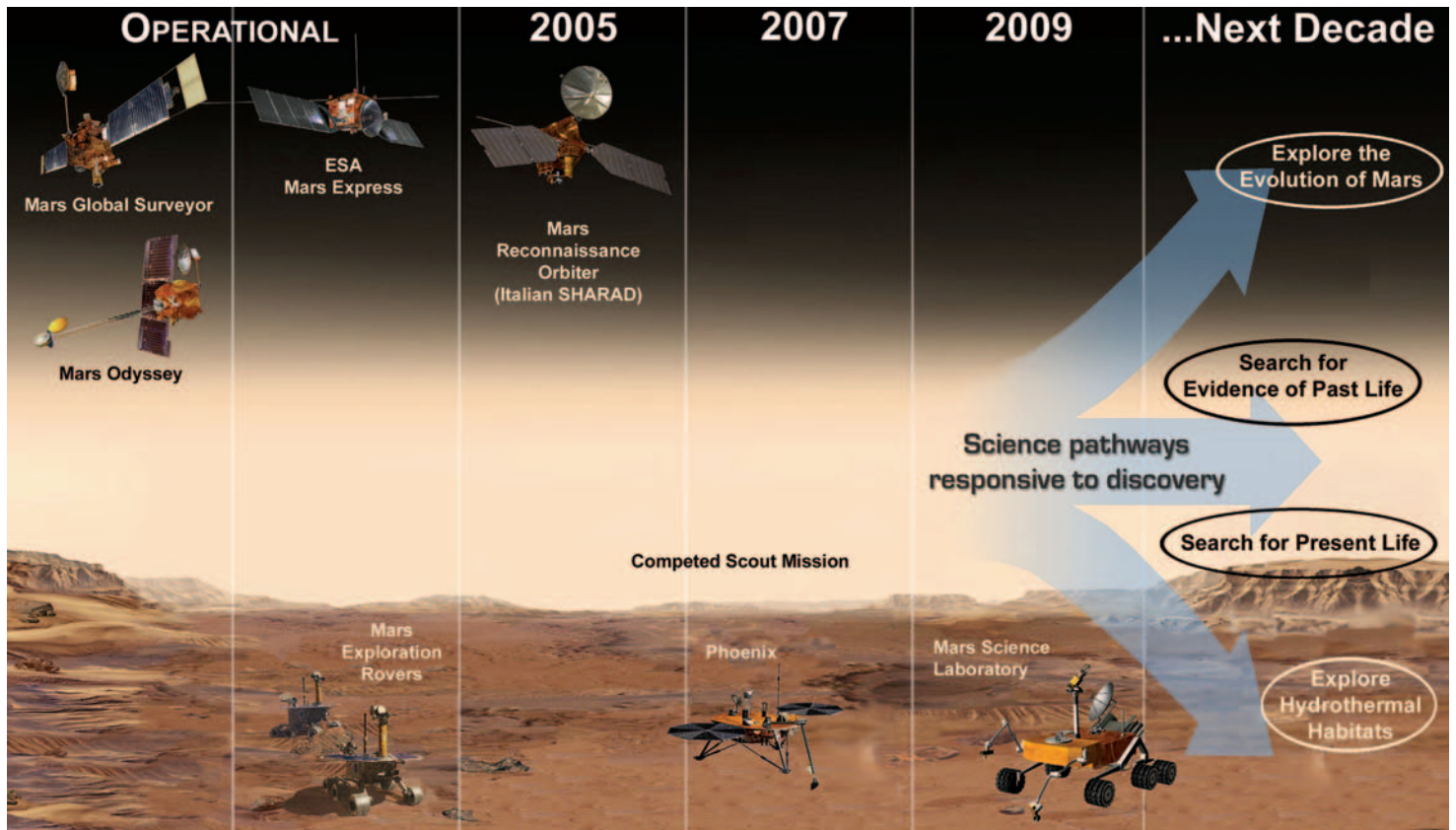
**Mars Orbiting Camera (MOC)** – High-resolution imager on Mars Global Surveyor

**Microscopic Imager** – A 30× microscope on Mars Exploration Rovers used to image rock and soil textures

**Miniature Thermal Emission Spectrometer (Mini-TES)** – Spectrometer on Mars Exploration Rovers used to identify minerals by their lattice vibrations

**Mössbauer Spectrometer** – Instrument on Mars Exploration Rovers used to identify Fe-bearing phases by measuring nuclear oscillations in crystal fields

**Omega Spectrometer** – Visible/near-infrared reflectance spectrometer on Mars Express used to identify minerals through absorptions due to electronic transitions and lattice molecular vibrations



**FIGURE 4** Timeline for Mars exploration. Three orbiters and two rovers are currently operational, another orbiter has been launched, and several landers are under development. COURTESY OF NASA

**Panoramic Camera (Pancam)**

– Color imaging system on Mars Exploration Rovers

**Thermal Emission Imaging System (THEMIS)**

– Imaging system on Mars Odyssey that records heat emitted from the Martian surface; THEMIS has high spatial resolution but low spectral resolution.

**Thermal Emission Spectrometer (TES)**

– Thermal infrared spectrometer on Mars Global Surveyor that is sensitive to vibrational motions of atoms in minerals; TES has high spectral resolution but low spatial resolution.

**Martian materials**

**Concretions** – Rounded masses formed by percolating waters

**Cements** – Minerals deposited among rock particles that bind them together

**Evaporites** – Salts formed by evaporation of brines

**Iddingsite** – Assemblage of minerals formed by alteration of olivine

**Martian meteorites** – Shergottites, nakhlites, chassignites (SNCs) and ALH84001—mafic and ultramafic rocks ejected from Mars by impacts

**Palagonite** – Amorphous or poorly crystalline clays formed by interaction of volcanic rocks with water

**Permafrost** – Perennially frozen ground

**Surface Types 1 and 2** – Global surface units that are distinguished by thermal emission spectra; ST1 is interpreted as basalt and ST2 as andesite or partly altered basalt.

**Regolith** – The particulate surface materials on a planet; differs from soil in that organic matter is absent.

**Minerals**

**Ferrihydrite, goethite, hematite, maghemite, magnetite** – Oxides and hydroxides of Fe<sup>2+</sup> and Fe<sup>3+</sup>

**Gypsum, jarosite, kieserite** – Sulfates of Ca, ferric Fe, and Mg

**Halite** – NaCl

**Olivine, pyroxene** – Mg, Fe, and Ca silicates common in mafic igneous rocks

**Smectites** – Swelling clay minerals rich in Fe or Mg

**Zeolites** – Hydrated Al silicates, with Na, K, or Ca

**Other terms**

**Albedo** – Percentage of incoming radiation that is reflected from a surface

**Geomorphology** – The nature and origin of landforms and landscapes

**Geographic locations** – See the map on the following website: [http://pubs.usgs.gov/imap/i2782/i2782\\_sh1.pdf](http://pubs.usgs.gov/imap/i2782/i2782_sh1.pdf)

**Noachian, Hesperian, Amazonian** – Time periods (oldest to youngest) defined for Mars' geologic evolution. Estimated time intervals are roughly before 3.5, 3.5–2.9, and after 2.9 billion years, respectively (Hartmann and Neukum 2005).

**Sol** – A Martian day, approximately 24 and a half hours

# Meet the Authors



**Victor R. Baker** is Regents' Professor of planetary sciences, geosciences, and hydrology and water resources at The University of Arizona. For 40 years, he has studied geological aspects of floods and other

hydrological phenomena. Since the discovery of large fluvial channels on Mars in the early 1970s, he has also worked on problems of planetary geomorphology. He is also interested in methodological and philosophical issues in the Earth and planetary sciences. He is a fellow of the American Association for the Advancement of Science, the American Geophysical Union, the European Union of Geosciences (Honorary Fellow), and the Polish Academy of Sciences (Foreign Fellow). In 1998, he was the president of the Geological Society of America.



**Philip R. Christensen** is a Regents' Professor and the Korrick Professor in the School of Earth and Space Exploration at Arizona State University. He completed his PhD in geophysics and space

physics at UCLA in 1981. His research focuses on composition, physical properties, and processes on planetary surfaces using infrared spectroscopy, radiometry, field observations, and numerical modeling. A major element of his research has been the development of spacecraft infrared instruments, including the Mars Odyssey THEMIS, the Mars Global Surveyor TES, and the Mars Exploration Rover Mini-TES instruments. Christensen received NASA's Exceptional Scientific Achievement Medal in 2003 and was elected a fellow of the American Geophysical Union in 2004.



**John Grotzinger** is the Fletcher Jones Professor of Geology at Caltech. A field geologist interested in the co-evolution of surficial environments and life on Earth and Mars, his research addresses the chemical

development of the early oceans and atmosphere and the environmental context of early evolution. Field mapping studies are the starting point for more topical laboratory-based studies involving geochemical, paleontological, and geochronological techniques. Currently, Grotzinger's research is focused on the reconstruction of environmental conditions associated with the Cambrian radiation of animals in Oman and Namibia. Grotzinger is also a member of the Mars Exploration Rover Athena Science Team.



**Bradley L. Jolliff** received a BS degree in geology at Furman University and, after five years of active duty with the Army Corps of Engineers, a PhD from the South Dakota School of Mines and

Technology. Now at Washington University in St. Louis, he studies the geology, geochemistry, and mineralogy of the Moon and Mars, and analyzes planetary materials either in the lab or working with exploration missions such as the Mars Exploration Rovers (MER). His involvement on MER has been as a long-term planner, along with co-author Scott McLennan, and he has worked primarily with the Opportunity Rover.



**Andrew H. Knoll** is the Fisher Professor of Natural History at Harvard. A paleontologist by training, he has spent more than two decades working to integrate geological and biological perspectives on

the early Earth. Current projects stress the insights that physiology can bring to studies of Earth history, including reconstruction of the silica cycle in Archean oceans, quantitative modeling of fluid flow in Paleozoic land plants, and the diversification of photosynthetic organisms across Proterozoic-Cambrian continental shelves. Knoll is a member of the Mars Exploration Rover Athena Science Team, whose goal is to evaluate the evidence for water on the early surface of Mars.



**Laurie A. Leshin** is Director of Sciences and Exploration at NASA's Goddard Space Flight Center. In this capacity, she leads the largest science organization within NASA, with responsibility for

ensuring the scientific integrity of Earth-observing missions, space-based telescopes, and instruments exploring the Moon, Mercury, Mars, Saturn, comets, and more. Before joining NASA in August 2005, Dr. Leshin was The Dee and John Whiteman Dean's Distinguished Professor of Geological Sciences and director of the Center for Meteorites Studies at Arizona State University. She received the NASA Distinguished Public Service Medal in 2004. She received her BS in chemistry from Arizona State University and her PhD in geochemistry in 1994 from California Institute of Technology.



**Scott M. McLennan** is a professor of geochemistry in the Department of Geosciences at the State University of New York at Stony Brook. For many years he carried out research in the area of terrestrial

sedimentary geochemistry and continental crustal evolution. Recently he has focused his attention on surficial processes, sedimentary geochemistry, and crustal evolution on Mars using a combination of laboratory experiments and data returned from the various orbital and landed missions. He is a member of the Athena Science Team for the Mars Exploration Rovers and is a collaborator on the Mars Odyssey Gamma Ray Spectrometer.



**Harry Y. McSween Jr.** is University Distinguished Professor of Science and professor of Earth and planetary sciences at the University of Tennessee.

His research focuses on the petrology of meteorites, cosmochemistry, and planetary exploration. He was one of the original proponents of the idea that some meteorites are Martian rocks, and he has participated on the science teams of various Mars spacecraft missions (Mars Pathfinder, Mars Global Surveyor, Mars Odyssey, and Mars Exploration Rovers), as well as the Dawn asteroid orbiter mission.



**Edward Vicenzi** is a research geochemist and director of the Analytical Laboratories in the Smithsonian Institution's Department of Mineral Sciences. Prior to joining the National Museum of

Natural History, he co-managed the Imaging and Analysis Center at Princeton University. He received his PhD from Rensselaer Polytechnic Institute, an MS from the University of Oregon, and a BSc from McGill University, all in Earth sciences. Currently on the executive council of the Microbeam Analysis Society, his research interests include elemental and molecular imaging of Earth and planetary materials.

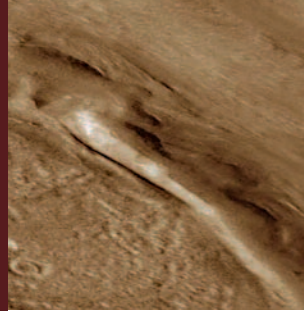


**Michael B. Wyatt** is a research scientist at the Mars Space Flight Facility at Arizona State University. His research interests include the origin and evolution of Martian igneous compositions, the effects of chemical

alteration on surface materials, and terrestrial analogs in the Dry Valleys of Antarctica and the Atacama Desert in Chile. He is a member of the Mars Exploration Rovers Mini-TES science team and has worked extensively on the analysis and interpretation of thermal infrared data from Mars orbiting spacecraft.

# Geomorphological Evidence for Water on Mars

Victor R. Baker<sup>1</sup>



**M**artian landscapes and landforms indicate episodic activity by water and ice, extending from the planet's earliest history up to the present day. Most of the relevant fluvial, glacial, volcano-ice, periglacial, lacustrine (even "marine"), and related landforms have direct counterparts on Earth. Moreover, they exist in causally related, holistic associations of space and time that confirm their relationship to a long-term history of water-related activity. Although strong geomorphological evidence for many of these relationships has been apparent for 30 years, its scientific importance has only been recently appreciated because of direct geochemical measurements of water and ice features by surface robotic and orbital instruments.

KEYWORDS: Mars, geomorphology, landforms, climatic change, hydrology

## INTRODUCTION

Despite 30 years of accumulating, increasingly abundant and unequivocal geomorphological evidence, the case for past water-related activity on Mars remained immensely controversial until very recently (Baker 2004). Ingenious models were proposed (e.g. Hoffman 2000) to ascribe non-aqueous origins to individual Martian landforms that otherwise had striking similarities to water-generated features on Earth. Nevertheless, this view is profoundly changed because of recent developments, notably the nuclear physical measurement of abundant, extant, near-surface ice (Boydton et al. 2002) and direct chemical analyses of aqueous minerals associated with sedimentary rocks (Squyres et al. 2004). Recent dampening of hydrophobic theorizing makes it appropriate to reassess the geomorphological evidence for water on Mars, and this brief overview will emphasize developments.

Geomorphology concerns the nature and origins of landforms and landscapes. Its application to extraterrestrial planetary surfaces relies upon known associations of form and process on Earth. However, the rationale for ascribing genesis to a newly discovered planetary landform is not simply a matter of comparative image analysis. Landforms and landscapes exist in complex, interrelated assemblages, in which the different elements relate to one another in time and space because of their generation by a unique sequence of formative processes. Scientifically productive alternative explanations must not merely satisfy individual, simple-minded, "look-alike" criteria. Instead, they must account holistically for the entire, genetically related assemblage, in the same way that the solution of a crime depends, not on a single clue, but on the whole interrelated web of evidence that is built up through connections of time and space by a master detective.

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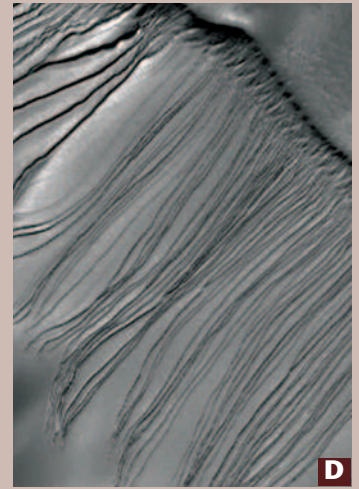
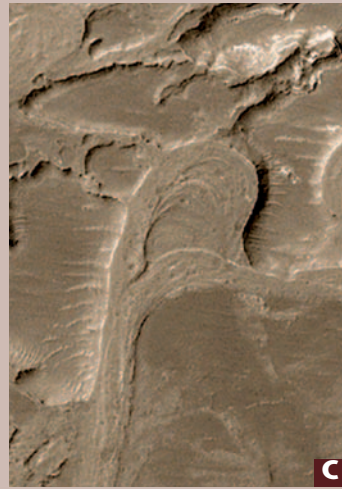
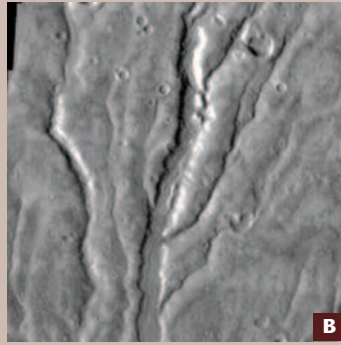
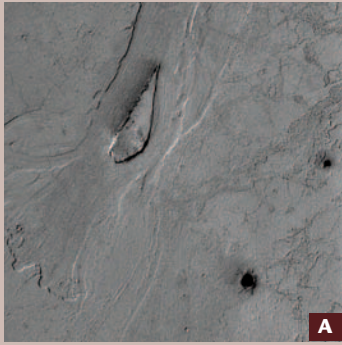
## CHANNELS, VALLEYS, ALLUVIAL FANS, AND SEDIMENTS

As recognized early in the era of spacecraft exploration, channels and valleys extensively dissect the surface of Mars. Channels are elongated troughs that display clear evidence for large-scale fluid flow across their floors and on parts of their walls or banks (FIG. 1A). Immense channels, with widths of tens of kilometers and lengths of up to a few thousand kilometers, display a suite of morphological attributes that are most consistent

with genesis by cataclysmic flows of water and sediment (Baker 2001). On Earth, such flows produced the distinctive landforms of the Channeled Scabland (FIG. 2A). An important recent discovery is that Martian flood channel activity, involving outbursts of water and associated lava flows, occurred in the Cerberus plains region on the order of 10 million years ago (Berman and Hartmann 2002; Burr et al. 2002). The huge discharges associated with these floods and the temporally related volcanism should have introduced considerable water into active hydrological circulation on Mars.

While the huge Martian channels are generally well characterized by the older imaging systems of the 1970s, it was not until a new generation of orbital imaging capabilities in the past several years that major advances occurred in understanding the nature of valley networks (FIG. 1B). These valleys dissect the Martian highlands much more extensively than was apparent from the earlier images (Hynek and Phillips 2003). Many valleys contain relict channels comparable in their dimensions to the active river channels associated with terrestrial valleys (Irwin et al. 2005). Formed about 3.9 billion years ago, Martian highland craters and impact basins were extensively eroded by surface runoff processes during episodes with Earth-like precipitation (Craddock and Howard 2002).

Large alluvial fans occur in ancient highland craters at middle-to-low southern latitudes. They are remarkably similar to low-relief terrestrial alluvial fans formed dominantly by fluvial, as opposed to debris flow, processes (Moore and Howard 2005). They probably formed during an episode of enhanced precipitation that followed the transition from the early period of heavy impact bombardment (the Noachian Epoch) to the period of lower impact rates after about 3.9 billion years ago. Relatively high denudation rates are inferred for the Noachian, and these are much greater than in later periods (Craddock and Howard 2002). The new observations are consistent with the discovery that



**FIGURE 1** Examples of Mars landforms indicative of water and ice processes. (A) Cataclysmic paleo-flood channel south of Cerberus (3.8°N, 204.7°W). The 3 km wide image shows a relatively small streamlined island and a cataract. (NASA MGS Press Release No. MOC2-866) (B) Portion of the Warrego valley network, 24 km wide (42.3°S, 267.5°W). (NASA MGS Press Release No. MOC2-868) (C) Ancient scroll topography and meander cutoff. This 2 km wide image is located at 24.3°S, 33.5°W. (NASA MGS Press Release No. MOC2-543) (D) Debris flow levees on a poleward-facing dune face in Russell crater (54.7°S, 347.4°W). (MOC IMAGE M19-01170)

upper layers of the ancient Martian crust of the highlands contain extensive sedimentary rocks that were emplaced during the intense denudation phases (Malin and Edgett 2000a). Now confirmed by in situ inspection (Squyres et al. 2004), sedimentary rocks were identified from orbit by their morphological expression. Imagery from the Mars Orbiter Camera (MOC) of the Mars Global Surveyor (MGS) mission shows that the Martian highlands do not consist of an initial lunar-like surface, underlain by an impact-generated megaregolith, as presumed in previous models (e.g. Carr 1996). Instead, cratering, fluvial erosion, and deposition of layered materials probably all occurred contemporaneously, leading to a complex interbedding of lava flows, igneous intrusions, sediments, buried crater forms, and erosional unconformities (Malin and Edgett 2000a).

## ANCIENT OCEANS, SEAS, LAKES, AND DELTAS

Morphological evidence for past large bodies of water covering the northern plains of Mars, apparent by the late 1980s, includes the morphological characteristics of sedimentary deposits and, more dramatically, a pattern of surrounding shorelines (Clifford and Parker 2001). Evidence for the latter was systematically criticized in a global sense (Carr and Head 2003), but was supported for local areas by very detailed mapping (e.g. Webb 2004). Nevertheless, the general concept of past inundations on the northern plains, constituting an “Oceanus Borealis,” at least for geologically short episodes, has been found to be generally consistent with considerable geomorphological evidence. The distinctive water-laid sedimentary deposits that cover parts of the northern plains, known as the Vastitas Borealis Formation, afford the most convincing evidence (Carr and Head 2003), including (1) margins that roughly mark the surface to which a body of water would approximate, (2) a distinctive population of impact craters indicating associated ice and sediments (Boyce et al. 2005), and (3) a phenomenally flat and smooth surface expression, similar to that of abyssal plains in Earth’s ocean basins.

The water body associated with emplacement of the Vastitas Borealis Formation was approximately contemporaneous with the floods responsible for the largest outflow channels, and it may have covered as much as 3 million km<sup>2</sup> to average depths of hundreds of meters. The largest estimates involve as much as 20 to 60 million km<sup>3</sup> of water, equivalent to 200 to 400 meters spread evenly over the whole planet and comparable to the inferred collective flows from the outflow channels (Carr and Head 2003; Boyce et al. 2005), as proposed by Baker et al. (1991). Other periods of outflow channel activity and associated inundations of the northern plains (Clifford and Parker 2001; Fairén et al. 2003) are far less certain as to the extent, relative timings, and durations of the various inundation episodes.

Though the debate over the Martian “ocean” has received much attention, even more compelling evidence supports the existence of numerous lakes and seas, which were temporarily extant on the surface of Mars at various times in the planet’s history (Cabrol and Grin 2002). The more ancient lakes occupied highland craters during the heavy bombardment epoch, spilling over to feed valleys such as Ma’adim Vallis (Irwin et al. 2004). The floodwater spilled from lakes that held up to several hundred thousand cubic kilometers of water, covering an area of about one million cubic kilometers, and flows achieved peak discharges of millions of cubic meters per second (Irwin et al. 2004). Abundant crater paleolakes seem to have developed just after the heavy bombardment, and very large lakes occupied the floors of the impact basins Hellas and Argyre.

Fluvial deltas are commonly associated with the paleolakes. One complex of ancient meandering alluvial channels, comprising a fan-delta partly filling the crater Eberswald or NE Holden (Malin and Edgett 2003; Moore et al. 2003), displays Earth-like morphologies that can only be explained by persistent fluvial activity on time scales ranging from centuries (Jerolmack et al. 2004) to hundreds of millennia (Bhattacharya et al. 2005). Paleo-meander bend topography (Fig. 1C) shows that these were laterally accreting, alluvial rivers of a similar type to the modern Mississippi.

## THE CRYOLITHOSPHERE OF MARS

What happened to the huge water inventory necessary for generating channelized megafloods and relatively short-lived lakes and seas? While a variety of atmospheric-loss processes undoubtedly occurred, the geomorphological evidence suggests that water, even the “Oceanus Borealis,” was not on the surface for prolonged periods. Instead it resided nearly all the time, except for brief, sometimes



**FIGURE 2** Examples of Earth water- and ice-related landforms with distinctive morphologies that have equivalents on Mars. (A) Longitudinal grooves and inner-channel cataract complex eroded into basalt by the catastrophic Pleistocene megafloods of the Channeled Scabland in east-central Washington, USA. (B) Ice-wedge polygons formed in permafrost terrain near Barrow, Alaska, USA. (C) Small rock glacier and adjacent periglacial debris fans in the Altai Mountains of south-central Siberia. (D) Esker on the Waterville Plateau in eastern Washington, formed by gravel deposition from meltwater that flowed through tunnels beneath the late Pleistocene Okanogan Lobe of the Cordilleran Ice Sheet. This esker is about 30 m wide and 3 km long.

spectacular episodes, within or beneath semipermanent, ice-rich permafrost. The long-term existence of this ice-rich layer, constituting a cryolithosphere about 1–2 km thick in equatorial areas and 5–6 km thick at the poles, is documented by a variety of geomorphological features (Kuzmin 2005). Most of these have been well known since the 1970s, including various types of flow-lobed ejecta blankets (rampart craters), debris flows, lobate debris aprons, and polygonal terrains. A variety of landforms related to volcano-ice interactions (e.g. Chapman et al. 2000) document the occasional short periods of volcanically induced water outbursts from this reservoir of ice and underlying ground water. Following these episodes, surface water seems to have very rapidly returned to the cryolithosphere. Thus, despite considerable theorizing (reviewed by Carr 1996), a clear indication of the size of Mars’ mostly hidden global water inventory cannot be gleaned from the isotopic composition of the tiny fraction of that inventory which was subject to long-term exospheric escape processes.

### RECENT GULLIES, GLACIERS, AND RELATED ACTIVITY

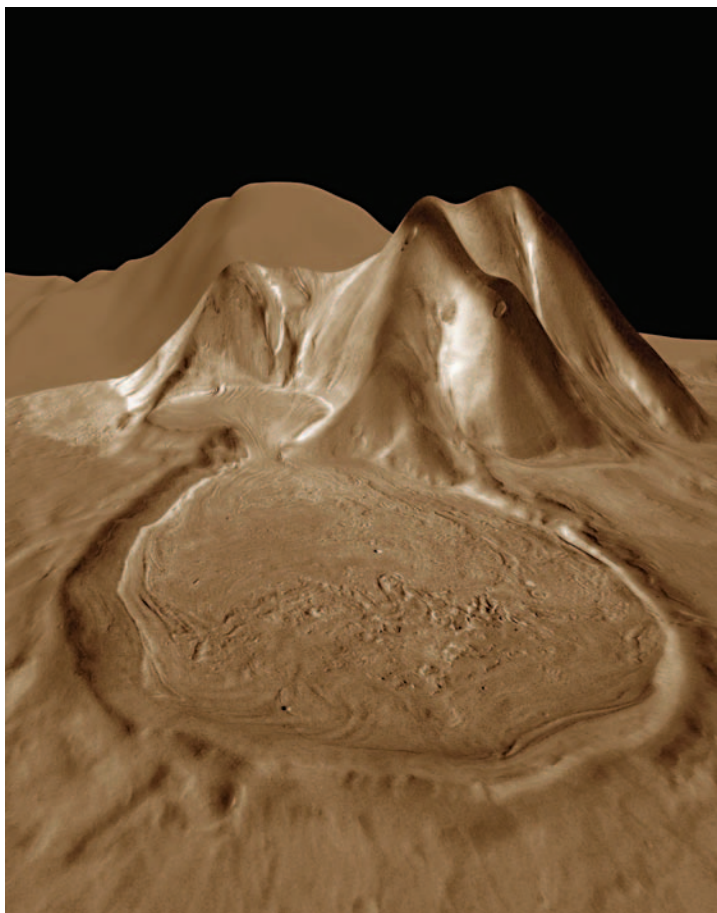
Recent discoveries from Mars Orbiter Camera (MOC) images show that Mars displays a diverse suite of exceptionally young, globally distributed landforms that are water related. If observed on Earth, these landforms would generally be well understood to have aqueous origins, involving dynamical hydrological cycling on relatively short time scales (hundreds to thousands of years) in a warmer, wetter, and denser atmosphere than occurs on Mars today. Perhaps the most striking of the recent discoveries made from the high-resolution MOC images is that of numerous small gullies (Malin and Edgett 2000b), developed on hillslopes associated with crater rims and channel or valley walls. Morphological similarity of these hillslope gullies to terrestrial, high-latitude, periglacial gullies suggests an origin by aqueous debris flows, involving the melting of

near-surface ground ice. The gullies are uncratered, and their associated debris-flow fan deposits are superimposed on both eolian bedforms (dunes or wind ripples) and polygonally patterned ground, all of which cover extensive areas that are also uncratered (Malin and Edgett 2000b). The patterned ground is itself a very strong indicator of near-surface, ice-related processes in the active (seasonally thawed) layer above the Martian permafrost zone (Siebert and Kargel 2001).

At the regional scale, gullies occur in high-latitude bands on Mars. They are associated with a variety of other landforms that indicate direct emplacement and local degradation of mantles of ice and dust, possibly even dirty snow, all derived from the atmosphere (Head et al. 2003). The evidence consists of small-scale polygonal or patterned terrains, similar to the ice-wedge phenomena of Earth’s high-latitude permafrost regions (Fig. 2B); the mobilization of rocky debris on slopes, similar to the rock glaciers of Earth’s periglacial regions (Fig. 2C); and a sort of regional smoothing of small-scale topography by deposits, a few to several meters thick, that are internally layered and locally eroded (Mustard et al. 2001). The emplacement of ice-rich deposits at low- to mid-latitudes seems to be consistent with geologically recent episodes of higher tilt (obliquity) of Mars’ axis of planetary spin. This would result in warming of the polar caps, thereby increasing the sublimation of ice and migration of water vapor to the then-cooler lower latitudes.

Another class of very distinctive debris flows occurs on the debris-mantled slopes of large sand dunes (Fig. 1D) (Mangold et al. 2003). Water-sediment mixtures afford the most likely mechanism for producing these landforms. More controversial are the abundant dark slope streaks developed in currently active dust mantles on hillslopes; a case can be made that these result from local, occasional water activity (Miyamoto et al. 2004).

Glaciated landscapes are some of the most important landform features documented by the newer high-resolution data. Earlier arguments for extensive glaciation on Mars were severely criticized, in part because glaciation has immense hydrological and climatological implications. The growth and persistence of large glaciers require a dynamic hydrological system that moves large quantities of water from surface-water reservoirs, such as lakes and seas, through the atmosphere to sites of precipitation. Resistance to the idea of ancient glaciers on Mars is especially curious, given that there was a general scientific consensus that Mars displays an immense variety of periglacial landforms, most of which require the activity of ground ice. The periglacial landforms include debris flows, polygonally patterned ground, thermokarst, frost mounds, pingos, and rock glaciers. On Earth, most of these landforms develop under climatic conditions that are both warmer and wetter than the conditions for the cold-based glacial landforms now known to abound on Mars (Baker 2001).



**FIGURE 3** Mars Express High Resolution Stereo Camera perspective view (30X vertical exaggeration) of debris that has flowed from a 4 km high mountain massif, into two adjacent craters. The debris is organized into crater-filling flow patterns of parallel ridges that spread out to a width of 16 km in the foreground. This landform assemblage, located east of Hellas, is analogous to terrestrial debris-covered piedmont glaciers. Numerous pits and depressions show wastage of the glacial ice, which may have been active only several tens of millions of years ago (Head et al. 2005).

The new evidence of glaciation is distinguished by its abundance, the complex detail of its assemblages, and the commonly very young geological ages (Kargel 2004). The glacial landforms of Mars include erosional grooves, streamlined/sculpted hills, drumlins, horns, cirques, and tunnel valleys; depositional eskers (Fig. 2D), moraines, and kames; and ice-marginal outwash plains, kettles, and glaciolacustrine plains. These landforms occur in spatial associations, proximal-to-distal in regard to past ice margins, that exactly parallel terrestrial glacial geomorphological settings. Long-recognized areas of past glaciation on Mars include lobate debris aprons near uplands surrounding Argyre and Hellas (Kargel 2004), lineated valley fills in the fretted troughs of the highlands/lowlands boundary north of Arabia Terra, and the polar regions, where the ice caps were much more extensive during portions of post-Noachian time. Huge glaciers marked the western flanks of the Tharsis volcanoes. Debris aprons at the bases of massifs in eastern Hellas show clear morphological evidence of sublimation, ice-rich substrates, and glacial-like viscous flow (Fig. 3). Geologically recent ice-rich rock glaciers (or debris-covered glaciers) occur at the base of the Olympus Mons scarp, where they are superimposed on older, much larger, relict, debris-covered piedmont glacial lobes (Head et al. 2005).

## DISCUSSION AND CONCLUSIONS

Theorizing about past water on Mars oscillates between a hydrophilic view of a wet surface environment and a hydrophobic view of a dry surface environment. Geomorphological evidence from the 1970s and 1980s pointed to a Mars that was episodically active in a hydrological sense during post-Noachian time. Hypotheses that explained all these features as interrelated were extensively criticized and pronounced inferior to the long-prevailing view that Mars had been continuously dead and dry since the Noachian. Though the latter view had considerable theoretical support, it failed to explain the mounting new data that Mars has experienced episodic hydrological activity throughout its geological history (Baker 2001)—most remarkably, even up to the last several million years. While much of the relevant new data, like those of the 1970s, is geomorphological, the change in scientific thinking is occasioned by geochemical and mineralogical measurements, both remote and in situ.

Geomorphology will continue to contribute to the understanding of Mars' watery past, but this contribution will be less in the realm of theoretical models and more in the realm of the unique realities that are distinctly Martian. The relevance is perhaps best expressed in Stephen Jay Gould's "principle of planetary individuality," described as follows (Gould 1991, pp 506–508):

The surfaces of planets and moons cannot be predicted from a few general rules. To understand planetary surfaces, we must learn the particular history of each body as an individual object ... their major features are set by unique events—mostly catastrophic—that shape their surfaces ... Planets are like individual organisms not water molecules; they have irreducible personalities built by history ...

## ACKNOWLEDGMENTS

This necessarily brief overview cites only a small sampling from hundreds of geomorphological publications that document past aqueous activity on Mars. The author both thanks and apologizes to authors of studies not included, especially to the many who recognized, as early as the 1970s and 1980s, the compelling geomorphological evidence for Mars' aqueous past. ■



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# The Orbital Search for Altered Materials on Mars

Michael B. Wyatt<sup>1</sup> and Harry Y. McSween Jr.<sup>2</sup>

**The Martian surface is dominated by primary igneous minerals common in basaltic rocks. Limited chemical alteration exists in fine-grained dust, and is likely in sands and rocks at high latitudes and in the northern lowland plains where materials have interacted with ice and snow. Evidence for extensive production of secondary phases is revealed at higher spatial resolutions, where alteration effects of unique, and perhaps time-limited, aqueous environments are observed. The distribution of ice on Mars thus appears to have a global influence on the production of alteration materials, whereas the effects of water are discovered in unique and locally diverse geological settings.**

## INTRODUCTION

Recent observations by the Mars Global Surveyor (MGS) TES, Mars Odyssey (MO) THEMIS, and Mars Express (MEX) OMEGA instruments (see glossary on page 138 for acronyms in text) have greatly improved knowledge of the abundances and distributions of Martian minerals and have provided insight into past geological environments. This paper summarizes major discoveries about surface compositions from orbital experiments, focusing on investigations of altered materials and their implications for the history of water on Mars. The search for chemically derived secondary phases on Mars is driven, in large part, by physical evidence of surface-volatile interactions in the form of ancient, fluvial, dissected channels and surfaces recently modified by ice. The search began over four decades ago with the use of Earth-based telescopes and early robotic explorers. Only recently, however, have observations from TES, THEMIS, and OMEGA been used to construct global surface-composition maps and search for local exposures of altered materials at high resolution. The production of secondary phases depends on a number of factors, including the compositions of precursor igneous minerals and glasses, the nature of the alteration environment (gas, aqueous, solid), temperature, pH, and time. Global variations in surface mineralogy are crucial to understanding the dynamic interaction between the atmosphere, hydrosphere, and crust.

## GEOLOGICAL SETTING

A globally projected simple-cylindrical image (FIG. 1A) made from MOC and MOLA datasets provides the geological context for the distributions of Martian mineral abundances. The

regolith consists of a mixture of bright (high-albedo), globally homogeneous, fine-grained dust and dark (low-albedo), locally derived, sand drifts and dunes atop variably indurated soil, rock fragments, and layered bedrock exposures. The ancient southern highlands are of Noachian to Hesperian age, whereas the northern lowlands are composed of younger Hesperian to Amazonian materials covering a Noachian basement. The white line in FIGURE 1A approximates a 40 km crustal-thickness dichotomy

separating thinner crust to the north from thicker crust to the south (Zuber et al. 2000), and the yellow line marks the boundary of the Vastitas Borealis Formation (VBF) (Tanaka et al. 2003). VBF materials have been interpreted as sediments reworked by near-surface, in situ volatile-driven processes (Tanaka et al. 2003) and as a sublimation residue from frozen bodies of water (Kreslavsky and Head 2002).

There is a bimodal distribution of near-surface H<sub>2</sub>O ice measured by the Gamma Ray Spectrometer (GRS) (e.g. Boynton et al. 2002) and MOC- and THEMIS-observed ice-rich mantles (FIG. 1B). Mantles have been interpreted as meter-thick, ice-rich sediments (Mustard et al. 2001) or remnant snowpacks (Christensen 2003) and are thought to form during phases of high obliquity. Development of near-surface ice is likely connected to surface ice deposition as abundances are too high to be accounted for by vapor diffusion alone (e.g. Mustard et al. 2001; Christensen 2003; Head et al. 2003).

## EARLY SEARCHES FOR ALTERATION

Investigations of high- and low-albedo surfaces with visible/near-infrared (VNIR) spectra from Earth-based telescopes and early Mars spacecraft provided a framework of Martian compositions (reviewed by Bell 1996). Spectral observations in the VNIR are sensitive to electron transitions of metals, especially iron, and molecular vibrational transitions in minerals, which can be used to determine chemical and mineralogical compositions. FIGURE 2A shows composite, telescopic-orbital (Phobos-2 Imaging Spectrometer for Mars) VNIR spectra representative of Martian high- and low-albedo surfaces (Mustard and Bell 1994).

### High-Albedo Surfaces

VNIR observations of high-albedo surfaces are consistent with highly oxidized, fine-grained materials characterized by poorly crystalline iron oxides and a small amount of crystalline iron oxides (e.g. Morris et al. 1997). Subtle spectral differences in high-albedo surfaces suggest small variations in the abundance, and possibly composition, of crystalline iron oxide materials. A weak spectral band in the 2.2 μm

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region may be indicative of a hydroxyl-bearing phase, while a strong 3  $\mu\text{m}$  feature suggests an  $\text{H}_2\text{O}$ -bearing phase in the dust. VNIR spectra of high-albedo surfaces on Mars are reasonably well matched by some terrestrial palagonitic tephtras.

### Low-Albedo Surfaces

VNIR observations of low-albedo surfaces are characterized by absorption at wavelengths of  $\sim 1$  and  $2 \mu\text{m}$ , which are attributed primarily to the presence of ferrous ( $\text{Fe}^{2+}$ ) iron in the form of pyroxene and hematite (both nanophase and crystalline). The identification of these features in spectra of dark surfaces in Syrtis Major is interpreted to represent the existence of two-pyroxene basalts similar to some Martian basaltic meteorites (Mustard and Sunshine 1995).

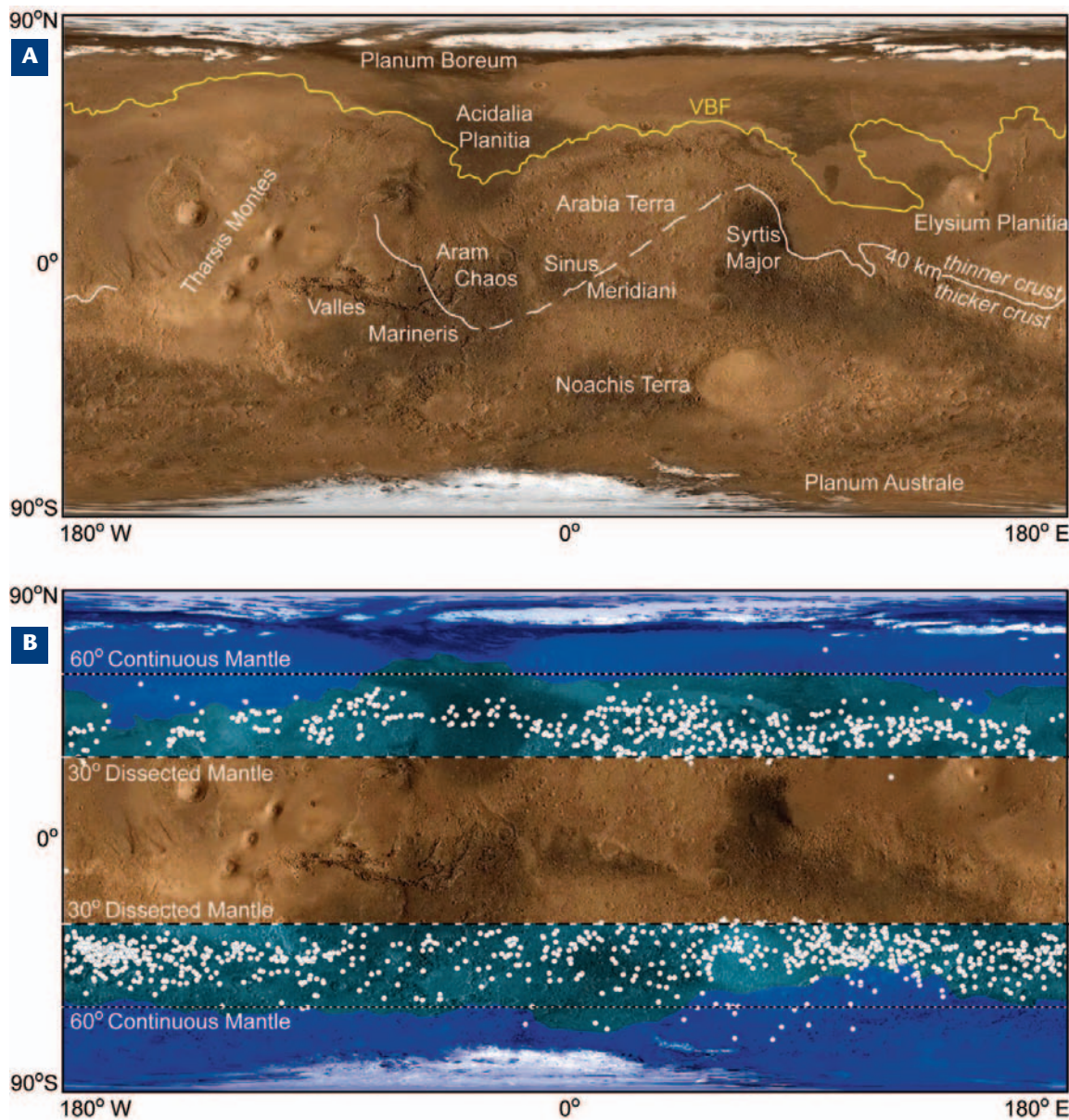
### Implications for Water

Based on these early studies, Mars appeared to be dominated by unaltered basalt and moderately altered, fine-grained dust, consistent with the current cold and dry Martian environment in which rates of physical weathering dominate

over rates of chemical alteration. This was the beginning of an apparent dichotomy between geomorphological evidence of extensive surface–volatile interactions and the lack of compositional evidence to support such observations. However, during the last decade, instruments on new orbiting spacecraft have produced an unprecedented amount of data to shed light on the history of water on Mars.

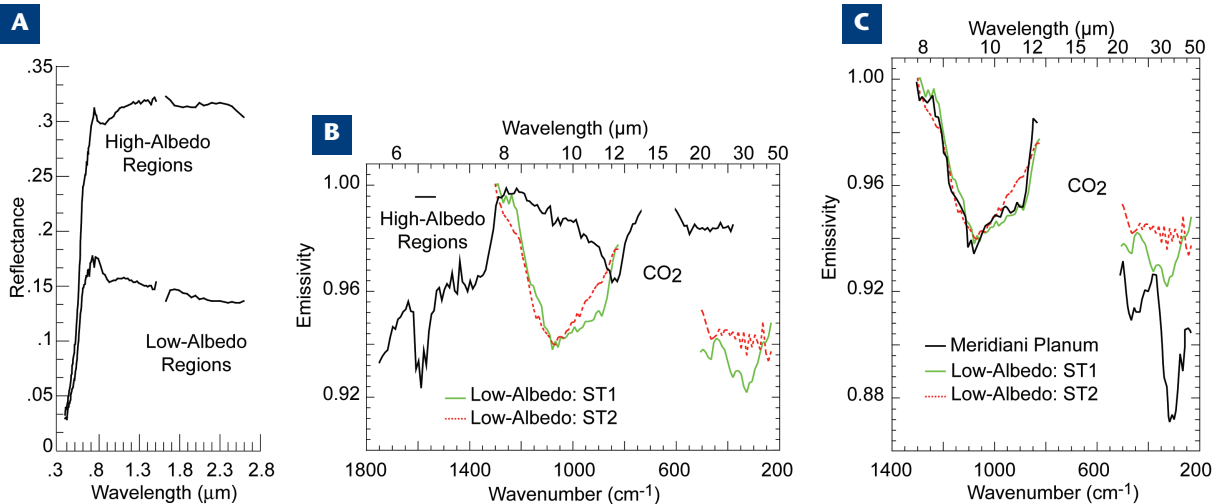
### MGS-TES GLOBAL SURFACE COMPOSITIONS

TES is a Fourier Transform Michelson Interferometer that measures emitted infrared energy from  $1700$  to  $200 \text{ cm}^{-1}$  ( $\sim 6$  to  $50 \mu\text{m}$ ) at  $10$  or  $5 \text{ cm}^{-1}$  sampling (e.g. Christensen et al. 2000a). TES began systematic mapping in 1999, and global coverage is now complete. Each spectrum represents the average emissivity of a  $3 \times 9 \text{ km}$  footprint on the Martian surface. Thermal infrared spectra are sensitive to the chemistry and structure of virtually all common rock-forming silicates and exhibit unique signatures that arise from the vibrational motions of atoms in the crystal structure



**FIGURE 1** (A) Major subdivisions of Martian crust illustrated by using MGS MOC and MOLA datasets. VBF—Vastitas Borealis Formation (Tanaka et al. 2003). (B) Distribution of near-surface  $\text{H}_2\text{O}$  ice and ice-rich mantles. MOC-MOLA context image with GRS near-surface

ice (blue) (e.g. Boynton et al. 2002) and mantle deposits (shaded gray from  $30^\circ$  to  $\sim 60^\circ$ ; poleward of  $60^\circ$ , continuous mantle deposits overlie GRS-measured near-surface ice). MOC observations of discontinuous mantle deposits are shown as white points (Mustard et al. 2001).



**FIGURE 2** (A) Composite telescopic-ISM VNIR spectra representative of Martian high- and low-albedo surfaces (Mustard and Bell 1994). (B) TES spectrum representative of high-albedo surfaces (Bandfield et al. 2003) and ST1 and ST2 spectral end members of low-albedo surfaces (Bandfield et al. 2000). (C) TES ST1 and ST2 spectral end members compared to Meridiani Planum spectrum showing hematite absorptions (Christensen et al. 2000b).

(e.g. Si–O stretching and bending in silicates). In complex mixtures, such as rocks, spectral features of component minerals combine linearly to produce a mixed, composite spectrum. Conversely, mixtures can be deconvolved into abundances of their component minerals (i.e. modal mineralogy) using a spectral end-member library of known mineral compositions (Ramsey and Christensen 1998).

### High-Albedo Surfaces

Analyses of TES data reveal a spectral shape that is representative of all high-albedo regions and is characterized by a relatively narrow absorption near 830  $\text{cm}^{-1}$  and a broad, deep absorption at  $>1250 \text{ cm}^{-1}$  (FIG. 2B) (Bandfield et al. 2003). The overall spectrum is best matched by the framework silicates plagioclase (Bandfield et al. 2003) and zeolite (Ruff 2004) and is consistent with volume scattering effects in fine particulates. The spectrum also exhibits the characteristic absorption band near 1600  $\text{cm}^{-1}$  of mineral-bound water. This feature is best matched by a similar peak in zeolite, whose structure, unlike plagioclase, contains molecular water (Ruff 2004). The spectral absorption near 1480  $\text{cm}^{-1}$  corresponds well to the 1450 to 1500  $\text{cm}^{-1}$  bands seen in anhydrous carbonates and most closely matches that of the Mg-carbonate magnesite (Bandfield et al. 2003). Only small concentrations of carbonate (~2 to 5 wt%) are required to produce the observed spectral signature.

### Implications for Water

Evidence of zeolite and carbonate in fine-grained dust implies widespread production of secondary phases on Mars; however, the amount of volatiles and the extent of alteration are likely limited. On Earth, abundant occurrences of zeolite are often found in tephra deposits altered by interactions with groundwater. However, zeolites are also produced in the cold and dry environment of Antarctica, a setting that is perhaps most analogous to current conditions on Mars (e.g. Gibson et al. 1983). Similarly, carbonates are found in a variety of environments as primary aqueous precipitates. However, Mg and Ca carbonates may also form under low- $\text{CO}_2$  pressure conditions, in which liquid water is not even stable but is present in a transient state, and should be common, stable weathering products in the present Martian atmosphere (Booth and Kieffer 1978). The lack of any spectral evidence for a carbonate bedrock source, which may be expected to form if large standing bodies of water ever existed on Mars, further supports an interpretation of limited global chemical weathering.

### Low-Albedo Surfaces

The bulk variability of low-albedo surface compositions measured by TES is accounted for by two distinct spectral end members (FIG. 2B) (Bandfield et al. 2000). The Surface Type 1 (ST1) spectrum is characterized by a broad, slightly square-shaped absorption between 800 and 1200  $\text{cm}^{-1}$ . Absorption from 200 to 500  $\text{cm}^{-1}$  has an overall negative slope with decreasing wavenumbers and contains minor, narrow absorption bands. The Surface Type 2 (ST2) spectrum is characterized by a more rounded, slightly V-shaped 800 to 1200  $\text{cm}^{-1}$  region of absorption and uniform absorption at low wavenumbers.

ST1 is spectrally similar to terrestrial continental flood basalts (Bandfield et al. 2000) and consists of high abundances of plagioclase (~40–50 vol%) and high-calcium clinopyroxene (~30–40 vol%) and small amounts of olivine (McSween et al. 2003). ST2 is spectrally similar to terrestrial arc andesites (Bandfield et al. 2000) and partly altered basalts (Wyatt and McSween 2002; Morris et al. 2003; Kraft et al. 2003; Ruff 2004; Michalski et al. 2005). Ambiguity in classifying the ST2 lithology arises because a spectral component of this unit (~20–30 vol%) can be interpreted as volcanic siliceous glass (an abundant phase in andesite) or a combination of secondary phases found in altered basalt (smectite, palagonite, amorphous silica-rich coatings, and zeolite). ST2 also contains high amounts of plagioclase (~30–40 vol%) and less-high-calcium clinopyroxene (~10–20 vol%) (McSween et al. 2003).

### Classification of ST2 Lithology

The debate over the ST2 lithology is significant for understanding the petrogenesis and subsequent alteration of the Martian crust. Identification of widespread andesite may imply an early episode of plate tectonics on Mars, while altered basalt would indicate extensive surface–volatile interactions. The competing spectral interpretations were addressed by Wyatt et al. (2004) by examining the geological context (FIG. 1A, 1B) of the ST1 and ST2 global distribution pattern illustrated in FIGURE 3.

**ST1 Basalt and ST2 Andesite:** FIGURE 3 shows no global systematic relationship between crustal thickness (40 km dichotomy white line) (Rogers and Christensen 2003) or

age and the distribution of ST1 (green) and ST2 (red), as would be expected in a basalt-andesite model. Andesitic volcanism on Earth is mostly associated with thick continental crust; however, on Mars the largest distribution of ST2 overlies thin crust in the northern plains. Moreover, the occurrence of ST2 without associated ST1 in the northern plains argues against its being derived by fractionation of basaltic magma. Fractionation should produce basaltic and andesitic rocks similar in age, but ST2 materials in the northern lowlands are significantly younger than southern highlands basalts. Partial melting of an ancient basaltic crust (rather than ultramafic mantle) might conceivably produce andesitic magmas, especially under wet conditions, but the absence of Martian meteorites having andesitic compositions and appropriate ages argues against this possibility.

**ST1 Basalt and ST2 Altered Basalt:** FIGURE 3 indicates that ST1 materials dominate in equatorial and mid-latitude regions and ST2 materials dominate in the high-latitude northern lowlands and southern highlands. Wyatt et al. (2004) relate this spatial distribution to near-surface ice and ice-rich mantle deposits (FIG. 1B) and propose both a latitude and topographic influence on the global surface alteration of Mars. The lower part of FIGURE 3 is a plot of ST1 and ST2 normalized abundances from 90° south to 90° north that are averaged across 0.5° bins of longitude and compared (in a histogram) to percentages of dissected ice-rich mantle deposits (Mustard et al. 2001). The gradual transition from ST1 to ST2 in the Southern Hemisphere correlates well with the transition from a lack of ice-rich material (0°–25°S), to a maximum percentage of dissection (25°S–60°S), to uniform mantles of ice-rich deposits (60°S–90°S). This trend is interpreted to reflect increased amounts of chemical weathering resulting from basalt interactions with icy mantles. In the Northern Hemisphere, an abrupt transition from ST1 to ST2 occurs at ~20° and is correlated both with ice-rich mantle

deposits and the VBF boundary. Thus, alteration of sediments in the northern lowlands may have been enhanced by temporary standing bodies of water and ice.

### Implications for Water

Although the dominance of igneous minerals measured by TES for ST1 and ST2 implies limited chemical alteration on Mars, alteration is nevertheless greater at high latitudes and in the low-lying northern plains. The Dry Valleys of Antarctica may be the best terrestrial analogue for weathering on Mars because of the cold, hyper-arid environment, stable permafrost, and ground ice (Gibson et al. 1983). Basalts in these environments are dominated by plagioclase and pyroxene, with limited abundances of alteration phases similar to those proposed for ST2 materials (palagonites, zeolites, smectites, and silica coatings). All of these secondary products can be produced on Mars by chemical weathering of basalt without an abundance of water.

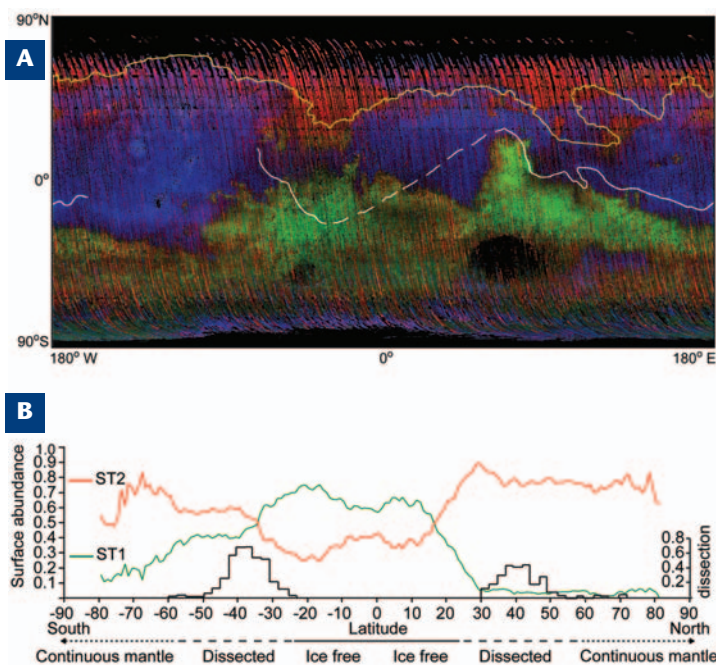
### LOCAL SURFACE COMPOSITIONS

We now take the orbital search for alteration materials and evidence of a possibly warmer and wetter ancient Mars climate to local scales using high-spatial-resolution observations from MGS TES, ODY THEMIS, and MEX OMEGA. The ODY THEMIS is a multispectral imager that measures nine thermal infrared (TIR) bands centered between 6.8 and 14.9 μm and five VNIR bands centered between 0.42 and 0.86 μm (Christensen et al. 2003). The spatial footprint of TIR images is 100 m/pixel while the VNIR is 18 m/pixel. The MEX OMEGA is a hyperspectral imaging spectrometer that measures 352 channels in the VNIR between 0.35 μm and 5.1 μm with a spatial resolution that varies from 300 m/pixel to 4.8 km/pixel (Bibring et al. 2005).

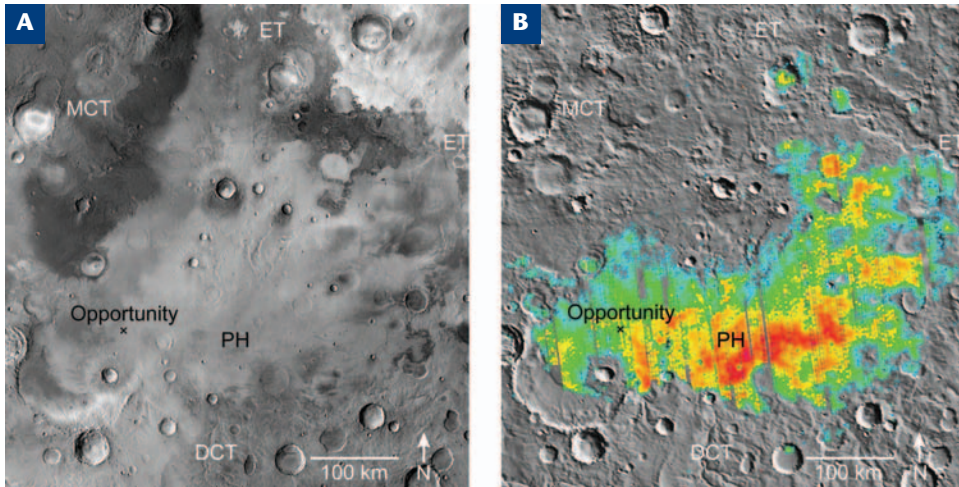
### Focus on Meridiani Planum

The geological setting of Terra Meridiani is among the most complex on Mars and includes exposures of ancient, fluvial-dissected cratered terrains (DCT) and younger, overlying layered materials and dust mantles (Arvidson et al. 2003). Physical erosion has shaped layered materials into domes, ridges, and plateaus, referred to collectively as etched terrains (ET). A smooth plains unit (PH) covers these landforms and is overlain by younger mantle deposits (MCT) to the north. A mosaic of THEMIS daytime infrared images of Meridiani Planum is shown in FIGURE 4A.

TES spectral analyses of the smooth plains unit reveal prominent absorptions in the 250–500 cm<sup>-1</sup> region that are significantly different from global end members (FIG. 2C) (Christensen et al. 2000b). These distinguishing spectral features are caused by gray crystalline hematite mixed with ST1 abundances of plagioclase and pyroxene. FIGURE 4B shows the occurrence of hematite-bearing material in Meridiani Planum superimposed on a shaded relief image derived from MOLA data. Hematite abundances vary from ~5% (blue) to ~20% (red) and make an irregularly shaped unit spanning 500 by 300 km. Comparisons of TES data with hematite laboratory spectra derived from different precursor phases suggests low-temperature (~100–300°C) dehydroxylation of goethite as the most plausible mechanism of formation (Glotch et al. 2004). Embayment relationships between hematite-bearing and hematite-poor units suggest that the formation of hematite was confined vertically and that precursor materials were likely deposited in a gravity-driven fluid, rather than as dispersed air fall (Christensen and Ruff 2004). The probable role of water in the formation of this large hematite deposit led to the selection of this site for in situ exploration by the Mars Exploration Rover (MER) Opportunity.



**FIGURE 3** (A) TES image of distribution of ST1 (green) and ST2 (red) materials and dust (blue). White line approximates a 40 km crustal-thickness dichotomy (Zuber et al. 2000), separating thinner crust to the north from thicker crust to the south. Yellow line marks the boundary of the VBF (Tanaka et al. 2003). (B) ST1 and ST2 normalized abundances from 90° south to 90° north, averaged across 0.5° bins of longitude and compared to percentages of MOC observations (histogram) (Mustard et al. 2001) of dissected ice-rich mantle deposits (Wyatt et al. 2004).



**FIGURE 4** (A) THEMIS daytime infrared mosaic of Meridiani Planum. DCT: dissected cratered terrains; ET: etched terrains; PH: smooth plains unit; MCT: mantle deposits. (B) MOLA shaded relief image with superimposed TES-measured hematite abundances (Christensen et al. 2000b).

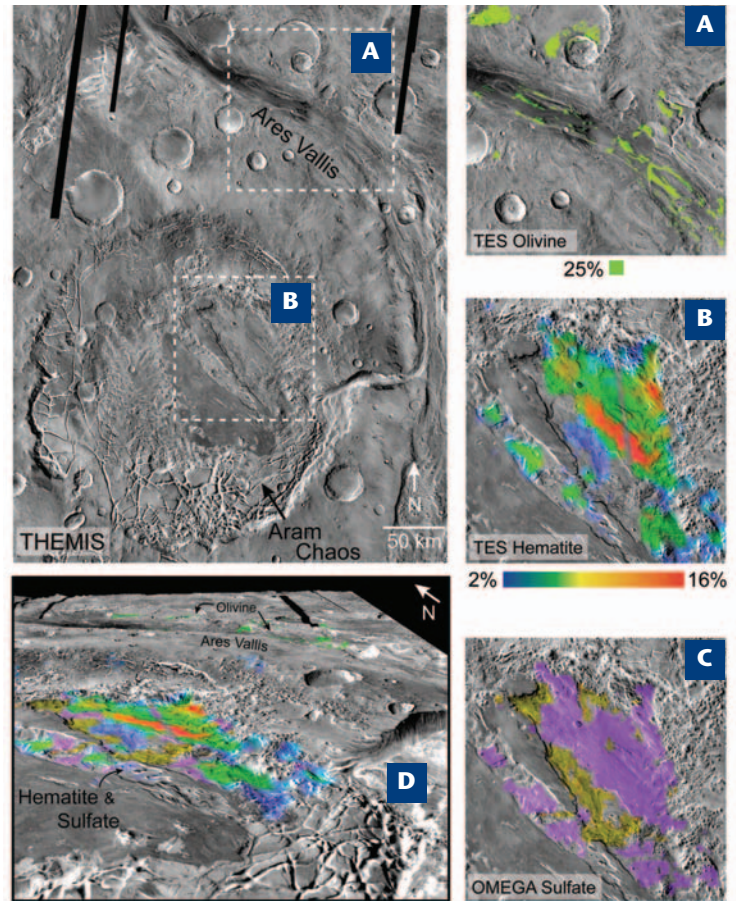
### Implications for Water

Opportunity instruments now on the surface of Meridiani Planum confirm the presence of coarse crystalline hematite previously detected in orbit by TES (Squyres et al. 2004). The layered bedrock from which hematite is derived is rich in Ca and Mg sulfates (Mini-TES and Alpha Particle X-Ray Spectrometer) and jarosite (Mössbauer Spectrometer), indicating extensive alteration and fluvial activity during hematite formation. Sulfate (kieserite) is also identified regionally in etched terrain materials from spectral analyses of OMEGA data (Gendrin et al. 2005; Arvidson et al. 2005). The mineralogical similarities among these deposits and the rocks examined by Opportunity imply that the inferred ancient aqueous environment extends over large scales and throughout the several-hundred-meter thickness of etched terrain deposits. However, the mixing of unaltered basaltic sands and hematite indicates that chemical alteration has been limited since hematite formation. These results complement interpretations by Christensen and Ruff (2004) that a small number of bodies of standing water altered Meridiani Planum surface materials but that these water bodies represent only localized phenomena against a backdrop of a cold, frozen Mars.

### THE SEARCH CONTINUES

The Martian surface is dominated by primary igneous minerals common in basaltic rocks. However, an imprint of limited chemical alteration exists in fine-grained dust and is likely in sands and rocks at high latitudes and in the northern lowland plains where materials have interacted with ice and snow. These secondary phases do not require abundant water and indicate that Mars has likely been a cold and frozen planet for an extensive period of geological time. However, it is at higher spatial resolutions that we observe the alteration effects of unique, and perhaps time-limited, environments where water once existed. Further detailed studies have resulted in the discovery of additional exposures of altered materials.

The discovery of hematite and sulfate in Valles Marineris and of sulfate in the dark longitudinal dunes of Olympia Planitia indicates that water played a major role in the formation of interlayered strata and northern circumpolar terrains (Christensen et al. 2000b; Gendrin et al. 2005; Langevin et al. 2005). Phyllosilicates that originate from the alteration of mafic and ultramafic igneous rocks have been identified in ancient terrains of Syrtis Major (Bibring et al. 2005). Each of these new local occurrences represents additional evidence for environmental change as compared with the cold and dry Martian climate of today. Such change is clearly illustrated in FIGURE 5, where secondary



**FIGURE 5** THEMIS daytime infrared mosaic of Aram Chaos and Ares Vallis showing TES-measured (A) olivine (Rogers et al. 2005) and (B) hematite abundances (Glotch and Christensen 2005) and (C) sulfate detected by OMEGA (Gendrin et al. 2005). The three-dimensional image of the THEMIS mosaic (D) has been overlain on MOLA topography.

and easily altered igneous minerals are mapped in close proximity. Hematite and sulfate occur in the center of the flat-floored impact crater Aram Chaos, where possible lake-bed sediments formed from the release of subsurface water (Glotch and Christensen 2005; Gendrin et al. 2005). Olivine has been identified in bedrock layers within Ares Vallis, a fluvial-dissected channel, but one where subsequent chemical alteration is limited (Rogers et al. 2005).

These mineral signatures reveal that Mars has been a dynamic and changing world. The orbital search for alteration

minerals has shed light on the role of water and ice in modifying the compositions of surface materials. Ice appears to have a global influence on the production of secondary phases, whereas the effects of water are discovered in unique and locally diverse geological settings. Future orbiters and landers will focus on these local settings in the search for evidence of habitable Martian environments, and perhaps even signs of extant or present life.

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# Water at the Poles and in Permafrost Regions of Mars

Philip R. Christensen<sup>1</sup>

**The poles and mid-latitudes of Mars contain abundant water in ice caps, thick sequences of ice-rich layers, and mantles of snow. The volume of the known reservoir is  $\geq 5 \times 10^6$  km<sup>3</sup>, corresponding to a layer ~35 m thick over the planet. Hydrogen in subsurface H<sub>2</sub>O ice has been detected at latitudes poleward of 50°. Morphological features show downslope flow of ice-rich sediment, and recent gullies have been produced from subsurface aquifers or melting snowpacks. Variations in Mars' orbit on timescales of 50,000 to 2,000,000 years produce significant changes in climate, which result in the transport of water from the poles, where it currently resides, to the lower latitudes, where it may play a critical role in surface geology, mineralogy, and geochemistry.**

KEYWORDS: Mars, ice, water, polar caps

## INTRODUCTION

Water has long been recognized as a major morphological agent on Mars (Baker this issue), but its present abundance and location remain enigmatic. A possible reservoir for a substantial amount of water is surface and subsurface ice at the poles and mid-latitudes. Recent observations have substantially improved our knowledge of this reservoir, but major questions remain as to its volume, age, and history. Oscillations in the axial tilt, eccentricity, and timing of closest approach to the Sun cause major changes in surface heating, which produce cyclic changes in Martian climate on timescales of  $10^5$  to  $10^6$  years (e.g. Pollack and Toon 1982). These changes redistribute polar ice, transferring it to lower latitudes as snow and ice during Martian "ice ages" (e.g. Jakosky et al. 1995). Today the major ice-bearing features are the polar ice caps, the layered units that surround them at both poles, and the mid-latitude permafrost zones that present morphologies strongly suggestive of subsurface ice. Each of these has unique properties, water abundances, and histories, and contributes to the water cycle in varying ways.

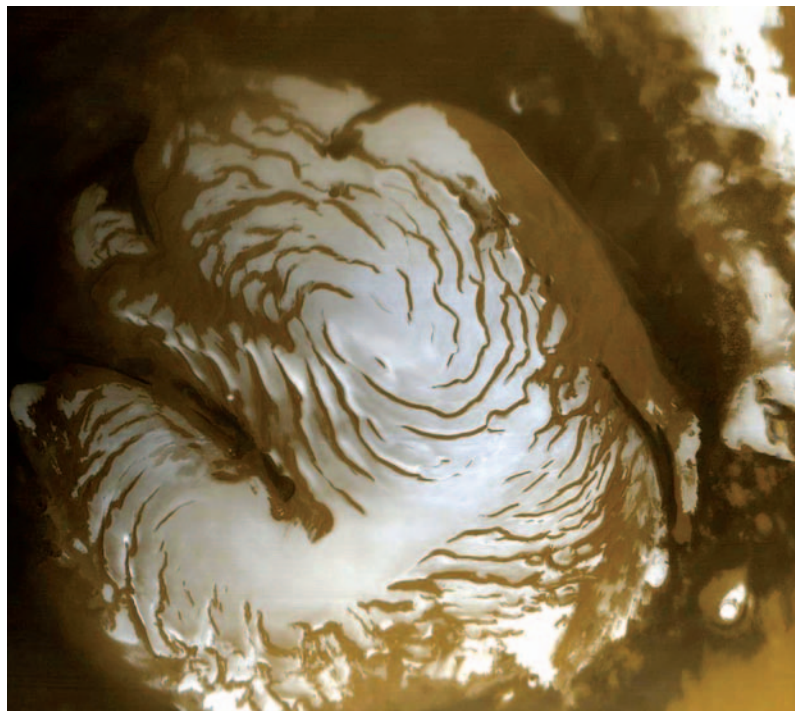
## POLAR CAPS

The polar caps of Mars (FIG. 1) have been observed since the 17<sup>th</sup> century and are assumed to be composed of some combination of H<sub>2</sub>O and CO<sub>2</sub> ice. The Martian atmosphere is composed of >95% CO<sub>2</sub> with a pressure of only a few millibars. This fact led to the prediction that CO<sub>2</sub> would accumulate at the poles during winter (Leighton and Murray 1966). This prediction was confirmed by orbital temperature measurements (e.g. Kieffer 1979), and global mapping has shown that seasonal CO<sub>2</sub> caps grow well into the mid-latitudes during winter, with perennial ice caps surviving

the summer at both poles. The thickness of the seasonal CO<sub>2</sub> ice caps has been estimated from Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) observations to reach approximately 1.5 m near the pole in both hemispheres (Smith et al. 2001), corresponding to ~25% of the total mass of the Martian atmosphere.

As the seasonal caps condense, they incorporate minor amounts of dust and H<sub>2</sub>O ice, which significantly affect the sublimation rates the following spring. Assuming a water vapor mass fraction of

$1 \times 10^{-5}$  in the condensing atmosphere, the amount of water stored in the seasonal caps is estimated at  $\sim 3 \times 10^{10}$  kg ( $\sim 3 \times 10^{-2}$  km<sup>3</sup>) (the Martian atmosphere contains  $\sim 10^{-1}$  km<sup>3</sup> of water). Overall, however, the water within the seasonal caps plays a relatively minor role in the global inventory or annual cycle of water on Mars.



**FIGURE 1** The north polar cap of Mars as seen by Viking. This mosaic of images was acquired during northern summer when the ice had retreated to its perennial size. The relatively bright material is H<sub>2</sub>O ice. The cap has shrunk to essentially the same location every year that it has been imaged by spacecraft (1971 to present) (James and Cantor 2001). Image width is ~900 km. IMAGE CREDIT NASA/JPL

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In their pioneering work, Leighton and Murray (1966) predicted that CO<sub>2</sub> would condense at the poles to sufficient depth for CO<sub>2</sub> to remain throughout the following summer. Spacecraft temperature observations show that CO<sub>2</sub> ice does survive the summer in the south, but is completely removed from the northern perennial cap, exposing H<sub>2</sub>O ice (Kieffer 1979). Sublimation of this ice releases water vapor into the atmosphere, which was initially detected by ground-based observations over 40 years ago (Jakosky and Barker 1984).

The Viking orbiter Mars Atmospheric Water Detector (MAWD) instrument provided the first global map of water vapor and confirmed that large quantities of vapor [ $\sim 100$  precipitable microns (pr  $\mu\text{m}$ )] were coming from the northern perennial cap (e.g. Jakosky and Farmer 1982). The MGS Thermal Emission Spectrometer (TES) instrument has provided detailed global maps of water vapor over three Martian years (1997–2004), confirming high water vapor abundances equatorward of the cap in the north, which rise rapidly to  $\sim 100$  pr  $\mu\text{m}$  in late spring once the CO<sub>2</sub> ice has disappeared (Smith 2004).

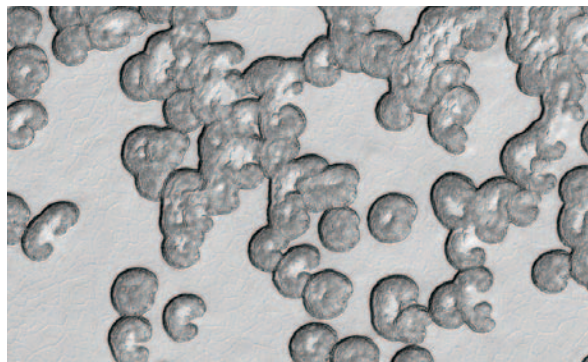
MAWD data showed no indication of water vapor coming from the perennial south polar cap (e.g. Jakosky and Farmer 1982), consistent with measured temperatures that correspond to CO<sub>2</sub> ice (Kieffer et al. 2000). A notable exception to this pattern was the ground-based water vapor measurements in 1969 that showed a significant increase in water vapor as compared with other seasons or other years. This has been interpreted to indicate that H<sub>2</sub>O ice was exposed that year in the south (e.g. Jakosky and Barker 1984). TES observations have confirmed the release of water vapor ( $\sim 45$  pr  $\mu\text{m}$ ) along the edge of the southern perennial cap, providing conclusive evidence that H<sub>2</sub>O ice is now being exposed on the southern cap (Smith 2004). The presence of this exposed ice has been confirmed by direct temperature measurements using the Mars Odyssey Thermal Emission Imaging System (THEMIS) infrared imager (Titus et al. 2003) and by near-IR spectral measurements from the Mars Express OMEGA spectrometer (Bibring et al. 2004).

A remarkable result from the high-resolution MGS Mars Orbiter Camera (MOC) was the discovery of quasi-circular depressions in the perennial south polar cap that are up to 1 km in diameter and uniformly  $\sim 8$  m deep (Thomas et al. 2000; Malin et al. 2001) (FIG. 2). Some depressions are expanding at rates of 1–3 m per year (Malin et al. 2001). They have been modeled as a layer of CO<sub>2</sub> ice over a substrate of either H<sub>2</sub>O ice or high-albedo (dust-free) CO<sub>2</sub> ice (Byrne and Ingersoll 2003). This thin layer of CO<sub>2</sub> ice may be relatively young and, even if completely sublimated, would be a minor contributor to the atmospheric CO<sub>2</sub> inventory. In this case, the atmospheric CO<sub>2</sub> partial pressure, and therefore the atmospheric temperature, would not be much higher than its current value.

## POLAR LAYERED DEPOSITS

Thick stacks of sedimentary deposits extend up to 600 km outward from the poles in both hemispheres. These units are  $\sim 3$  km thick at both poles and are layered down to the resolution of the MOC camera (Malin and Edgett 2001). These layers may have been produced by differences in the amount of airfall dust incorporated into the ice, perhaps as a result of orbit-driven cyclic changes in climate (e.g. Pollack and Toon 1982; Milkovich and Head 2005).

The volume of the north polar layered deposits is estimated to be  $\sim 1.2\text{--}1.6 \times 10^6 \text{ km}^3$  (Zuber et al. 1998). Attempts have been made to determine the density, and thus the ice to sediment ratio, of the layered materials using gravity and topography, but this value has been difficult to constrain.



**FIGURE 2** “Swiss cheese” terrain with quasi-circular depressions, located near 86.9°S, 352.4°E. These pits are several hundred meters across and have a remarkably uniform depth of  $\sim 8$  m wherever they are observed (Thomas et al. 2000; Malin et al. 2001). Some pits have been observed to increase in size over one Martian year (Malin et al. 2001). A possible explanation is that the upper  $\sim 8$  m thick layer is CO<sub>2</sub> ice, which is gradually disappearing and exposing a stable layer of H<sub>2</sub>O ice beneath it (Byrne and Ingersoll 2003). Image width is about 3 km. MOC IMAGE R1303615; MGS MOC RELEASE NO. MOC2-695

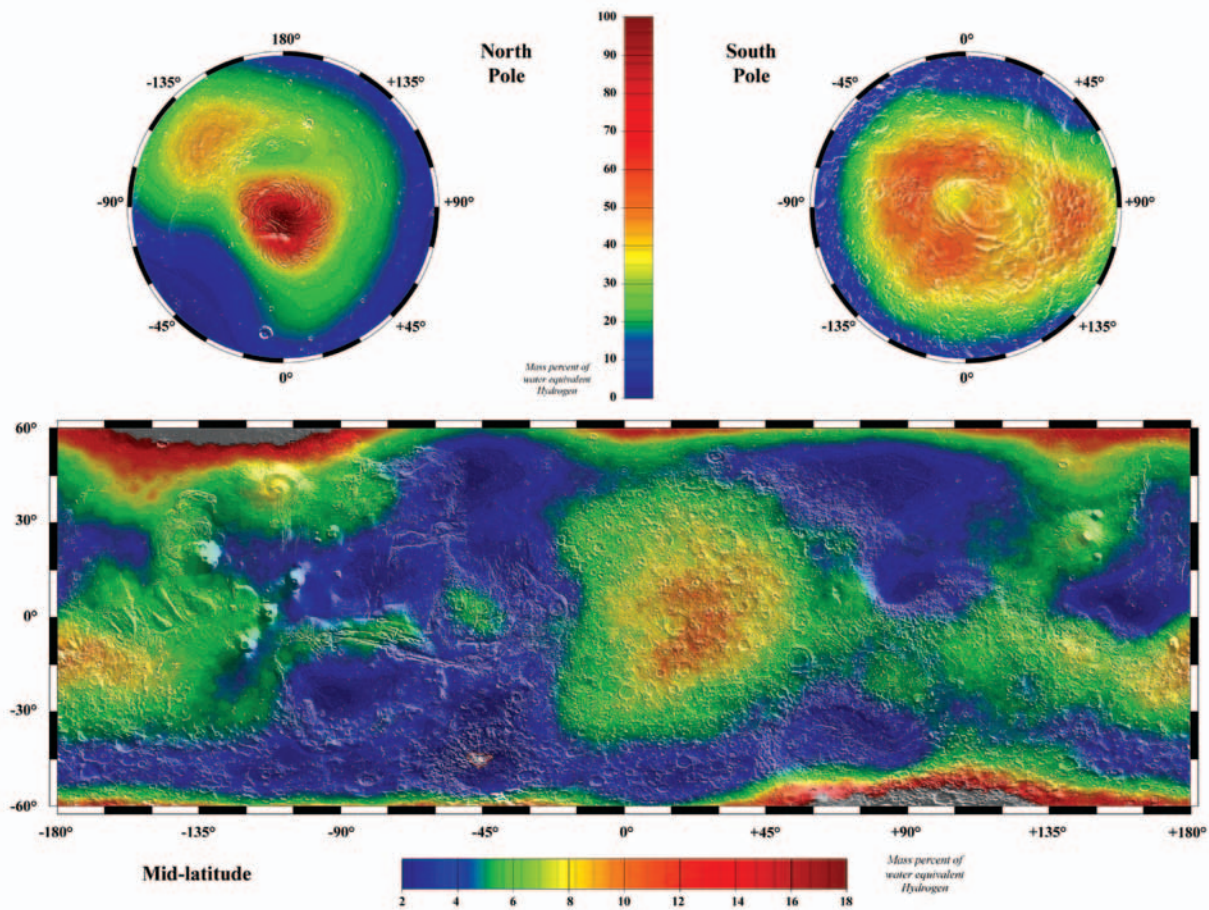
The topographic slopes and gently undulating surface of the northern layered materials are consistent with the slow radial flow velocities for H<sub>2</sub>O, but not CO<sub>2</sub>, ice rheology. Assuming that the layered deposits are made of essentially pure H<sub>2</sub>O ice, the upper limit for the quantity of water in the northern layered terrains is  $\sim 1.6 \times 10^{18} \text{ kg}$  ( $\sim 1.6 \times 10^6 \text{ km}^3$ ), which corresponds to an equivalent global layer of water  $\sim 12$  m deep. The areal extent of the southern deposits, which have a similar average thickness, is roughly twice that of the northern deposits, suggesting a water inventory (again assuming pure H<sub>2</sub>O ice) that is roughly twice that in the north.

Units within these deposits can be traced for hundreds of kilometers at both poles, suggesting a regional process of formation (Byrne and Murray 2002; Milkovich and Head 2005). A stratigraphic horizon near the base of the northern units is interpreted to have been an extensive sand sea that formed during a period when no icy cap was present (Byrne and Murray 2002). The lack of an ice cap would require a dramatic climate change and would represent a major event in Martian history. Analysis of layers within the upper units of the northern layered terrain shows the existence of  $\sim 30$  m periodicity, possibly associated with the 50,000 year obliquity cycle (Milkovich and Head 2005); a 100 m unit within this sequence lacks this layering and may represent a recent (0.5–2 Ma) period of ice removal and the formation of a sediment-rich lag. Crater counts also suggest an active process, with ages for the upper surfaces of these deposits of  $\sim 30\text{--}100$  Ma for the southern and  $<0.1$  Ma for the northern deposits (e.g. Herkenhoff and Plaut 2000). These ages likely reflect only the most recent cycle in this process, and cyclic deposition and erosion may have been occurring in the polar regions throughout Martian history.

## SUBSURFACE ICE

### Ice Stability Models

The stability of subsurface ice depends strongly on the porosity, tortuosity, and thermal conductivity of the surface (Mellon and Jakosky 1995; Mellon et al. 2004). Ice stability models predict that H<sub>2</sub>O ice will be stable at all latitudes for obliquities  $>32^\circ$  but will diffuse outward from the upper 1–2 m in the equatorial and mid-latitude regions when the obliquity decreases. Mars is currently in an “interglacial” period, with an obliquity of  $\sim 25^\circ$  (Mustard et al. 2001; Christensen 2003), and near-surface ice is predicted to be stable only poleward of  $\sim 50^\circ$  (Mellon and Jakosky 1995; Mellon et al. 2004).



**FIGURE 3** Distribution of subsurface H<sub>2</sub>O ice. This global map was made using data from the neutron spectrometer that is part of the Odyssey Gamma Ray Spectrometer suite. The abundance of hydrogen in the form of H<sub>2</sub>O ice is >30% poleward of ~60° in both hemispheres. Equatorial water-equivalent hydrogen abundances vary from 2% by mass (blue) to 18% (red); polar abundances vary from 0% (blue) to 100% (red). DATA ADAPTED FROM FELDMAN ET AL. (2002)

This prediction is in excellent agreement with the mapping of H<sub>2</sub>O ice abundances by the Mars Odyssey Neutron Spectrometer, High Energy Neutron Detector, and Gamma Ray instruments (Boydton et al. 2002; Mitrofanov et al. 2002; Feldman et al. 2002). These instruments discovered high hydrogen abundances in the uppermost meter extending from the pole to 50° in both hemispheres (e.g. Feldman et al. 2002) (FIG. 3). Assuming that the hydrogen is in H<sub>2</sub>O ice, the ice content of the upper meter is >70% by volume over large regions in the high latitudes. This great abundance is unlikely to have resulted from gas diffusion into soil pores; instead, it more likely represents accumulation as surface snow or frost.

### Morphological Evidence for Subsurface Ice

The presence of ice-rich materials in the mid-latitudes has long been postulated on the basis of (1) lobate, grooved, and ridged textures suggestive of flow on channel, crater, and mesa walls (FIG. 4); (2) unusual lobate crater ejecta possibly formed by fluidization of ground ice; (3) evidence for volcano-ice interactions; and (4) possible evidence for glacial landforms and processes (see review by Clifford et al. 2000).

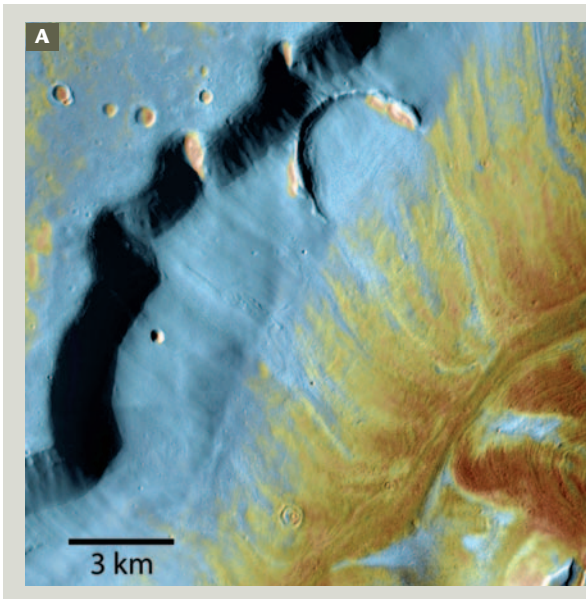
Additional evidence for ground ice comes from a pervasive “basketball” surface texture found between 30° and 50° in both hemispheres (Mustard et al. 2001). This unit is 1–10 m thick and is interpreted to result from the desiccation and erosion of once ice-rich soils that formed through diffusion of water vapor into soil pore spaces (Mustard et al. 2001). This material does not have a hydrogen signature, in agreement with the predicted desiccation of the upper 1–2 m at these latitudes (e.g. Mellon and Jakosky 1995; Mellon et al. 2004). However, the mantle changes poleward to a smooth, unpitted surface with a high hydrogen abundance, suggesting that it may also have formed by direct condensation of

snow or frost. In this case, this unit may contain substantially more water than the  $1.5\text{--}6.0 \times 10^4 \text{ km}^3$  initially suggested (Mustard et al. 2001). The number of small, fresh craters on these mantling units is low, suggesting that these mantles are possibly as young as 0.15 Ma but most certainly less than 10 Ma (Mustard et al. 2001).

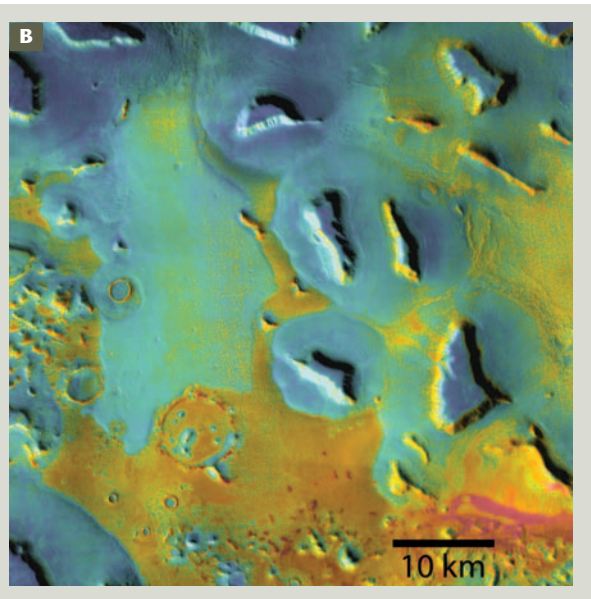
Further evidence for ice-rich mantles is found in 1–10 m thick deposits that preferentially occur on pole-facing slopes, have features suggestive of flow, and have a distinct, rounded edge marking the upslope boundary (FIG. 5) (Carr 2001; Christensen 2003). These characteristics suggest ice-rich mantles that were once more extensive but have been removed from all but the cold, pole-facing slopes where near-surface ice is stable under solar illumination. Ice-rich materials have also been suggested in glaciers in numerous areas including Hellas and the western flanks of the Tharsis volcanoes (e.g. Head et al. 2005).

### MODERN GULLIES

Recent gullies are found in the 30–50° latitude range in both hemispheres (e.g. Malin and Edgett 2001), and their origin is the topic of vigorous, ongoing discussion. It has been proposed that they form from a range of processes, but the most plausible hypotheses are the discharge of liquid water from subsurface aquifers, the melting of pore ice that diffused inward from the atmosphere during periods of colder temperatures, and the melting of a snow layer



**FIGURE 4A** Ice-rich terrains in the northern mid-latitude region. Ice-rich soils have flowed down the wall of this valley centered near 37.6°N, 15.8°E. This image is a mosaic of THEMIS VIS images that has been colorized using the daytime temperatures determined by the THEMIS IR camera. Bands of bright material can be traced more than 10 km downslope. They show the flow reaching the bottom of the local slope and turning northeast to continue to flow down the valley. Temperatures range from -40°C to -34°C, with colder temperatures (blue tones) associated with darker or rockier surfaces and warmer temperatures (reddish tones) related to brighter or dustier surfaces. IMAGE CREDIT NASA/JPL/ARIZONA STATE UNIVERSITY

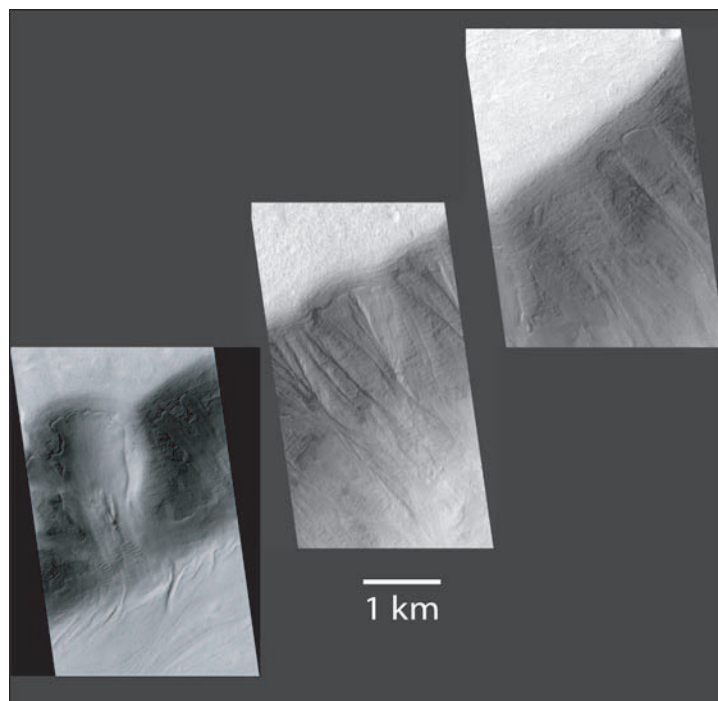


**FIGURE 4B** Lobes of ice-rich material flowing off mesas in the northern hemisphere. THEMIS VIS images colorized using nighttime temperatures from the THEMIS IR camera. Lobes of material are colder at night, and therefore they are finer-grained and less rocky than the substrate over which they are flowing. These distinct differences in surface properties between the lobes and the substrate provide strong evidence that this process is youthful and possibly active, because there has not been sufficient time for the homogenization of the properties of these different surfaces. Mosaic of THEMIS images centered near 43°N, 27.5°E. IMAGE CREDIT NASA/JPL/ARIZONA STATE UNIVERSITY

deposited during periods of higher obliquity when surface ice was stable at these latitudes (see review by Heldmann and Mellon 2004).

Of these models, the melting of pore ice does not account for the fact that as the surface and subsurface temperatures warm, the upper soil layer will become desiccated before significant liquid water can be produced (Mellon and Phillips 2001; Christensen 2003); if ice forms by vapor diffusion, it will dissipate by the same mechanism. Water released from subsurface aquifers (Malin and Edgett 2001) explains gully morphology, latitudinal distribution, and slope position (Heldmann and Mellon 2004). However, this model does not account for the presence of gullies on isolated knobs and dunes where there is no obvious aquifer source—the survival and recharge mechanism that would allow these aquifers to persist to the present—nor their formation only at latitudes poleward of 30°.

Lee et al. (2001) and Hartmann (2002) suggested that melting snow might carve Martian gullies, based on analogies with similar gully morphologies in cold regions on Earth. This model was developed (Christensen 2003) by noting the association of gullies with ice-rich, pole-facing slope mantles (FIG. 5), and by incorporating models for snow formation at high obliquity (e.g. Jakosky et al. 1995) and a model of melting within dusty Martian snow (Clow 1987). In this snowmelt model, water is transported from the poles to mid-latitudes during periods of high obliquity. Melting of this snow layer occurs at low obliquity as mid-latitude temperatures increase, producing liquid water that is stable beneath the insulating layer of snow. Gullies form within and beneath the snow as meltwater seeps into the loose slope materials and destabilizes them. Patches of snow remain today on pole-facing slopes, where they are protected against sublimation by a layer of desiccated dust/sediment. The primary argument against snowmelt is the presence of gullies on slopes of all azimuths (Heldmann and Mellon 2004).



**FIGURE 5** Ice-rich mantles and associated gullies on poleward-facing slopes in the southern hemisphere. This collage shows MOC images from the northwest wall of Dao Valles, between 33° and 35°S. These images show (1) well-developed flow features with compressive ridges, which are strongly suggestive of ice (left panel); (2) mantles of ice-rich material and gullies that are present only where the mantles are lacking (center panel), and (3) depressions with associated gullies, some of which still have mantles, whereas others are free of mantling material (right panel). These landforms could be explained by the melting of a snow mantle, forming gullies that are visible only in those locations where the snow has completely disappeared. MOC IMAGES LEFT TO RIGHT: M03-04950, M09-02885, AND M0-3-6266

## SUMMARY AND OUTSTANDING QUESTIONS

The poles and mid-latitudes of Mars contain a large reservoir of H<sub>2</sub>O ice, including  $\sim 5 \times 10^6$  km<sup>3</sup> in polar layered materials,  $>6 \times 10^4$  km<sup>3</sup> in mid-latitude mantles and ice-rich sediments, and  $\sim 3 \times 10^{-2}$  km<sup>3</sup> in the seasonal ice caps and atmosphere. This known reservoir, if melted, would form a layer of water  $\sim 35$  m deep over the entire planet. Portions of this reservoir appear to move to lower latitudes on 10<sup>5</sup>–10<sup>6</sup> year timescales. Aquifers or melting snow or both have produced liquid water at the surface in the very recent past, and these areas hold exciting promise for future exploration for past or present life. Many questions remain, and among the most intriguing are the following:

1. What is the age and history of the polar layered deposits?
2. Have the polar ice caps ever been completely removed, and what produced the significant climate change that this would imply?
3. What is the total inventory of subsurface ice?
4. What are the source(s) of the water responsible for forming the modern gullies?

## ACKNOWLEDGMENTS

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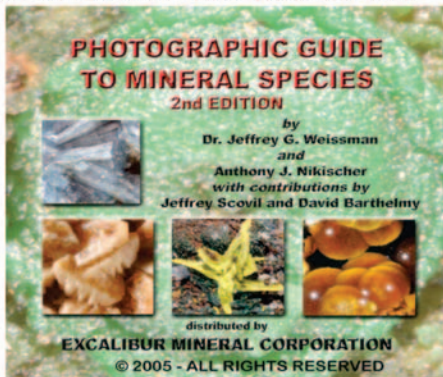
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# Aqueous Processes Recorded by Martian Meteorites: Analyzing Martian Water on Earth



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**M**artian meteorites have delivered to Earth water molecules and minerals produced by aqueous processes on Mars. The study of these samples, using powerful analytical instrumentation, provides a basis for understanding aqueous activity on Mars. Although most analyses are at the scale of microns, the conclusions reached have important implications for large-scale aqueous processes. Secondary minerals, such as clays, salts, and carbonates, are present at some level in all Martian meteorite subtypes and are especially important in the nakhlites and ALH84001. Light element stable isotope analyses show evidence for mixing between atmosphere and magmatic fluids into a crustal reservoir, and that this crustal water was not in equilibrium with the host rocks. The mineralogical and isotopic data present a fairly consistent picture of the aqueous history of Mars: low levels of aqueous alteration are generally present but extensive aqueous processes are probably limited in space and time.

KEYWORDS: Mars, meteorites, stable isotopes, carbonates, water-rock interaction

## OVERVIEW OF MARTIAN METEORITES

The Martian meteorites (also called SNC, for shergottite-nakhlite-chassignite) comprise a group of 36 specimens. Evidence for the Martian origin of these rocks is discussed in the sidebar. The meteorites are igneous rocks, consistent with the abundant evidence for past volcanic activity on Mars. However, the igneous nature of the samples also likely reflects the mechanism by which they were ejected from Mars, during a small number (probably 3–5) of impact events over the past ~15 million years. Friable samples, such as poorly cemented sedimentary rocks, would probably not survive this violent process.

The meteorites can be separated into subclasses on the basis of their mineralogy or rock type. The four major subclasses are the shergottites, the nakhlites, the chassignites, and the unique sample ALH84001. The shergottites are the most abundant group and are further subdivided into basaltic, lherzolithic, and olivine-phyric types. The nakhlites are cumulate clinopyroxenites with up to 10% olivine. Chassignites are dunites (olivine cumulates), and ALH84001 is a cumulate orthopyroxenite. The meteorites show a range in age, from 4.5 Ga for ancient ALH84001 to 175–575 Ma for the shergottites; the nakhlites and chassignites formed at about 1.3 Ga (e.g. Nyquist et al. 2001). Photomicrographs of two specimens are shown in Fig. 1. McSween and Treiman

Although it would be extremely desirable to study Martian sedimentary rocks in laboratories on Earth, such rocks are unlikely to be in our hands in the near future, as missions to return samples from Mars are expensive and complex. Therefore it is imperative to extract all possible information about water on Mars from the samples we have in hand. Because of the igneous nature of the samples, in most cases this information is contained within very rare and/or complex minerals, and thus the desire to extract knowledge has driven the development and application of new, cutting-edge analytical techniques. In the following sections, we highlight key mineralogical and isotopic observations from these meteorites that provide significant insights into aqueous processes on Mars.

## SECONDARY MINERALIZATION IN MARTIAN METEORITES: THE NAKHLITE EXAMPLE

Unlike rare primary hydrous minerals, such as apatite and amphibole, crystallized at high temperatures in Martian magmas, most hydrous minerals in the SNC meteorites formed at low temperatures through secondary processes. If the alteration is preterrestrial in origin (i.e. it formed prior to the meteorite's entry into Earth's atmosphere and therefore presumably on Mars), then by examining secondary

(1998) provide an overview of the mineralogy and petrology of these samples and review in detail the evidence for a Martian origin. An up-to-date catalog of descriptions of the specimens can be found at the Mars Meteorite Compendium website [www.curator.jsc.nasa.gov/antmet/mmc/index.cfm](http://www.curator.jsc.nasa.gov/antmet/mmc/index.cfm)

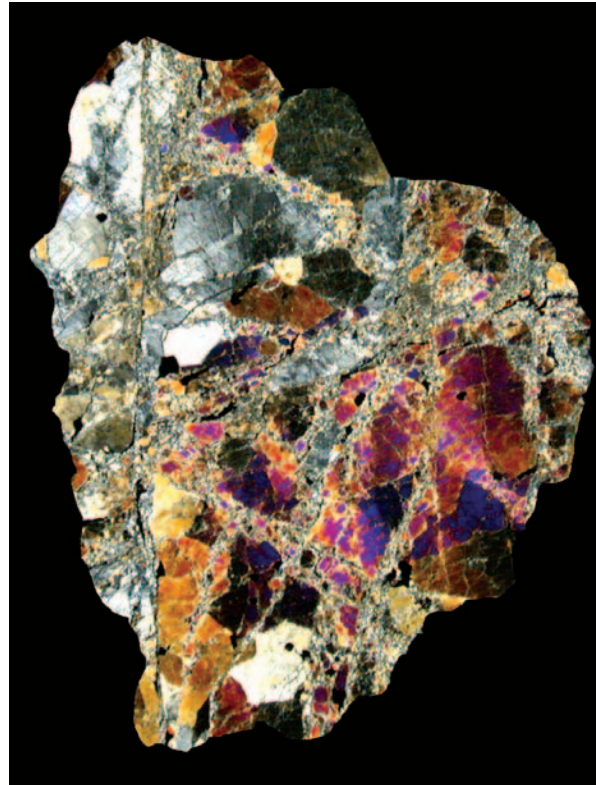
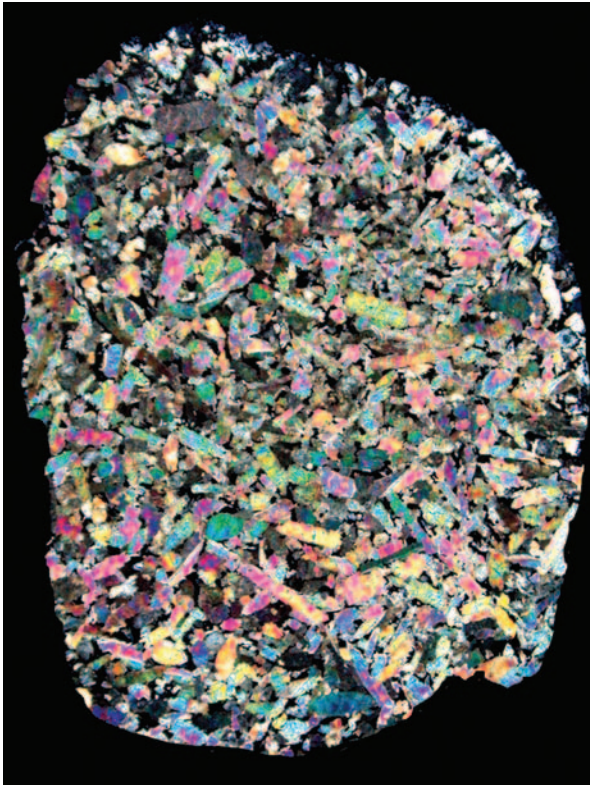
### EVIDENCE FOR A MARTIAN ORIGIN

Compelling evidence has been found that some meteorites originated on Mars:

- ◆ All specimens (except ALH84001) are igneous rocks with geologically young crystallization ages, suggesting they formed on a planet-sized object capable of sustaining geological activity throughout the history of the solar system.
- ◆ Despite variable bulk mineralogy and ages, the samples are linked together and to a common parent object through common geochemical signatures, such as bulk oxygen isotope composition, K/La ratios, and Fe/Mn ratios.
- ◆ A direct tie to Mars is provided by the discovery, in several samples, of gases such as N<sub>2</sub>, Ar, and Xe trapped in impact-produced glasses. The isotopic compositions and relative abundances of the gases closely match the composition of the current Martian atmosphere.

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**FIGURE 1** Photomicrographs of Martian meteorites Zagami (basaltic shergottite) and ALH84001 in cross-polarized light. Thin sections are approximately 2 cm across. IMAGES FROM *A COLOR ATLAS OF METEORITES IN THIN SECTION*, COURTESY OF DANTE LAURETTA

hydrous minerals, we may be able to constrain the volatile reservoirs and processes in the near surface and potentially in the ancient Martian atmosphere (Gooding et al. 1991).

All Martian meteorite subgroups show some mineralogical evidence of aqueous alteration. Shergottites and chassignites show the least, with only trace sulfate and carbonate salts, and ALH84001 contains ~1% carbonate. However, some of the best evidence for aqueous alteration in Martian meteorites is found in the nakhlites. The near absence of shock metamorphism and the relative abundance of alteration products make the nakhlites ideal for the study of delicate low-temperature minerals that would decompose if subjected to elevated pressures and temperatures.

The alteration materials in the nakhlites constitute only a minor fraction (<1%) of the rock. In conducting studies of meteorite alteration, it is imperative to first determine whether these minor phases formed on Mars or on Earth. Several criteria may be applied to establish the origin of the alteration minerals:

1. Petrography – Are alteration veinlets cut by the fusion crust, indicating formation before atmospheric heating (Gooding et al. 1991; Treiman 1993)?
2. Age – Does the age of the secondary minerals exceed the time the meteorite has resided on Earth (Swindle et al. 2000)?
3. Isotopic fingerprinting – Are the stable isotope compositions of the alteration minerals inconsistent with terrestrial values (Karlsson et al. 1992; Leshin et al. 1996)?

If the answer is Yes to these questions, then one can conclude that the alteration formed on Mars, as is the case for the secondary minerals discussed below.

### **Alteration Types and Mineral Assemblages**

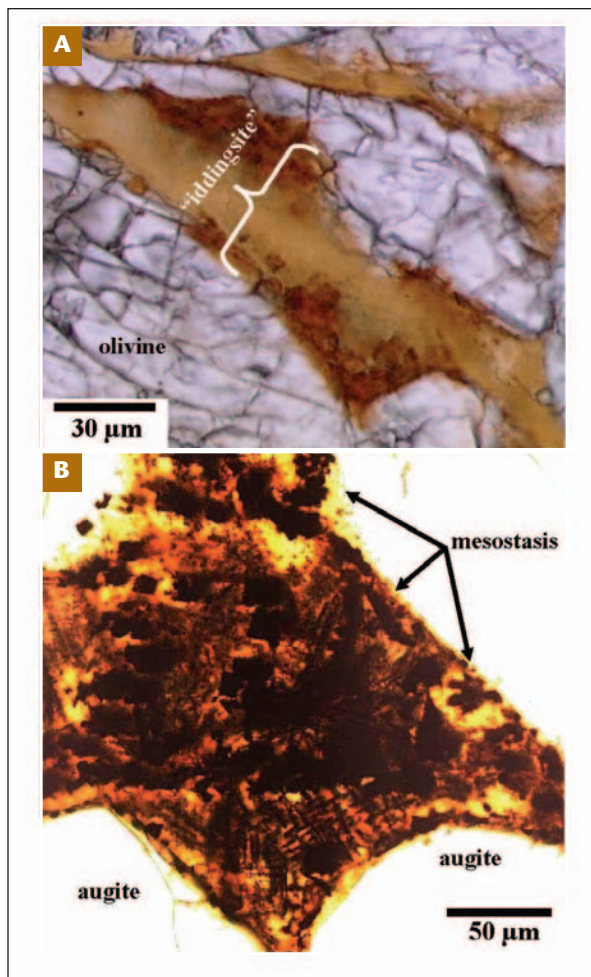
*Olivine-hosted veinlets:* Although Fe-rich olivine composes only ~10 vol% of most nakhlites, it contains a disproportionate quantity of secondary minerals. This observation is

consistent with the fact that olivine breaks down rapidly in most terrestrial weathering environments compared to other magmatic minerals such as pyroxene. Veinlets in olivine are typically several to tens of micrometers across and hundreds of micrometers in length. They are most often filled with “iddingsite,” a term used to describe an assemblage of minerals representing the hydrous breakdown products of olivine (FIG. 2A). Iddingsite is reddish brown in color, contains Fe<sup>3+</sup>, is variable in composition, and was referred to as “iron-rich silicate rust” by Gooding et al. (1991). The number and types of phases that compose iddingsite are not uniform among the nakhlites; however, clay is common to all. Fine-scale mineralogical heterogeneity is observed within the veinlets, and transmission electron microscopy is required to properly identify sheet silicates such as smectite (Gooding et al. 1991; Treiman 1993). Other phases found in association with smectite are ferrihydrite, maghemite, goethite, and two varieties of amorphous silicates, one rich in silicon and the other in iron (Treiman 1993; Vicenzi and Heaney 1999; Bridges and Grady 2000). Trace quantities of carbonates, often chemically heterogeneous on a scale of tens of micrometers, can also be found in veins formed by silicate alteration of olivine (FIG. 3A, B). The preservation of fine-scale carbonate heterogeneity is interpreted to be an indicator of a low water/rock ratio (Bridges and Grady 2000; Vicenzi and Heaney 2000).

*Mesostasis grain boundaries:* In transmitted light, all nakhlites appear rich in alteration products within mesostasis—pockets in the rock where the last melt fraction solidified (FIG. 2B). Yet when the crystals in mesostasis are imaged using high-resolution methods, scant evidence for the secondary materials is found, suggesting the alteration is present as a thin surface coating.

*Salt-bearing veinlets and mesostasis:* Identification of gypsum and halite within olivine veinlets constrains the salinity of





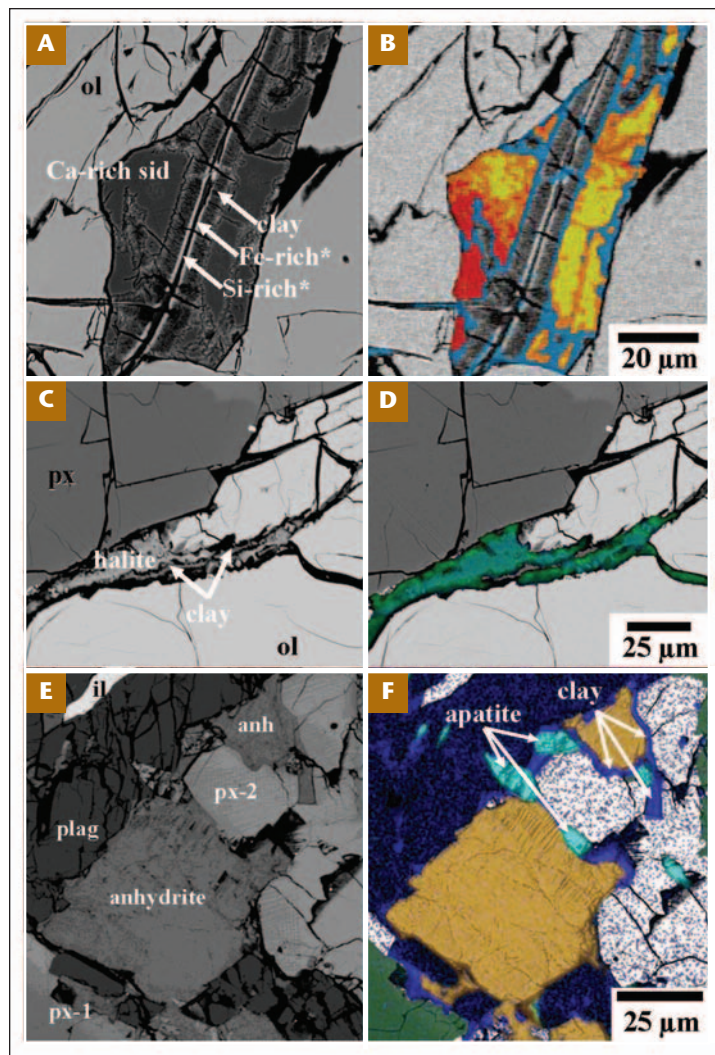
**FIGURE 2** Transmitted-light images of low-temperature alteration products in Martian meteorites. (A) Olivine-hosted veinlet filled with “iddingsite” (Lafayette meteorite). (B) High-contrast image showing secondary minerals concentrated in mesostasis (MIL03346 meteorite).

alteration brines (Bridges and Grady 2000; Rost et al. 2005). Given the high solubility of halite, the material may represent remobilization of NaCl from an earlier vein-filling event (Fig. 3C, D). Anhydrite is found exclusively as larger grains, sometimes in association with halite within mesostasis (Fig. 3E, F).

### Temperature and Timing of Alteration Fluids

The limited stability of the alteration phases with respect to temperature (e.g. ferrihydrite) suggests that aqueous alteration took place at <100°C (Treiman 1993). Application of oxygen isotope thermometry, based upon coprecipitated Fe-carbonate and smectite, yields a temperature range of -34 to 19°C, consistent with the mineralogical constraint (Romanek et al. 1998). The high salinity of some aqueous fluids would lower the freezing point, yet textural relationships between carbonate and clay suggest they are associated with temporally different pulses of alteration fluid (Vicenzi and Heaney 2000).

Efforts to determine precisely the age of the secondary minerals, and hence the timing of fluid flow in the Martian crust, are hampered by the chemical complexity of the minerals. Despite this complication, age estimates for the precipitation of iddingsite determined by K–Ar dating are ~600–700 Ma (Swindle et al. 2000). Hence, low-temperature liquid water was available relatively recently for chemical alteration of near-surface igneous rocks, although the



**FIGURE 3** Electron, X-ray images, and phase maps of Martian meteorite alteration. (A) Back-scattered electron (BSE) image of an olivine-hosted veinlet containing both iddingsite and siderite (Lafayette meteorite). (B) False-color phase map of A depicting the compositional heterogeneity of the carbonate. Blue: silicate-carbonate intergrowth; yellow: carbonate enriched in Ca; orange: carbonate enriched in Fe; red: carbonate enriched in Mn. (C) BSE image of a pyroxene-olivine grain boundary with an olivine-hosted veinlet filled with a halite and clay assemblage (Nakhla meteorite). (D) False-color X-ray image overlay of C: Na (blue) and Cl (green), highlighting NaCl mineralization. (E) BSE image of massive CaSO<sub>4</sub> (anhydrite) bounded by plagioclase, augite (px-1), and low-Ca pyroxene (px-2) in the mesostasis of the Nakhla meteorite. (F) False-color X-ray image overlay of E showing clays and magmatic phosphate adjacent to anhydrite: S (red), Ca (green), K (blue), and P (cyan).

chemistry and mineralogy (and isotopes, see below) indicate that the water was likely transient and volumetrically limited.

### ISOTOPIC EVIDENCE OF AQUEOUS PROCESSES

The use of the stable isotopes of hydrogen, carbon, and oxygen to determine the nature of aqueous processes has become a cornerstone of terrestrial geochemistry. Similarly the application of these isotopic techniques to Martian materials has provided critical information about Martian aqueous processes. However, in the case of Martian materials, there are important challenges. First, the numbers of different samples and rock types are extremely small—imagine trying to determine the history of Earth’s volatiles from a few dozen igneous rocks! Second, the samples themselves are typically small and, as discussed above, contain only small amounts of alteration minerals. Third, the isotopic “reference frame” is not always clear. On Earth the widespread

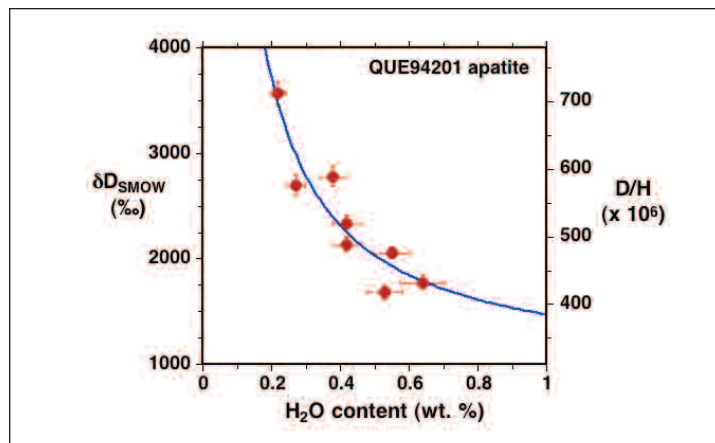
and reasonably well-understood reservoir of ocean water and ocean-produced minerals, as well as the global plate tectonic cycle, are strong drivers for many isotopic effects. On Mars, processes recorded in the meteorites are not dominated by processes related to an ocean, and in many cases the observed isotope variations are found to be large and complex. Of course, large variations in isotopic ratios make the signal easier to detect, and give insights into processes that may not be common on Earth. Below we discuss key conclusions from three isotopic systems: hydrogen, carbon, and oxygen.

### Hydrogen Isotopes

Ground-based infrared telescopic observations have revealed that the deuterium-to-hydrogen ratio (D/H) of water in the Martian atmosphere is ~5 times terrestrial values, significantly higher than the D/H of any hydrogen on Earth (Owen et al. 1988; Krasnopolsky et al. 1997). The high D/H value is a result of preferential loss of H relative to heavier D from the Martian atmosphere throughout the planet's history. The initial Martian D/H ratio, the timing of water loss, and the evolution of the deuterium enrichment remain matters of debate. Nonetheless, the heavy isotope enrichment in the atmosphere can be used as a tracer of the interaction of the atmospheric volatile reservoir with other water in the crustal or interior reservoirs.

Martian meteorites record elevated D/H signatures that provide direct evidence of surface-atmosphere interaction on Mars and offer important windows into Martian hydrologic cycles. Many Martian meteorites contain D-enriched water, both in bulk samples (Leshin et al. 1996; Eiler et al. 2002a) and in individual hydrous minerals (e.g. Watson et al. 1994; Leshin 2000; Boctor et al. 2003). For example, shergottites, nakhlites, and ALH84001 all show D-enriched water in bulk extraction (when bulk samples are heated under vacuum) (Leshin et al. 1996), with  $\delta D$  values<sup>†</sup> approaching +2000‰. In situ SIMS (secondary ion mass spectrometer) analyses of individual minerals and glasses in meteorites from all subclasses, including apatite, amphibole, biotite, feldspathic glass, silica, carbonate, and mafic glasses, all show some evidence of D-enrichment (Watson et al. 1994; Leshin 2000; Sugiura and Hoshino 2000; Boctor et al. 2003). However, these analyses also suggest mixing between two components: a D-rich component derived from the atmosphere (with values up to ~+4000‰) and a D-poor component, probably representing a mantle or magmatic contribution (Fig. 4). It is important to note that many of the analyses that show atmospheric signatures were not performed on secondary minerals but on primary magmatic phases (such as apatite and amphibole), suggesting an overprinting caused by post-crystallization circulation of atmosphere-derived crustal fluids.

In addition to providing evidence of an atmosphere-derived component in igneous and alteration minerals, these studies provide constraints on the isotopic composition of the magmatic water reservoir on Mars, critical for comparing the accretionary histories of Mars and Earth. From careful correlation of water content and  $\delta D$  of hydrous magmatic



**FIGURE 4**  $\delta D$  values and water contents of apatite grains from Martian meteorite QUE94201. The data are interpreted to represent a mixture of two end members, and most plausibly represent addition (or exchange) of water with an atmospheric D/H signature ( $\delta D \sim +4000\%$ ) to minerals that initially uniformly contained water with  $\delta D$  of  $\sim +900 \pm 250\%$ . The curve shows the mixing model from which the initial D/H of the minerals was calculated. FROM LESHIN (2000)

minerals analyzed in the QUE94201 shergottite, Leshin (2000) proposed that magmatic water on Mars has a  $\delta D$  value of about +900‰, approximately twice the terrestrial value (Fig. 4). This value has been used to argue for an accretionary history for Mars dominated by small bodies, and that the mechanism for water acquisition was different from Earth's (Lunine et al. 2003). An alternative view is suggested by the SIMS work of Gillet et al. (2002) and Boctor et al. (2003). Although Boctor et al. (2003) observed D-rich water in all phases analyzed (many of which are nominally anhydrous minerals), they also found low  $\delta D$  values, consistent with a more Earth-like composition for the low  $\delta D$  end member. Gillet et al. (2002) analyzed secondary alteration in nakhlite NWA817 by SIMS and found only low, Earth-like values for  $\delta D$ . It is difficult to rule out terrestrial contamination when analyzing minerals that are either nominally anhydrous or highly susceptible to contamination and recrystallization on Earth. To resolve these complexities, more studies that systematically examine hydrous magmatic phases in Martian meteorites are needed.

Secondary hydrous minerals in Martian meteorites are probably the best indicators of the changes in composition of crustal water on Mars through time, but little is known about their D/H ratio. The only data come from bulk sample studies by Leshin et al. (1996) and Eiler et al. (2002a), and from SIMS work by Gillet et al. (2002) and Sugiura and Hoshino (2000). Studying hydrogen in secondary minerals is especially difficult because these minerals are often highly susceptible to terrestrial contamination and H is an abundant contaminant on Earth. As discussed above, the studies provide conflicting evidence about the absolute D/H value of secondary minerals (ranging from Earth-like values to values up to ~3× terrestrial) and therefore result in conflicting hypotheses for their origin. Terrestrial contamination is probably the cause of the wide range of D/H values, and the most conservative conclusion is that most meteorites show evidence of elevated D/H values in secondary minerals and that these values can be traced to interactions with atmosphere-derived D-rich groundwaters. This is consistent with the results of studies of other isotopic pairs, as discussed below.

### Carbon Isotopes

As is the case for hydrogen, carbon isotopic signatures in Martian meteorites record evidence of contributions from multiple reservoirs. There have been many reports on the abundances and  $^{13}C/^{12}C$  values of  $CO_2$  extracted from bulk

<sup>†</sup> Isotope data are often expressed using the  $\delta$  notation:

$$\delta = \left( \frac{R_x - R_{std}}{R_{std}} \right) \cdot 1000$$

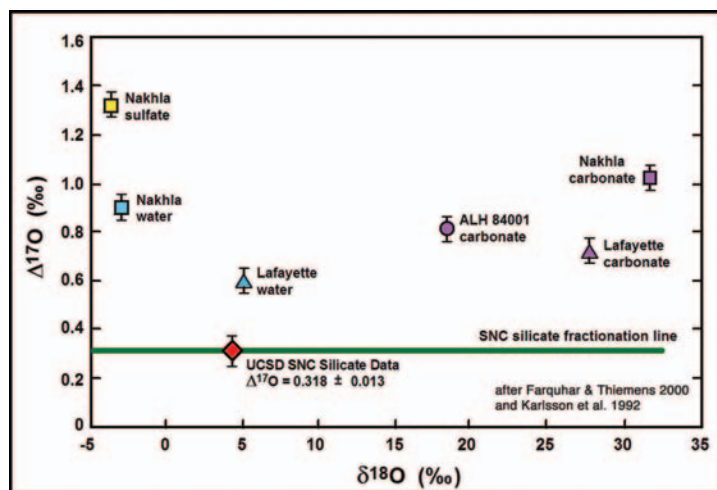
where  $R$  is the ratio of the heavy to the light isotope,  $x$  is the sample and  $std$  is a standard. For the elements hydrogen, carbon, and oxygen,  $R$  is D/H,  $^{13}C/^{12}C$ , and  $^{18}O/^{16}O$  (or  $^{17}O/^{16}O$ ), respectively. A delta value is reported in units of ‰ ("per mil"), or parts per thousand deviation from the standard. For hydrogen and oxygen, the reference standard is Standard Mean Ocean Water (SMOW), and for carbon the standard is a carbonate called Pee Dee Belemnite (PDB).

Martian meteorites and their probable implications for the evolution of CO<sub>2</sub> on Mars (e.g. Carr et al. 1985; Clayton and Mayeda 1988; Wright et al. 1990; Romanek et al. 1994; Leshin et al. 1996). Three main carbon-bearing components are distinguished in Martian meteorites by their temperature of release (or release by reaction with acid) and their  $\delta^{13}\text{C}$  values. The first component, released at temperatures below ~500°C, is interpreted as low-temperature carbonaceous material derived mostly from contamination by terrestrial organic matter but possibly mixed with extraterrestrial organics. This component has a  $\delta^{13}\text{C}$  value of -20 to -30‰. The second component, released between 400 and 700°C in heating experiments or by reaction of samples with acid, originates from breakdown of carbonate. This component is associated with <sup>13</sup>C-enriched CO<sub>2</sub> in several Martian meteorites and gives  $\delta^{13}\text{C}$  values up to ~+42‰. The third component consists of carbon released at temperatures above 700°C, has  $\delta^{13}\text{C}$  values of -20 to -30‰, and has been interpreted as a “magmatic” component representative of the C isotope composition of CO<sub>2</sub> in the Martian interior. However, Goreva et al. (2003) analyzed the C isotope composition of individual magmatic phosphate grains in two shergottites and found a  $\delta^{13}\text{C}$  value of -15 ± 5‰. In either case, the “magmatic” value is lower than the terrestrial mantle C isotope composition of ~-5‰. However, the Goreva et al. (2003) value is isotopically consistent with the bulk of organic matter in carbonaceous meteorites, supporting the idea that such materials are the likely source of C on Mars. These results support the hypothesis that the Martian magmatic C isotope ratio accurately reflects the planet’s accretionary history rather than tectonic recycling.

Near-surface aqueous processes are recorded by carbonates in ALH84001, and these carbonates have been especially well studied due to the controversial hypothesis that they preserve Martian fossils (McKay et al. 1996). The environment of formation of these secondary minerals has remained enigmatic despite extensive chemical and mineralogical characterization showing that the carbonates are strongly zoned in chemical composition (from ankerite to magnesite) and also despite several in situ O isotope studies that show strong microscale zoning, with  $\delta^{18}\text{O}$  from ~+3 to +25‰, which correlates with mineral chemistry (Leshin et al. 1996; Valley et al. 1997; Saxton et al. 1998; Eiler et al. 2002b). Extensive in situ C isotope analyses of these carbonates were recently reported by Niles et al. (2005), who found that the  $\delta^{13}\text{C}$  values are also highly zoned, ranging from ~+30‰ for Ca-rich carbonates to +60‰ for magnesite. The isotopically heavy carbon, similar to the heavy carbon found in many bulk Martian meteorite samples (discussed above), is consistent with derivation of fluids from a <sup>13</sup>C-enriched Martian atmosphere and suggests an origin comparable to that of D-enriched waters in Martian meteorite samples. Hypotheses for carbonate formation that account for the large isotopic variation in C and O (see below) and that also consider the mineralogical constraints include mixing of fluids derived from two different environments (e.g. with different contributions from atmospheric components), a coupled evaporation/CO<sub>2</sub> degassing model, and formation from high-pH fluids. These ideas agree particularly well with the environments that are expected on Mars and suggest that large, abiotic isotopic variations may be common. For all hypotheses, the elevated <sup>13</sup>C values are thought to result from atmospheric contributions to the carbon in the fluid(s) that formed the carbonates.

### Oxygen Isotopes

Oxygen isotope data for whole-rock Martian meteorites demonstrate that the meteorites originated on a common parent object. This is because, on a <sup>17</sup>O/<sup>16</sup>O vs <sup>18</sup>O/<sup>16</sup>O diagram, the data plot on a line of slope approximately +1/2



**FIGURE 5** Oxygen isotopic compositions—specifically the value of  $\Delta^{17}\text{O}$ —of waters and secondary minerals from several Martian meteorites differ from those of the primary silicates. This indicates that the waters and alteration minerals formed from a reservoir not in equilibrium with the crustal rocks. The elevated  $\Delta^{17}\text{O}$  values are likely a signature of atmosphere-derived volatiles.

that is displaced from the line for terrestrial rocks by 0.32‰ (the so-called  $\Delta^{17}\text{O}$  value<sup>‡</sup>; Franchi et al. 1999). The meteorites have bulk  $\delta^{18}\text{O}$  values between ~+4 and +5.5‰, consistent with an igneous origin (e.g. Franchi et al. 1999) and similar to the value for terrestrial mafic rocks. However, the most important O isotope data with respect to aqueous processes come from analyses of all three O isotopes (<sup>16</sup>O, <sup>17</sup>O, <sup>18</sup>O) in waters, carbonates, and sulfates extracted from bulk samples (e.g. Karlsson et al. 1992; Farquhar and Thiemens 2000). These data (FIG. 5) show O isotope anomalies (as demonstrated by  $\Delta^{17}\text{O}$  values that differ from those of Martian meteorite igneous minerals) of more than 1‰, and the anomalies have been used to argue for an atmospheric chemistry conducive to the production of mass-independent isotope effects (e.g. Thiemens 2002). Such atmospheric volatiles are incorporated into meteoric fluids and then transferred to secondary minerals and waters in the meteorites. The  $\Delta^{17}\text{O}$  values also clearly show that the water and alteration minerals in the samples are extraterrestrial in origin, as terrestrial contamination would be expected to result in  $\Delta^{17}\text{O}$  of zero, equivalent to waters on Earth.

$\delta^{18}\text{O}$  values in secondary minerals are generally higher than values in igneous minerals. For example, carbonates in the nakhlites have  $\delta^{18}\text{O}$  values of -20–30‰, consistent with formation in low-temperature aqueous environments (Romanek et al. 1998; Saxton et al. 1998). Taken together, the oxygen isotopic data indicate that Martian secondary minerals formed at relatively low temperatures from atmosphere-derived fluids. The observation of  $\Delta^{17}\text{O}$  anomalies in many different samples supports the idea that waters in the Martian crust are not generally in isotopic equilibrium with the crust. This suggests that intensive hydrothermal circulation of fluids, which would lead to equilibration of the isotopes and loss of the anomalous  $\Delta^{17}\text{O}$  values, is not common on Mars.

### SUMMARY: WHAT MARTIAN METEORITES TELL US ABOUT WATER ON MARS

The evidence from Martian meteorites supports the hypothesis that the history of volatiles on Mars is complex in space and time due to atmospheric evolution, the probable lack of long-lived oceans, and the absence of plate tectonics. Still,

<sup>‡</sup>  $\Delta^{17}\text{O}$  (‰) =  $\delta^{17}\text{O} - (0.52 \times \delta^{18}\text{O})$

Martian meteorites of all ages show evidence of some interaction with Martian crustal water after crystallization. Thus aqueous activity, to some degree, is common on Mars. However, none of the samples show evidence of *extensive* water-rock interaction, which would have resulted in more abundant and well-formed secondary minerals and equilibrated isotope signatures. Aqueous processes that operate locally and sporadically, rather than globally and continuously, appear to be required. In addition, Martian surface conditions may be conducive to production of large abiotic C isotope effects, which could confound attempts to use C isotopes as a biomarker. These conclusions suggest that the

search for life on Mars should focus on localized habitable environments and that these environments should be characterized intensively in order to interpret correctly any potential biosignatures in the context of the local geologic setting.

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# Evidence for Water at Meridiani

Bradley L. Jolliff,<sup>1</sup> Scott M. McLennan,<sup>2</sup> and the Athena Science Team



**The Mars Exploration Rover Opportunity has examined sedimentary structures in the Burns formation at Meridiani Planum. The materials in this formation reflect, in part, subaqueous deposition of reworked, sulfate-rich, clastic sediments that likely formed in a playa–interdune setting. The chemistry and mineralogy of the sedimentary rocks record an origin by evaporation of sulfate- and chloride-rich brines mixed with a fine, altered, basaltic mud or dust component, prior to reworking. Cementation and postdepositional reactions to form hematite-rich concretions and crystal-mold porosity reflect diagenesis in a groundwater-saturated subsurface. More recent dehydration events are evidenced by polygonal textures in rocks within craters and exposed on the plains. The timing of formation of fracture fillings that cut across bedding is not well constrained and may be early postdiagenetic or later. The fracture fillings may have formed by solutions remobilized along zones of weakness. Alteration rinds may reflect more recent interactions between rock and atmospheric water vapor.**

KEYWORDS: Mars Exploration Rovers, Opportunity, water on Mars

## INTRODUCTION

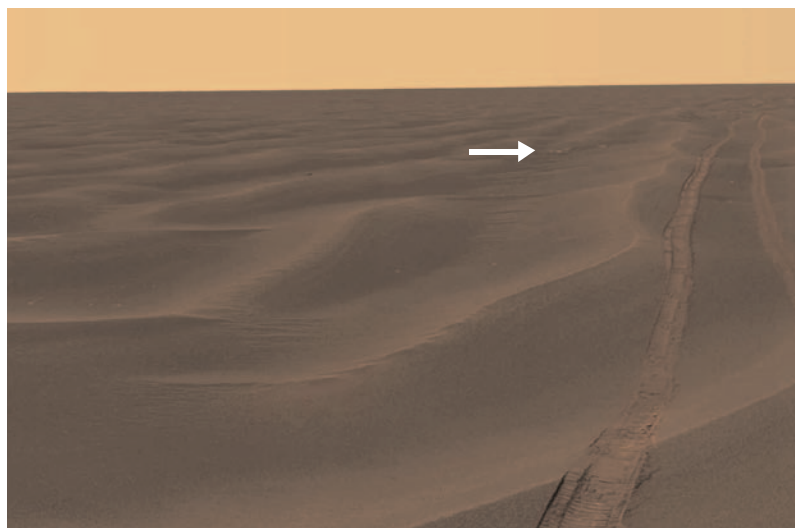
The Mars Exploration Rover Opportunity has now completed investigations of several craters near its landing site on Meridiani Planum (Squyres et al. 2004a, b; Squyres and Knoll 2005) and is roving southward past the boundary of its landing ellipse, exploring transitions between major geological and geomorphological terrain types identified from orbit. This surface mobility is unprecedented in the exploration of Mars and is changing how we think about future surface exploration.

The present-day surface of the Meridiani plains, as seen during the first year and a half of this trek, could be described as a sea of ripples across an ocean of sand (FIG. 1). Ironically this surface is a cold, arid desert where the ripples are driven by Martian winds. Yet just about a meter or less beneath the eolian surface sand sheet lies an ancient, layered, sulfate-rich rock formation that tells the story of ancient Martian sediments once saturated with water and of the occasional emergence—and subsequent evaporation—of stable surface water (Squyres et al. 2004b; Grotzinger et al. 2005; McLennan et al. 2005). Fortunately, the aptly named Opportunity rover has been able to investigate the rocks of this formation in a series of craters of different sizes that have penetrated,

excavated, and exposed rocks to a variety of depths; it has also examined the formation at several locations between craters on the plains. Within the ~150 m diameter Endurance crater, where Opportunity spent six months, these layered rocks are informally called the Burns formation (FIG. 2) after the late Roger Burns, who presciently predicted the occurrence of jarosite on Mars (Burns 1987; Grotzinger et al. 2005).

Here, we describe some of the features seen by Opportunity's cameras and measured with its robotic arm instruments that tell of this watery past. Such evidence includes preserved primary sedimentary structures, as well as chemical and mineralogical clues, that allow interpretation of depositional environments and the subsequent diagenetic history, both during and after burial. The rover has also observed features that reflect later remobilization of materials, possibly involving water, and features that hold a record of more recent and perhaps ongoing interaction with tenuous atmospheric water vapor.

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**FIGURE 1** Pancam view looking NNW showing rover tracks and eolian sand ripples on the Meridiani plains (extracted from the “Rub al Khali” Panorama, sol 462, L256, approximate true color). A small exposure of sulfate-rich rocks of the underlying Burns formation is just barely visible at the arrow. The sheer flatness of the Meridiani surface suggests a water-related environment of deposition for the underlying rock formation. IMAGE CREDIT NASA/JPL/CORNELL

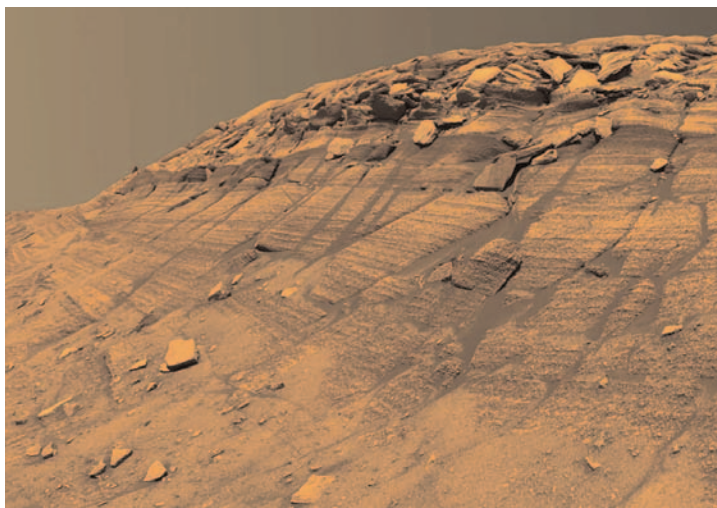
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## SEDIMENTARY FEATURES

### Lamination

Opportunity's first view of the surface of Mars was of a "ledge" of outcrop in the interior wall of Eagle crater where it landed (Squyres et al. 2004a). Although layering was evident from the beginning, a close approach and increasingly closer imaging showed that the scale of layering extended down to millimeter-scale laminations (FIGS. 2, 3). Further examination has shown that these laminations are pervasive and reflect variable resistance to wind erosion. Microscopic imaging has revealed the granular nature of the sediment. The rock is a sandstone (McLennan et al. 2005) consisting of grains that appear to be reworked, sulfate-cemented, altered basaltic mud likely formed from desiccation of a contemporaneous playa lake (see below).



**FIGURE 2** Pancam image of the eastern side of Burns cliff, Endurance crater, investigated on ca. sols 275–295. This is the type locality for the Burns formation. The image shows the lamination and bedding that characterize the upper parts of the Burns formation. For a sense of scale, the stratigraphic section exposed at Burns cliff is about seven meters high, and the large, bright, tabular rock in the lower left is some 25 cm across. The image is from sol 278, sequence P2440, L257. IMAGE CREDIT NASA/JPL/CORNELL

### Festoon Cross-Bedding

Lamination alone is not necessarily evidence of a watery depositional environment because planar laminae can also form in an eolian sedimentary environment. However, features resembling fine-scale trough or festoon cross-lamination, seen early-on in parts of the Eagle crater outcrop, indeed suggest the action of surface water in reworking and depositing sediments. FIGURE 3 shows the rock named Last Chance in Eagle crater, which has some of the best-exposed small-scale festoon cross-laminae. These and other primary depositional features in Last Chance and other rocks are described and discussed in detail by Grotzinger et al. (2005). These rocks occur within the "upper" Burns formation, as exposed at Eagle and Endurance craters, in what is inferred to be a "wetting upward" sequence. They mark the transition from eolian dune and sand sheet facies, below, to interdune or playa deposits in which groundwater occasionally emerged.

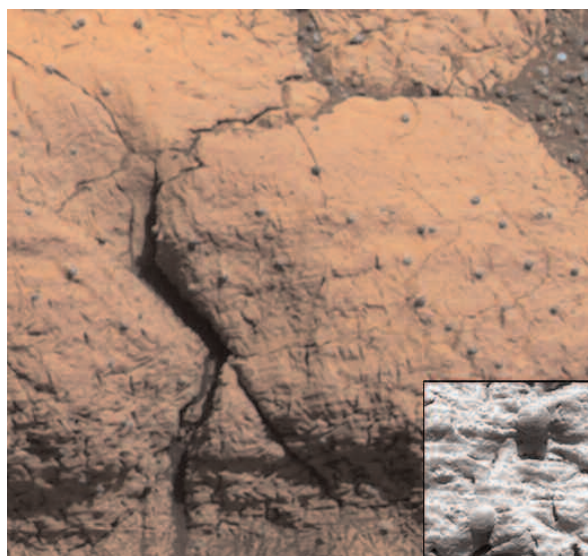
### Concretions

One of the great surprises of the mission was the discovery at Meridiani Planum that the surface hematite signature observed from orbit was largely due to a surface enrichment of hematite-rich spherules (Christensen et al. 2004). Lithological, mineralogical, and chemical features of the spherules indicate that they are concretions, formed during



**FIGURE 3** Pancam false color image of Last Chance exhibiting trough or festoon cross laminations, taken on sol 40 in Eagle crater (L456, P2541). Rock is ~30 cm across. IMAGE CREDIT NASA/JPL/CORNELL

diagenesis in a groundwater/brine-saturated environment. Observed in outcrops at Eagle, Fram, and Endurance craters, the spherules are dispersed and rather uniform in size, typically 2–4 mm in diameter (FIG. 4). They constitute about 1–2% of the volume of the rocks in which they occur, judging by their abundance in surfaces ground by the rock abrasion tool (RAT). They are harder and denser than the sulfate-rich matrix in which they occur; thus they weather out, drop to the ground, and form a resistant lag deposit covering a vast area. In exposures abraded by the RAT, cross sections of spherules appear to be fine grained, homogeneous, and lacking internal structure. These characteristics are consistent with diffusion-limited growth and a concretionary origin (McLennan et al. 2005). In all outcrop exposures observed to date, spherules have a dispersed distribution and do not concentrate preferentially along bedding planes, arguing against their formation as accretionary lapilli or impact spherules.



**FIGURE 4** Sol 27 (P2387) L257 portion of the Guadalupe outcrop in Eagle crater showing bluish concretions embedded in laminated outcrop rock. Concretions are several millimeters in diameter. Also notable in this exposure are the "bird track" mineral casts formed by selective dissolution of lenticular mineral grains. Inset is a cropped microscopic image of concretions. Width of Pancam image ~20 cm; width of inset image ~2 cm. IMAGE CREDIT: NASA/JPL/CORNELL/USGS

Measurements made using the Pancam, Mini-TES, and Mössbauer spectrometer confirm the hematite-rich mineralogy of the concretions (Bell et al. 2004; Christensen et al. 2004; Klingelhöfer et al. 2004). Analysis of the data indicates that the spherules contain at least 50 wt% and perhaps as much as 90 wt% hematite. Chemical data from the Alpha Particle X-ray Spectrometer (APXS) indicate that the concretions also contain a significant siliciclastic component, but determining the exact composition is hindered by contributions from dust, soil, and rock to most analyses (Jolliff et al. 2005).

### Cements and Secondary Porosity

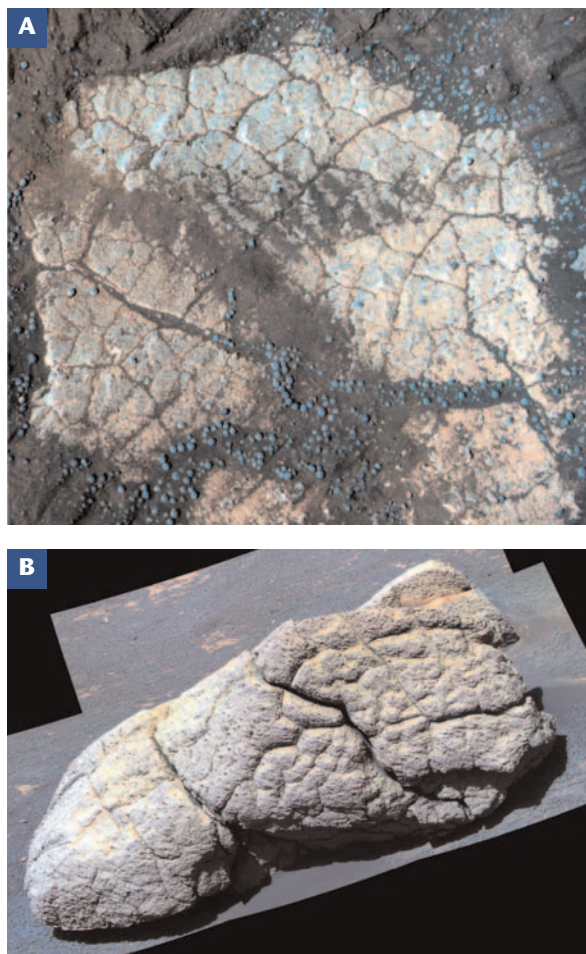
Sandstones of the Burns formation preserve microtextural features consistent with diagenetic processes commonly associated with groundwater recharge and evaporation in eolian settings. Two temporally distinct episodes of cementation are recognized: early pore-filling cement, leading to primary lithification, and post-concretion cement, resulting from a combination of recrystallization and new growth. Later cements take the form of millimeter-scale concretion overgrowths and irregular nodules consisting of cemented sandstone.

The rocks contain many millimeter-scale voids that are too large to be primary depositional features. They are thus interpreted to be secondary porosity, formed after concretion growth but prior to the second generation of cements. Two porosity types are observed. The first is characterized by crystal-shaped pores interpreted to be crystal molds formed by dissolution of a highly soluble syndepositional evaporite mineral. The second consists of elongate to sheet-like pores, also thought to be groundwater dissolution features. Later in the diagenetic history, notably during the formation of distinct stratigraphic horizons such as the “Whatanga” contact separating the middle and upper units of the Burns formation, pores were substantially modified and enlarged due to further groundwater dissolution.

## LATER ALTERATION FEATURES

### Polygonal Texture

Numerous rocks observed in Endurance crater and on the Meridiani plains away from craters exhibit polygonal texture. This is seen in flat-lying rocks close to the ground surface, as in FIGURE 5A, as well as on rock surfaces in three dimensions standing above the ground surface, e.g. in Wopmay, a large rock lying in the interior of Endurance crater (FIG. 5B). These features cut across bedding structures and thus did not form by desiccation contemporaneous with sediment deposition. They more likely formed as a result of later dehydration of originally hydrated salts. Not all exposed rock surfaces show these features. A possible explanation for this lies in the ease with which the sulfate-rich sediments erode by wind abrasion. Rock surfaces that are exposed to prevailing winds erode quickly, so that only rocks with a long exposure history but some protection from wind-driven abrasion retain this record of dehydration. In the case of the rock Wopmay, the side of the rock facing into prevailing winds is relatively smooth (although it has a weak polygonal texture), whereas the downwind side of the rock exhibits a deep, well-exposed polygonal texture (FIG. 5B). McLennan et al. (2005) noted the similarity of the polygonal texture of Wopmay to septarian nodules, which commonly form three-dimensional polygonal networks caused by tensional failure associated with volume changes. In Wopmay, this texture could result from volume decrease caused by dehydration of sulfate salts and was possibly related to unloading following impact excavation.



**FIGURE 5** (A) Pancam L256 false-color image of Fuller, taken on sol 208 (P2565), showing polygonal texture most likely caused by dehydration or desiccation. Exposure is about 30 cm across. (B) Pancam L257 false-color image mosaic of Wopmay from sol 251 (P2432) in approximate true orientation within Endurance crater. The inferred predominant wind direction is from left to right. Polygonal texture occurs on all surfaces of the rock but is more pronounced on the downwind side (center to upper right). Boulder is about 1.4 m in length. IMAGE CREDIT NASA/ JPL/CORNELL

### Fracture Fillings

Fractures that show evidence of mineralization along their length occur in several locations, notably in rock exposures within Endurance crater. One such fracture with mineralized linings along its edges is shown in FIGURE 6A. This particular fracture is oriented approximately radially relative to the crater, so one possibility is that it formed as a result of impact. This fracture could also be related to a regional NE–SW-trending fracture pattern. In places where it has been analyzed, material making up the lining is compositionally similar to the outcrop rock, so it may represent a relatively minor fluid-assisted remobilization of local material. Closed fractures with fillings also have been observed in rocks, especially one named Ellesmere in Endurance crater (McLennan et al. 2005). Such features reflect an earlier period of deformation and fluid mobilization of materials. Imaging from several meters suggested the possibility of radial-fibrous texture, consistent with recrystallization along the fracture. In this case, however, the detail of the texture was at the limit of resolution, and it was not possible to position the rover so as to analyze or image these fracture fillings with the microscopic imager.



**FIGURE 6** (A) Pancam false-color image of fracture in Endurance crater showing erosion-resistant fracture-lining materials (sol 152, P2380, L257; inset: sol 170, P2598, L257). (B) Detail of Pancam image showing a rock rind in Eagle crater, sol 50, P2578, L257, false-color. The relatively resistant rind is indicated by shadowed overhang. IMAGE CREDIT NASA/JPL/CORNELL

### Rock Rinds

Weathered rock surfaces, as exposed within craters and on the smooth Meridiani plains surface, exhibit rinds that differ in chemical composition and resistance to weathering. Such rinds are readily distinguished by their morphology and subtle differences in Pancam color images (FIG. 6B). The rinds are observed on exposures within craters and on the plains. Chemically, they are similar to the rocks on which they form, but they appear to have less sulfate and a higher proportion of siliciclastic components. These rinds most likely represent relatively recent alteration and minor redistribution of salts associated with interaction between rock surfaces and transient water, possibly in the form of frost, from the thin, H<sub>2</sub>O-poor atmosphere.

## MINERALS, ROCK COMPOSITIONS, AND CHEMICAL TRENDS

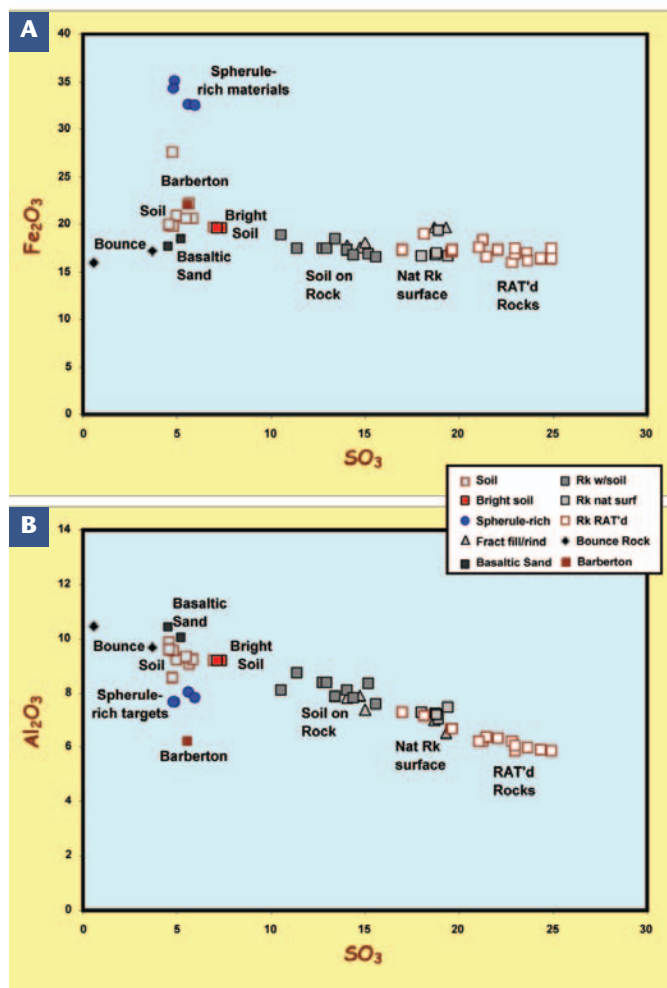
### Mineralogy

Mössbauer spectra show that the outcropping sulfate-rich lithology in all Meridiani exposures thus far examined contains the Fe-bearing minerals hematite and jarosite (Klingelhöfer et al. 2004). Fine-grained hematite (other than concretions) accounts for some 40 wt% of the Fe. The firm identification of jarosite indicates the presence of significant OH in these rocks and formation by precipitation from acidic, sulfate-rich brine. Two other Fe-bearing components have been identified in outcrop from Mössbauer spectra

(Klingelhöfer et al. 2004). One is an octahedral Fe<sup>2+</sup> doublet that could be from pyroxene, but this assignment cannot be made with certainty; ferrous sulfate or glass are also possibilities. The second component is a ferric doublet that could represent a variety of ferric oxyhydroxide. From the Mössbauer spectra, olivine is precluded as a component of the outcrop rocks. Mini-TES spectra of the outcrop rocks are consistent with a mixture of hematite, jarosite, Mg- and Ca-sulfates, a non-crystalline silica-rich phase, feldspar, and possibly sheet silicates (Christensen et al. 2004; Clark et al. 2005).

### Chemical Compositions

Compositional analyses of Meridiani outcrop rocks from the APXS (Rieder et al. 2004) have shown the rocks to be extremely rich in S, presumably in the form of sulfate, and rich in Cl and Br, either as halides or in sulfates. This is the key bit of evidence regarding the evaporite-rich nature of



**FIGURE 7** Chemical compositions (in wt%) of Meridiani materials (analyzed from sol 1 through sol 250) illustrating the extreme sulfate enrichment of the outcrop rocks. The highest levels measured previously by the Viking and Pathfinder landers were around 10 wt% as SO<sub>3</sub>. Natural rock surfaces and fracture-filling or lining materials have compositions intermediate between those of abraded rock and soils. Two of the soils measured in Endurance crater were especially well sorted and rich in basaltic components; these are represented by the black square symbols. Two rock compositions are shown: (1) Bounce Rock, which is a pyroxene basalt similar to the Martian meteorites EETA79001 (lithology B) and Zagami, and (2) Barberton, which is a small cobble that has a Mg-rich composition and is probably a fragment of a meteorite. (A) total Fe as Fe<sub>2</sub>O<sub>3</sub> versus SO<sub>3</sub>, showing the Fe enrichment of the spherule concretions. (B) Al<sub>2</sub>O<sub>3</sub> versus SO<sub>3</sub>, showing the trend of decreasing alumina with increasing sulfate. Alumina extrapolates to zero at about 58 wt% SO<sub>3</sub>.



Burns formation rocks. FIGURE 7 shows the distribution of compositions in terms of  $\text{SO}_3$ , total iron as  $\text{Fe}_2\text{O}_3$ , and  $\text{Al}_2\text{O}_3$ ; these plots illustrate some of the important major-element compositional relations among different groups of materials at the landing site. In general, alumina, silica, and other elements associated with the siliciclastic component vary inversely with  $\text{SO}_3$ , whereas  $\text{Fe}_2\text{O}_3$  and  $\text{CaO}$  decrease slightly and  $\text{MgO}$  remains relatively constant. These relations result from the association of a portion of the Ca and Fe with S in sulfates and the abundance of Mg sulfate in the evaporite component. The inferred abundance of Mg sulfate leaves open the possibility of significant amounts of  $\text{H}_2\text{O}$ , perhaps as much as 10 wt% or more, if the Mg sulfate is present as one or more hydrated forms, such as kieserite, starkeyite, hexahydrate, or amorphous  $\text{MgSO}_4 \cdot x\text{H}_2\text{O}$ .

The observed variations of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  with  $\text{SO}_3$  indicate the presence of a silica phase, e.g. opaline silica, with the evaporite component, but little or no Al sulfate or aluminous jarosite. A strong correlation of Na and K with  $\text{Al}_2\text{O}_3$  suggests the presence of a feldspar component. Compositional trends for the RAT-ground rock surfaces are consistent with limited variability in the evaporite component and only modest variation in the proportion of sulfate to siliciclastic components. This lack of variability is in turn consistent with sedimentary reworking and some degree of homogenization of the original evaporitic deposits. If the rocks had formed primarily by evaporation and have remained where they formed until today, we would expect to find more significant and systematic variations in cation ratios, and evaporite mineral abundances should follow some systematic evaporation sequence (e.g. Hardie et al. 1985).

## IMPLICATIONS

Clearly a water-related history is indicated for the sedimentary origin and diagenesis of the Meridiani sulfate-rich rocks. These rocks may well record one of the late occurrences of surface-water stability on Mars before the atmosphere became cold, thin, and  $\text{CO}_2$  rich. The survival of soluble salts in Burns formation rocks, which may be several billion years old, argues against any significant interaction with surface water or precipitation in this region following the formation of craters such as Eagle and Endurance. The sulfate-

rich clastic sediments most likely formed by evaporative cementation of mainly eolian-reworked primary evaporites and subaqueous, sulfate-rich, basalt-derived muds associated with playa lake or interdune groundwater (brine). The composition of the rocks indicates that the sediments are composed of about half evaporite components and half very fine-grained siliciclastic components. Following reworking and deposition, burial and interaction with groundwater brines resulted in several stages of diagenesis. The stages include syndepositional formation of tabular crystals cutting across primary laminations; fine-grained cementation and filling of primary porosity; formation of hematite-cemented concretions; selective dissolution of early-formed minerals, e.g. ferrous iron sulfates; local sulfate recrystallization; and dissolution of tabular crystals to form crystal-mold porosity. Subsequent to diagenesis, these rocks were affected by the formation of fractures, fracture fillings, and veins, possibly associated with impact and/or dehydration. More recently, erosion by wind abrasion of overlying concretion-bearing strata and removal of fine materials produced a lag deposit of spherules and possibly granular siliciclastic debris, in addition to basaltic eolian sands and dust. Interaction of exposed rock surfaces with atmospheric water vapor, and possibly small amounts of transient liquid water, produced rinds and generated micron- to millimeter-scale redistribution of soluble components. The presence of jarosite and inferred Mg- and Ca- sulfates holds open the possibility that these sedimentary rocks sequestered and still contain a significant reservoir of water.

## ACKNOWLEDGMENTS

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# Water on Mars and the Prospect of Martian Life

Andrew H. Knoll<sup>1</sup> and John Grotzinger<sup>2</sup>



**E**vidence of water on Mars dates back to the first observations of channeled landscapes made by Mariner 9 and Viking. More recent images from Mars Global Surveyor and Mars Express strikingly confirm that fluids have sculpted the Martian surface at least episodically through its history. The Mars Exploration Rovers Opportunity and Spirit have added evidence for extensive rock–water chemical interactions in the regions where these remote geologists landed, while OMEGA and THEMIS have shown that similar processes took place in many parts of the planet.

Because of the close relationship between water and biological activity on Earth, such observations have been taken as hopeful signs that Mars, as well, might once have supported life and, indeed, might still do so in subterranean oases. There is, however, much more to consider. Water appears to be necessary for life, at least as it exists on Earth and can be contemplated on Mars, but it does not, by itself, insure habitability. In this paper, we review the broader requirements for biological activity as they relate to water and use these to constrain astrobiological inferences about Mars.

KEYWORDS: Mars, Meridiani, water, life, astrobiology

## WHY IS WATER KEY TO RECIPES FOR LIFE?

In chemistry, geometry is destiny, and it is the distinctive molecular geometry of H<sub>2</sub>O that accounts for many of its biofriendly attributes (Finney 2004). In water molecules, a relatively large oxygen nucleus is flanked by two smaller, asymmetrically placed hydrogen nuclei, forming a distinctly polar molecule with a mean HOH angle of 104.5°. Because of their pronounced dipole moment, water molecules interact strongly with one another via hydrogen bonding. Not only do these molecular interactions determine the crystallographic structure of ice, which famously (and, from a biological standpoint, usefully) floats in water, they also explain why H<sub>2</sub>O is liquid at temperatures where most comparably small molecules are gases.

Water ionizes readily, resulting in anomalously high rates of molecular diffusion and a pronounced capacity to conduct excess protons (Finney 2004). Also, water effectively dissociates ionic species. Thus, water provides a particularly

*Water, water, every where,  
And all the boards did shrink;  
Water, water, every where,  
Nor any drop to drink.*

*“Rime of the Ancient Mariner”  
Samuel Taylor Coleridge*

(Benner et al. 2004). But such compounds are, at best, trivially important as fluid environments on Earth and are doubtfully more relevant to Mars. The fact that water molecules interact in complex and specific ways with enzymes (e.g. Rand 2004) might be taken as further evidence for the unique fit between H<sub>2</sub>O and life, but this may tell us only that life on Earth has evolved to maximize biochemical function in an aqueous milieu (Ball 2005).

## WHY THERE IS MORE TO THE RECIPE

### Nutrients

Water may be necessary for biological activity, but as the plight of the Ancient Mariner illustrates, it is certainly not sufficient. Terrestrial life is based on carbon, and collectively, C, H, and O make up nearly 80% of the dry weight of a bacterial cell. (“Dripping wet,” bacteria are about 70% water.) Cells, however, contain many additional elements—more than thirty in typical microorganisms. Other major constituents include N and P, with cellular C:N:P lying near 106:16:1 (what biologists call the Redfield ratio). N and P find obligate use in proteins, membranes, and nucleic acids, the fundamental structural, functional, and informational molecules of the cell. It is by no means clear that the same molecules will characterize life wherever we may find it, but it is hard to conceive of functional and informational macromolecules that do not contain N or P. Sulfur also plays key roles in cells, notably in S–S bonds that govern the three-dimensional conformation of proteins and FeS

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clusters that form the functional heart of some ancient and critically important enzymes. Indeed, De Duve (1995) has speculated that thioesters played a crucial role in the origin of life on Earth. For these reasons, life likely can form and persist only on planets where N, P, and possibly S are present in biologically available forms.

Other elements are required in minor or trace abundances. For example, Fe and, in many organisms, Mo are essential cofactors in biological fixation of nitrogen. Mo is required, as well, by organisms that use nitrate as a source of N for proteins, nucleic acids, and other biomolecules. Thus, on Earth there could be no biological nitrogen cycle without metal ions available in solution. Mg occupies the structural and functional center of chlorophyll, while Mn atoms mediate the extraction of electrons from water by plants and algae. Similarly, then, without Mg and Mn, photosynthesis as we know it could not exist. Fe plays a central role in hemoglobin, extending the metabolic role of metals to respiration. The recipe for life, then, is complex, and likely has been from the beginning—metallic cofactors have been implicated in many prebiotic chemical reactions and in purportedly primitive biochemical reactions (Williams and Fraústo da Silva 1996). The origin and long-term persistence of life requires not only water, but adequate supplies of major, minor, and trace elements, whose availability will be determined by source rocks and their chemical weathering, as well as by pH, redox, and other environmental parameters. Thus, while water sparked early astrobiological interest in Mars, we have come to the point in planetary exploration where a far more sophisticated understanding of environmental geochemistry is required.

### Water Activity

Clearly, environments where life can thrive do not contain pure H<sub>2</sub>O, but an aqueous solution of ionic and dissolved organic constituents. Through their interactions with water molecules, however, these substances limit the availability of H<sub>2</sub>O for hydration reactions, and at high concentrations, ions and organic molecules can inhibit cellular physiology. Water activity is the effective water content of a solution (in the notation used by microbiologists,  $a_w = n_1/(n_1 + n_2)$ , where  $n_1$  equals moles of water and  $n_2$  equals moles of solute; Grant 2004). Most terrestrial organisms cannot grow and reproduce at water activities below 0.9. A few bacteria grow where  $a_w$  is as low as 0.85, and some archaea can live at an  $a_w$  of 0.75 (the water activity of a halite-saturated solution). In terms of this parameter, however, fungi define the limits of life: one remarkable species has been shown to grow at  $a_w = 0.61$  (Grant 2004). (Honey has such a long shelf life because its water activity falls below the limit for microbial spoilage.) The important point is that in brines where  $a_w$  is persistently low, water may be present but uninhabitable.

### The Persistence of Water

Regardless of their ability to persevere at chronically low water activities, many organisms—from bacteria to animals—can tolerate episodic dryness. Desiccation-tolerant organisms persist in a dormant state, forming spores, glycoprotein capsules, or other structural phases that retard water loss.

The key variable is the return time of habitable water. Endolithic lichens in Antarctic boulders are metabolically active only a few weeks each year, but it is enough for populations to persist over geological time scales (Friedmann et al. 1993). Cyanobacteria, dried onto herbarium sheets in the nineteenth century, resume photosynthesis almost immediately upon wetting. Even lotus seeds preserved in lake beds from China have been germinated

successfully after  $1288 \pm 271$  years (radiocarbon dates) of dormancy (Shen-Miller et al 1995).

Scientists have reported much longer dormancy in bacteria from Pleistocene permafrost and longer still in salt deposits formed more than 250 million years ago. Such claims are controversial—even dormant cells must expend energy now and again to repair molecular damage such as spontaneous DNA breakage. But these reports underscore the fact that we cannot yet place a precise limit on the duration of cellular dormancy. Nor do we know with confidence what biochemical features account for prolonged dormancy in organisms that exhibit this trait.

Regardless of this uncertainty, the time scale of return for liquid water must loom as a key variable in ongoing assessments of Martian habitability. Playas that receive water once every decade likely persist as habitable environments indefinitely; those that recharge once every ten million years may not—unless there exists a reservoir of populations elsewhere that can recolonize ambient waters whenever they reappear.

This latter point is worth underscoring. On Earth, habitable extremes exist in the context of “normal” environments that provide nutrient subsidies and persistent reservoirs of colonizing populations. Maintenance of a viable biota may be far more difficult on planets where environments at or near the extremes of habitability are the *most* favorable sites for life.

### Acidity

On Earth, the habitability of aqueous environments is influenced by additional factors, including pH, Eh, and temperature (Knoll and Bauld 1989). Acidity is particularly relevant because geochemical data from Meridiani Planum indicate that sulfuric acid was present when Meridiani sedimentary rocks formed (McLennan et al. 2005). Places like Rio Tinto, Spain, where strongly acidic waters deposit jarosite and iron oxides, provide insights into acid tolerance (Fig. 1, Fernández-Remolar et al. 2005). Acid-tolerant populations thrive in such environments, not because they can run their biochemistry at low pH, but because they efficiently expel protons from their cytoplasm, enabling cell chemistry to continue under more or less neutral conditions.

Acid and desiccation tolerance are not universal attributes of terrestrial organisms, and most groups that accommodate these environmental challenges are descended from ancestors that tolerated them poorly. On Earth, then, life can persist in arid, oxidizing, and acidic habitats, but it might not do so if those were the *only* habitable environments on the planet. Moreover, accumulated data on prebiotic chemistry suggest that life could not have *arisen* under such conditions (Knoll et al. 2005).

## ASTROBIOLOGY AND THE RECORD OF WATER ON MARS

### Geomorphological and Sedimentological Observations

Much of the ancient cratered terrain of Mars is dissected by small valley systems similar to terrestrial river networks (Baker and Milton 1974). Because significant precipitation and surface runoff are not possible under modern conditions, some researchers have interpreted the valley networks as evidence of warmer, more humid ancient climates (Carr 1996). Alternatively, these drainage patterns could have been created through venting of underground water to the surface, events hypothesized to have been vigorous, but short-lived (Baker and Milton 1974). More recently, the discovery of a channelized alluvial fan northeast of Holden

crater has provided evidence for deposition of loose sediment under aggrading conditions (Malin and Edgett 2003) within well-developed meandering channels—water flowed freely across the fan surface. The characteristic time scale for such deposits leads to a minimum estimate for the volume (900–5000 km<sup>3</sup>) and duration (50–1000 yrs) of water flow (Jerolmack et al. 2004). This modest estimate does not require precipitation, so long as a local source of water is present.

Geomorphological evidence for larger and longer-lived water bodies remains controversial (Baker and Milton 1974). Most recently, high-resolution images of the Elysium region obtained by Mars Express have indicated the possible presence of pack ice preserved beneath a mantle of soil (Murray et al. 2005). In this interpretation, a lake or shallow sea perhaps 50 m deep formed during catastrophic eruption of groundwater from nearby fractures, only to freeze partially, generating pack ice that subsequently became embedded in a larger ice body. Alternatively, these features may be rafts of frozen lava which floated atop a larger pool of igneous melt that flash-froze to preserve the observed geometry. Even if the water–ice hypothesis proves correct, however, liquid water need not have been stable for long intervals (>1000s of years) on the Martian surface.

Ground-based observations by the Mars Exploration Rovers provide considerable insight into the mechanisms by which sulfate minerals may have formed on Mars. Opportunity images provide compelling evidence for the accumulation of sediment particles—formed of admixtures of sulfate salts and silicate minerals—in a variety of sedimentary depositional environments. Eolian strata are capped by interdune fluvial strata that document shallow overland flows with moderate flow velocities (Fig. 2, Grotzinger et al. 2005). Further evidence for an active water table is found in stratigraphically restricted zones of recrystallization and secondary porosity, millimeter-scale hematitic concretions, and millimeter-scale crystal molds that cut across primary layering (McLennan et al. 2005).

## Geochemical Observations

The Mars Exploration Rover Opportunity has discovered jarosite [(K,Na,H<sub>3</sub>O)(Fe<sub>3-x</sub>Al<sub>x</sub>)(SO<sub>4</sub>)<sub>2</sub>(OH)<sub>6</sub>, where  $x < 1$ ] in Meridiani outcrop rocks, while its mechanical twin Spirit found goethite [FeO(OH)] in Gusev crater; both minerals form in the presence of water (Klingelhöfer et al. 2004, 2005). Elemental abundances indicate that Ca and Mg sulfates occur with the jarosite at Meridiani, although their precise mineralogy cannot be ascertained (Clark et al. 2005). Mars Express has identified gypsum (CaSO<sub>4</sub>•2H<sub>2</sub>O), kieserite (MgSO<sub>4</sub>•H<sub>2</sub>O), and, possibly, other polyhydrated sulfates on the Meridiani plain and more widely on the Martian surface (Gendrin et al. 2005). Finally, as noted above, Opportunity has confirmed the presence of hematite at Meridiani, most conspicuously as millimeter-scale concretions that formed during early diagenesis of sulfate-rich sediments (McLennan et al. 2005). Thus, geochemical measurements at outcrop level confirm and extend geomorphological and sedimentological evidence for water on the ancient surface of Mars.

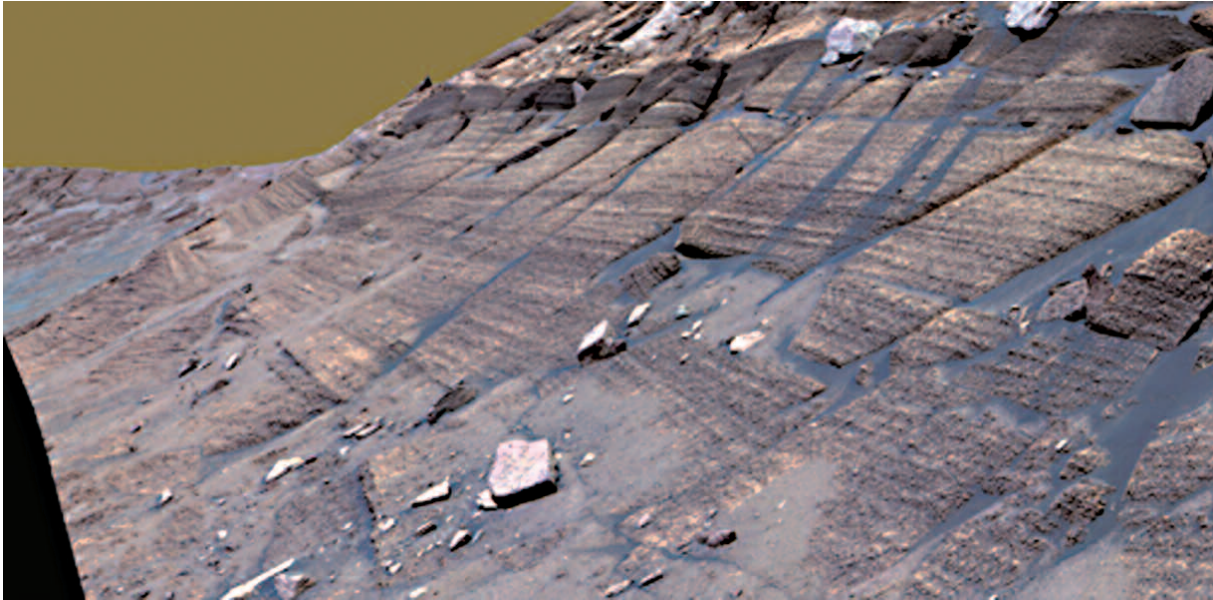
## Climate Evolution

The climatic history of Mars since the end of heavy bombardment (ca. 3.8 Ga) is clearly controversial. Some hold that oceans persisted episodically long after bombardment ended. Others argue that while Noachian oceans existed, the Martian surface froze near the end of heavy bombardment and has remained that way ever since. Indeed, based on the thermochronology of Martian meteorites, Shuster and Weiss (2005) claim that Mars has not seen temperatures significantly above freezing for the past four billion years.

We can reconcile geochemical and geomorphological evidence for liquid water with subzero Martian tempera-

**FIGURE 1** Blood red waters of Rio Tinto, southwestern Spain. Ferric iron colors this highly acidic river (pH 0.9 to 3); the orange precipitates are comprised of jarosite, schwertmannite, and other iron sulfate minerals, as well as nanophase iron oxides (Fernández-Remolar et al. 2005).





**FIGURE 2** A seven-meter section of sedimentary rocks exposed within Endurance crater, Meridiani Planum, Mars. These rocks, the first sedimentary succession ever examined at outcrop scale on Mars, preserve a record of ancient water. Large-scale cross-bedding visible in the lower left indicates the passage of ancient sand dunes. These cross-bedded deposits are overlain by laminated sand sheet deposits also formed by wind-blown sand; however, the overlying sediments include cross-laminated, rippled beds deposited by shallow, sub-aqueous flows. The dark band visible near the top of the succession is interpreted to have formed during alteration and cementation of the sediments by percolating groundwater.

tures in a simple way: by invoking antifreeze. Salts, present in abundance at Meridiani Planum, would lower the freezing temperatures of ambient waters, as would sulfuric acid. Dilute aqueous solutions of sulfuric acid can depress the freezing temperature of water by as much as 70°C, providing a particularly effective way of reconciling diverse observations of Martian environments through time (Knoll et al. 2005).

Considered collectively, and conservatively, there are no geomorphological, geochemical, or sedimentological features yet discovered on Mars that cannot be accounted for by intermittent, short-term flow of surface water, supplied by underground sources and dispersed in a cold, dry climatic regime. The simple observation that channels cut early in Mars history persist to the present tells us that surface water flow has been limited for a long time. This does not eliminate the possibility of a persistently warm, wet Mars in Noachian time, but does emphasize that evidence to support such a model remains meager (Gaidos and Marion 2003).

## DISCUSSION

Mars today is a forbidding place. Temperature and atmospheric pressure lie near the triple point of water—indeed liquid water is not stable on the present-day Martian surface (Gaidos and Marion 2003). The surface is also chemically harsh and subject to strong radiation. It is doubtful that organisms thrive today at the Martian surface.

From the preceding paragraphs, one might well conclude that surface environments have been biologically challenging for *most* of Mars' history. The salty dunes and transient interdune streams that covered Meridiani Planum three to four billion years ago indicate that while chemical weathering and erosion provided many of the elements required for life, ambient environments were arid, acidic, and oxidizing (Knoll et al. 2005). Terrestrial ecology suggests that microorganisms could survive many aspects of the inferred Meridiani environment, but habitability would depend critically on the time scale of water with sufficiently high water activity to support cell biology—a parameter that is currently unknown. Meridiani waters may have been habitable upon introduction, but water activity would have dipped below habitable levels as groundwater, playas, or both, evaporated to dryness.

Whether Meridiani is broadly representative of the Martian surface three to four billion years ago is unknown, but remote sensing from Mars Express suggests that it could

be—equally, it could be unusually *favorable* from an astrobiological perspective. All in all, the aqueous deposits of Meridiani Planum are biologically permissive, but they may record the sunset of a habitable Martian surface, not its beginning.

The briny acidic waters of Meridiani Planum would certainly constitute a formidable challenge to the types of prebiotic chemical reactions thought to have played a role in the origin of life on Earth (Knoll et al. 2005). This is a relevant consideration because heavy bombardment could have eradicated any surficial life that evolved during Mars' earliest history. One might argue that Mars could have been (re?)colonized after late heavy bombardment by organisms transported by meteorites from Earth. The physical mechanism is plausible—the key question, however, is: what is the probability that terrestrial colonists would have landed in a Martian environment that could support sustained metabolism?

The most promising places to look for evidence of surface life on Mars are probably sedimentary basins that preserve a record of Mars' earliest history, when water was most abundant and persistent and both oxidation and acidity were least developed. We know relatively little about such terrains, but they would seem prime candidates for future missions aimed at understanding Mars' environmental history, as well as astrobiology.

## The Subsurface Alternative

If surface environments on Mars have been challenging for life for the past several billion years, what about the subsurface? There is inherent skepticism when environments deemed most likely to support life are those least amenable to observation. Nonetheless, the subsurface was (and may still be) the most likely place on Mars to find persistent reservoirs of liquid water. Given a continuing supply

of nutrients (which introduces its own set of challenges), life in the Martian crust might be sustained by a primordial hydrogen economy—chemical energy in the form of H<sub>2</sub> produced by aqueous alteration of basalts.

The only Martian rocks known to contain carbonate minerals are meteorites that preserve iron and magnesium carbonates precipitated in subsurface cracks flushed by groundwater (McKay et al. 1996; Bridges and Grady 2000). Sulfide minerals formed as well, indicating that at least some subsurface environments were neither acidic nor oxidizing early in Martian history. At present, however, we know little about water activity or persistence in such environments.

Several laboratories have reported methane emissions from the Martian surface (Krasnopolsky et al. 2004; Formisano et al. 2005), and the argument has been advanced that these exceed fluxes expected for abiotic methanogenesis (Krasnopolsky et al. 2004). Hydrothermal alteration of crustal rocks may, however, be sufficient to explain the reported fluxes (Lyons et al. 2005). Moreover, the proximal source of methane (if correctly identified) need not be limited to current biological or hydrothermal processes. Possibly, current methane fluxes reflect release from permafrost as it sublimates, decoupling current emanations from physical processes of formation.

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## The Future

In future exploration, astrobiologists need to learn about the time scales on which water has persisted on Mars, and geochemical analyses must be extended to include nutrients, especially nitrogen in Martian soils. Better models and experiments can sharpen our sense of water activity during the deposition and early diagenesis of Meridiani-type sedimentary rocks, while future orbital and lander missions will tell us the extent to which such environments were representative of the early Martian surface. Was ancient Mars generally arid, acidic, and oxidizing, and if so, when did it become that way?

Of course, the biggest hurdle for astrobiology concerns biology, itself. To what extent can we generalize from observations of the only biological planet we know? That problem will not be solved soon, meaning that the search for evidence of life elsewhere will remain empirical and difficult. But as future missions provide improved data on the environmental history of Mars, we may yet learn whether life on Earth is unique or merely uniquely successful in our solar system.

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## Mineralogical Society of Great Britain and Ireland

### FRONTIERS IN MINERAL SCIENCES, CAMBRIDGE, JUNE 2007 CALL FOR PRESENTATIONS

Since our announcements in the June and December 2005 issues of *Elements* about this important joint meeting of the Mineralogical Society (MinSoc), the Mineralogical Society of America (MSA) and the Mineralogical Association of Canada (MAC), we are pleased to welcome the Société Française de Minéralogie et de Cristallographie (SFMC) to the organising committee. The meeting, to be held at Fitzwilliam College, Cambridge, on 26–28 June 2007, will include six plenary lectures and over twenty symposia. The scientific focus of the meeting will be on recent advances in research into the properties and behaviour of minerals, together with their geological contexts in rocks and biosystems, under the overall theme of 'Frontiers in Mineral Sciences'. Plenary lecturers will include Dana lecturer Frank Spear (Rensselaer Polytechnic Institute, USA), George Brown lecturer Gerhard Lagaly (Kiel University) and Pascal Richet (IPGP, Paris).



MICHAEL CARPENTER

The organising committee met in Cambridge earlier in the year to finalise the programme of symposia, and a list of these with convenors is given below. The committee members feel that these symposia cover the major areas of topical interest in the mineral sciences and urge readers to make contact with their most appropriate symposium convener as soon as possible if they would like to make a presentation at the conference. At

this stage it would be helpful to have a rough title for your presentation and whether it will be an oral or poster one. The deadline for final registration and abstract submission is 28 February 2007. The overall convener of the conference is Prof. Michael Carpenter (Cambridge), who will be happy to put you in touch with the most appropriate symposium convener if you are unsure where your presentation might fit. His e-mail address is [mc43@esc.cam.ac.uk](mailto:mc43@esc.cam.ac.uk). The second circular for the conference, with full registration and accommodation details, can be found on the conference website at [www.minersoc.org/Frontiers2007.htm](http://www.minersoc.org/Frontiers2007.htm)

Adrian Lloyd-Lawrence



Punting on the Cam, one of the events planned as part of the social programme for 'Frontiers 2007'

### LIST OF SYMPOSIA IN 'FRONTIERS IN MINERAL SCIENCES 2007'

- Interactions between minerals and organic molecules**  
Convener: Bob Hazen (Geophysical Lab.; [r.hazen@gl.ciw.edu](mailto:r.hazen@gl.ciw.edu)); co-convenors: David Fowle (U. of Kansas; [fowle@ku.edu](mailto:fowle@ku.edu)), François Guyot (U. Pierre et Marie Curie; [guyot@lmcp.jussieu.fr](mailto:guyot@lmcp.jussieu.fr))
- Minerals in biological systems**  
Convener: David Manning (U. of Newcastle; [david.manning@ncl.ac.uk](mailto:david.manning@ncl.ac.uk))
- Internal textures, and trace element and isotope geochemistry in accessory minerals: Advances in imaging and in situ microanalysis**  
Convener: John Hanchar (Memorial U. of Newfoundland; [johnh@esd.mun.ca](mailto:johnh@esd.mun.ca)); co-convener: Jean-Marc Montel (U. de Toulouse; [montel@lmtg.obs-mip.fr](mailto:montel@lmtg.obs-mip.fr))
- Feldspars 2007**  
Convener: Ian Parsons (U. of Edinburgh; [ian.parsons@ed.ac.uk](mailto:ian.parsons@ed.ac.uk)); co-convenors: Ross Angel (Virginia Tech; [rangel@vt.edu](mailto:rangel@vt.edu)), Bob Martin (McGill U.; [bobm@eps.mcgill.ca](mailto:bobm@eps.mcgill.ca))
- Minerals in contaminated environments: Characterization, stability, impact**  
Convener: Karen Hudson-Edwards (Birkbeck, U. of London; [k.hudson-edwards@bbk.ac.uk](mailto:k.hudson-edwards@bbk.ac.uk)); co-convenors: Heather Jamieson (Queen's U.; [jamieson@geol.queensu.ca](mailto:jamieson@geol.queensu.ca)), Kurt Kyser (Queen's U.; [kyser@geol.queensu.ca](mailto:kyser@geol.queensu.ca)), Kaye Savage (Vanderbilt U.; [kaye.s.savage@vanderbilt.edu](mailto:kaye.s.savage@vanderbilt.edu)), Kevin Taylor (Manchester Metropolitan U.; [k.g.taylor@mmu.ac.uk](mailto:k.g.taylor@mmu.ac.uk))
- Adsorption processes on clay mineral surfaces**  
Convener: Dave Wray (U. of Greenwich; [d.wray@greenwich.ac.uk](mailto:d.wray@greenwich.ac.uk)); co-convener: Chris Breen (U. of Sheffield; [c.breen@shu.ac.uk](mailto:c.breen@shu.ac.uk))
- Applications of synchrotron and neutron radiation in mineralogy**  
Convener: Annette Kleppe (U. of Oxford; [annettek@earth.ox.ac.uk](mailto:annettek@earth.ox.ac.uk)); co-convenors: Jean-Louis Hazemann (CNRS Grenoble; [jean.louis.hazemann@grenoble.cnrs.fr](mailto:jean.louis.hazemann@grenoble.cnrs.fr)), Alan Anderson (St. Francis Xavier U.; [aanderso@stfx.ca](mailto:aanderso@stfx.ca))
- Simulations of Earth and planetary materials: Advances and limitations**  
Convener: Emilio Artacho (U. of Cambridge; [emilio@esc.cam.ac.uk](mailto:emilio@esc.cam.ac.uk)); co-convenors: Bjoern Winkler (Frankfurt U.; [B.Winkler@kristall.uni-frankfurt.de](mailto:B.Winkler@kristall.uni-frankfurt.de)), Etienne Balan (U. Pierre et Marie Curie; [etienne.balan@lmcp.jussieu.fr](mailto:etienne.balan@lmcp.jussieu.fr))
- Mineral magnetism from the nanometre to the planetary scale**  
Convener: Richard Harrison (U. of Cambridge; [rjh40@esc.cam.ac.uk](mailto:rjh40@esc.cam.ac.uk)); co-convener: Josh Feinberg (U. of Cambridge; [jfei05@esc.cam.ac.uk](mailto:jfei05@esc.cam.ac.uk))
- Mineral reactions from the transition zone to the core – Implications for the structure, dynamics and chemical evolution of the Earth's mantle and core-mantle boundary.**  
Convener: Ben Harte (U. of Edinburgh; [ben.harte@glg.ed.ac.uk](mailto:ben.harte@glg.ed.ac.uk)); co-convenors: Annette Kleppe (U. of Oxford; [annettek@earth.ox.ac.uk](mailto:annettek@earth.ox.ac.uk)), Yingwei Fei (Geophysical Lab.; [fei@gl.ciw.edu](mailto:fei@gl.ciw.edu))
- Elasticity of minerals: From trace element geochemistry to geophysics**  
Convener: Simon Redfern (U. of Cambridge; [satr@esc.cam.ac.uk](mailto:satr@esc.cam.ac.uk)); co-convener: Steve Jacobsen (Geophysical Lab.; [s.jacobsen@gl.ciw.edu](mailto:s.jacobsen@gl.ciw.edu))
- Mineralogical models for nuclear waste disposal**  
Convener: Ian Farnan (U. of Cambridge; [ifarnan@esc.cam.ac.uk](mailto:ifarnan@esc.cam.ac.uk)); co-convenors: Rod Ewing (U. of Michigan; [rodewing@umich.edu](mailto:rodewing@umich.edu)), Scott Kroeker (U. of Manitoba; [scott\\_kroeker@umanitoba.ca](mailto:scott_kroeker@umanitoba.ca))
- Amorphous materials: Properties, structure and durability**  
Convener: Daniel Neuville (U. Pierre et Marie Curie; [neuville@ipgp.jussieu.fr](mailto:neuville@ipgp.jussieu.fr)); co-convenors: Grant Henderson (U. of Toronto; [henders@geology.utoronto.ca](mailto:henders@geology.utoronto.ca)), Donald Dingwell (U. of Munich; [dingwell@uni-muenchen.de](mailto:dingwell@uni-muenchen.de))
- Developments in textural analysis of rocks**  
Convener: Marian Holness (U. of Cambridge; [marian@esc.cam.ac.uk](mailto:marian@esc.cam.ac.uk)); co-convener: Ed Sawyer (UQAC; [ewsawyer@uqac.ca](mailto:ewsawyer@uqac.ca))
- The development of the North Atlantic Igneous Province with special reference to the platinum-group element concentrations in the magmas**  
Convener: Tony Naldrett (U. of Toronto; [ajaldrett@yahoo.com](mailto:ajaldrett@yahoo.com))
- Magma chamber processes and models of magma extraction**  
Convener: Jon Davidson (Durham U.; [j.p.davidson@durham.ac.uk](mailto:j.p.davidson@durham.ac.uk)); co-convener: Teal Riley (BAS; [t.riley@bas.ac.uk](mailto:t.riley@bas.ac.uk))
- Magmatic fluids and volcanic degassing: From ores to aerosols**  
Convener: David Pyle (U. of Cambridge; [dmp11@cam.ac.uk](mailto:dmp11@cam.ac.uk)); co-convenors: Anthony Williams-Jones (McGill U.; [willyj@eps.mcgill.ca](mailto:willyj@eps.mcgill.ca)), Florian Schwandner (Arizona State U.; [florimax@schwandner-web.org](mailto:florimax@schwandner-web.org))
- Metamorphic phase equilibria, chronology, and tectonics: A tribute to Frank S. Spear**  
Convener: Matt Kohn (U. of South Carolina; [mjk@geol.sc.edu](mailto:mjk@geol.sc.edu)); co-convenors: Doug Rumble (Geophysical Lab.; [rumble@gl.ciw.edu](mailto:rumble@gl.ciw.edu)), Gerhard Franz (TU Berlin; [gerhard.franz@tu-berlin.de](mailto:gerhard.franz@tu-berlin.de)), Dave Pattison (U. of Calgary; [pattison@ucalgary.ca](mailto:pattison@ucalgary.ca))
- Volatiles in minerals and their petrologic implications**  
Convener: Bernardo Cesare (U. di Padova; [bernardo.cesare@unipd.it](mailto:bernardo.cesare@unipd.it)); co-convenors: Giuseppe Cruciani (U. di Ferrara; [Giuseppe.cruciani@unife.it](mailto:Giuseppe.cruciani@unife.it)), Simon Harley (U. of Edinburgh; [simon.harley@glg.ed.ac.uk](mailto:simon.harley@glg.ed.ac.uk))
- Minerals and fluid-rock interaction**  
Convener: Iain Samson (U. of Windsor; [ims@uwindsor.ca](mailto:ims@uwindsor.ca)); co-convener: Kurt Kyser (Queen's U.; [kyser@geol.queensu.ca](mailto:kyser@geol.queensu.ca))
- Respirable natural dusts: Sources, characterisation and health effects**  
Convener: Claire Horwell (U. of Cambridge; [chor05@esc.cam.ac.uk](mailto:chor05@esc.cam.ac.uk)); co-convenors: Ben Williamson (NHM; [bw@nhm.ac.uk](mailto:bw@nhm.ac.uk)), Bob Finkelman (U. of Texas at Dallas; [rbbf@usgs.gov](mailto:rbbf@usgs.gov))



## THE SOCIETY'S SPECIAL INTEREST GROUPS THE ENVIRONMENTAL MINERALOGY GROUP (EMG)



Karen Hudson-Edwards is lecturer in environmental geology at Birkbeck University of London, and director of the Wolfson Laboratory for Environmental Geochemistry at UCL-Birkbeck. Here, as Chair of the Society's Environmental Mineralogy Group, she outlines the group's wide interests and recent and upcoming activities.

The Environmental Mineralogy Group (EMG) was formed in 2003 as a result of increasing interest in mineralogical research that contributes to the fundamental understanding of environmental science. The group focuses on the integration of mineralogy with life sciences and geochemistry in an environmental context. Within this broad theme, topics such as the chemistry, crystal structure, sorption capacities and stabilities of contaminant element-bearing minerals, bacterial-, fungal-, lichen-, worm-mineral interactions, minerals and human health, mineral weathering and minerals and waste disposal are of interest.

The group was recently involved in two meetings: 'Speciation and Toxicity' in London in 2004, and 'Environmental Mineralogy, Geochemistry and Human Health' in Bath in 2005. Twenty-eight papers arising from these meetings were recently published

in a special issue of *Mineralogical Magazine* (October 2005, volume 69, no. 5), which was guest edited by members of the group. An EMG research-in-progress (RIP) meeting is held every year, and is aimed at presentations by post-graduate students and new researchers, although all contributions are welcome. The 2006 RIP meeting was held on the 6<sup>th</sup> of April at UCL-Birkbeck, University of London.

The group will also be involved in two upcoming major international meetings. The 'Frontiers in Mineral Sciences 2007' meeting in Cambridge will feature a scientific session organised and supported by the group on the characterisation, stability and impact of minerals in contamination environments. The next 'Geochemistry of the Earth's Surface' meeting, which is held every three years and is in Reading in 2008, will also be supported by the group.

Each year we recruit two new members to the committee. We welcome people who are interested in promoting research and activities in environmental mineralogy. If you are interested, please contact the group secretary, Kevin Taylor (K.G.Taylor@mmu.ac.uk) or Karen Hudson-Edwards (k.hudson-edwards@bbk.ac.uk).

Karen Hudson-Edwards

## BURSARY AWARDS FOR 2006

The Council is pleased to announce the names of the individuals awarded bursaries in 2006.

SENIOR BURSARIES were awarded to Alan Boyle (The University of Liverpool), Kevin Taylor (Manchester Metropolitan University), Carolyn Pearce (The University of Manchester) and David Brown (University of Glasgow).

STUDENT BURSARIES were awarded to Dominique Tobler (University of Leeds), Victoria Coker (The University of Manchester), Steven Smith (Durham University), Charlotte Vye (The Open University), Michael Mawby (Durham University), Alessandra Costanzo (National University of Ireland Galway), Mark Pearce (The University of Liverpool), Duncan Hay (University of Glasgow), Daniel Smith (University of Leicester), Aimé Moore (Keele University) and Judith Barrett (Manchester Metropolitan University).

Details on the Society's bursary awards can be found at [www.minersoc.org/pages/awards/awards.html](http://www.minersoc.org/pages/awards/awards.html). In 2007 there will be two opportunities to apply for bursary awards, one in January and one in July.

## 2006

### Mineralogical Society Training Workshops in Electron Probe Microanalysis (EPMA) in Mineralogy For Postgraduates and Advanced Researchers



For full details and how to register for these 'hands on' training workshops go to <http://www.minersoc.org/education>

Natural History Museum, London

Final Course Dates for 2006  
7-10 November 2006

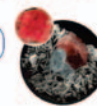


MINERALOGICAL SOCIETY



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 **MINABS Online**



This e-journal is a unique reference tool giving instant access to over 122,000 abstracts of papers in the mineral sciences\* published in the last 24 years. Based on 75 years experience of the provision of reliable and consistent data to the scientific community.

The journal via CrossRef links you electronically to many full-text papers. The service comprises a database of abstracts going back to 1982 and is updated with the abstracts of new papers as soon as they become available.

\* This special 50% introductory subscription offer brings you access to MinAbs Online and free copies of the bimonthly *Elements* magazine. For just £5.00 more you can get access to the Society's other two online journals *Mineralogical Magazine* and *Clay Minerals*. **Students can join for only £5.00.** We anticipate lowering subscription rates in 2007 so your next year's full subscription rate will only be a little higher than this offer.

#### Membership Application

Go to the Society website at [www.minersoc.org](http://www.minersoc.org) and click on the **MinSoc Info** and **How to Join** buttons for more information and to download an application form. Alternatively contact the Mineralogical Society at 41 Queen's Gate, London SW7 5HR or phone +44 (0)20 7584 7516 or e-mail [info@minersoc.org](mailto:info@minersoc.org)



www.clays.org

## The Clay Minerals Society

### FROM THE PRESIDENT



My term as president of The Clay Minerals Society (CMS) will be completed in June 2006 at the conclusion of the joint CMS-GFA meeting in Oléron, France. I want to take this opportunity to thank the very able and skilled people who run CMS for their sustained efforts and hard work. I am humbled by the countless hours and efforts of so many who contribute to the success of CMS on a volunteer basis. At the same time, we are faced with the challenge of being largely a volunteer organization. In the past year, the leadership of

CMS has strived to make our society more responsive to the needs of its members. You may not be aware that CMS, in addition to publishing *Clays and Clay Minerals* and hosting annual meetings, provides travel and research grants to young clay scientists, maintains and distributes 'source' and 'special' clay mineral samples throughout the world, provides input on regulatory issues, is involved in outreach at all educational levels, and is a leading authority on issues related to clay nomenclature.

This past year has been particularly eventful, and I want to touch briefly on some of the highlights. CMS is truly an 'international' organization, with >40% of our membership residing outside of North America. This trend is growing as clay science extends across the globe. As a tangible reflection of this change, for the first time, we are co-hosting our annual meeting with the Groupe Français des Argiles (GFA) in Oléron, France. We are very thankful to Sabine Petit and her co-workers for the invitation to join with GFA and for their hard work.

Like many of our sister societies, we strive to find the right balance between our available resources (financial and human) and our desire to meet the needs of our members and help others who avail of our services. In order to increase the visibility of CMS and to interact more closely with our sister societies, we have moved our society office to the Washington DC area. Our new office manager is Michelle Johnson, who brings considerable expertise to this position. Don't forget to say "hi" the next time you contact the office. Her e-mail address is cms@clays.org. Our new society office is in partnership with the Mineralogical Society of America; we have strong links with the Mineralogical Society of Great Britain and Ireland, and in particular with its Clay Minerals Group, which publishes our sister journal *Clay Minerals*; and soon, we will have a formal link with the Geological Society of America.

*Clays and Clay Minerals* is one of the leading clay science journals and is now available in paper format and in two online formats. Through Ingenta we provide all members and library subscribers complete online access, including hot-linked reference lists, table of contents alerts, and many more technical advantages we have come to expect of the e-publishing world. In addition, our participation in the e-journal aggregate GeoScienceWorld (GSW) offers our individual members the opportunity to search and view the online content. It is our goal that GSW, as part of a 30-journal-strong aggregate, will help to secure our financial future

and to demonstrate the common ground that exists between the many publishers involved. We have initiated and hope to soon finalize a contract to digitize the entire journal archive dating back to the 1950s. It is our goal that this digital content be made available on our website, free to all to access. In addition to retrodigitization of CCM, we hope to soon deploy an online manuscript submission and tracking system to help those involved in the editorial process. We are extremely fortunate to have a capable editorial staff of Derek Bain and Kevin Murphy and a team of associate editors, who together make CCM the leading clay science journal it is.

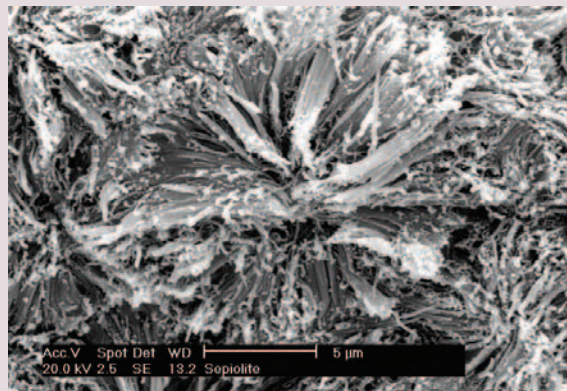
One of the things expected of presidents is an appeal for new members. CMS depends critically on its members, not just for their subscription money, but for the skills they bring and the services they provide. We offer a bargain basic membership fee of \$35, which includes a subscription to *Elements*. For only \$35 more, members receive a subscription to CCM. If you already are a member, please help by spreading the word about all that CMS does.

Thanks for all your help in the past twelve months.

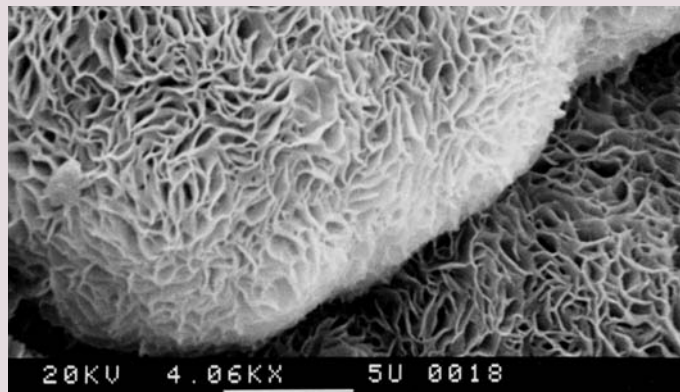
Cliff Johnston

### IMAGES OF CLAY

Here are some images recently deposited in the 'Images of Clay' photo-archive. The archive is co-hosted by The Clay Minerals Society and the Mineralogical Society of Great Britain and Ireland. Go to [www.minersoc.org/pages/gallery/claypix/index.html](http://www.minersoc.org/pages/gallery/claypix/index.html) for details. All the images are available for download. Please consider submitting to the archive some clay images from your personal collection. Contact Steve Hillier at [s.hillier@macaulay.ac.uk](mailto:s.hillier@macaulay.ac.uk) or Ray Ferrell at [rferrell@lsu.edu](mailto:rferrell@lsu.edu).



Fibrous sepiolite from Eskisehir, Turkey. PHOTO M. ROE, MACAULAY INSTITUTE, ABERDEEN, UK



Dioctahedral smectite from Yucca Mountain, Nevada, drill hole UE25a#1 at a depth of 1292.2 feet. Field of view ~28  $\mu$ m. PHOTO STEVE CHIPARA, LOS ALAMOS NATIONAL LABORATORY

## TRIBUTE TO RICHARD L. HAY

The geological and archaeological sciences suffered a sad loss in February 2006, when Richard L. Hay passed away after a short illness. Perhaps best known for his study of the geological record of Plio-Pleistocene environmental change in the Olduvai Gorge and nearby Laetoli in northern Tanzania, Richard Hay worked closely for many years with Mary D. Leakey, developing an understanding of paleoenvironments and hominid activities. He wrote numerous articles on zeolites, clay minerals, and the diagenesis of volcanoclastics, demonstrating the importance of petrographic and mineralogical analyses in paleoenvironmental reconstruction.

Dick received his PhD from Princeton University in 1952 and taught in the Department of Geology and Geophysics at the University of California Berkeley until 1983. He was the Ralph E. Grim Professor of Geology at the University of Illinois at Urbana until 1997. Dick spent the last years of his life in Tucson, actively pursuing research through the University of Arizona, including the study of the tuff building stones and pozzolanic mortars of ancient Rome. In the foreword to Dick's *The Geology of the Olduvai Gorge* (University of California Press, 1976), Mary Leakey wrote, "The picture now seems so complete and is presented so clearly and precisely that one has the impression that pieces fit neatly and effortlessly together at the right places and at the right times, but this was seldom the case..." Those of us fortunate enough to have worked closely with Dick remember his exacting, thorough research methods; the sound reasoning that



Richard L. (Dick) Hay (left) pictured with friend and colleague Desmond Clark at Olduvai Gorge. IMAGE COURTESY OF L. HALL

he brought to scientific puzzles; his unabashed delight (and subsequent caution) at a new discovery; and his patient, meticulous collection and critical evaluation of data.

Dick was a geologist's geologist. Immersing himself in rigorous field work on three continents, he made countless important observations and contributions to archaeological geology, low- and high-temperature geochemistry, geochronology, geomorphology, igneous petrology, limnogeology, mineralogy, sedimentology, and volcanology.

Mary Leakey wrote, "The following lines from Emerson truly reflect Richard Hay's contribution: 'What is originality? It is being one's self and reporting accurately what we see.'" Dick's publications will long stand as models of originality and fine-scale precision for future researchers. As a modest, reliable, and generous colleague and friend, he will be sorely missed.

**Marie Jackson**

Department of History, Northern Arizona University

## ACTINET WORKSHOP "CHARACTERIZATION OF SOLID-WATER INTERFACE REACTIONS OF METALS AND ACTINIDES ON CLAYS AND CLAY MINERALS"

The 3<sup>rd</sup> European Workshop of Clay Geosciences was held March 14–15, 2006, in Jena, Germany. The workshop, "Characterization of Solid-Water Interface Reactions of Metals and Actinides on Clays and Clay Minerals," was hosted by the Geosciences Department at the University of Jena. Its objectives were to give graduate students a broad overview and in-depth training in the most recent advanced analytical approaches and techniques in the field of actinide and clay interaction. The training also provided the students with motivation and possibilities to remain in this field of science. Andreas Bauer of Forschungszentrum Karlsruhe, Institut für Nukleare Entsorgung, Germany, organized the workshop with funding from ACTINET, the European Network of Excellency dedicated to actinide sciences. There is great interest in this field of research, as displayed by the more than 40 applications received to attend the workshop.

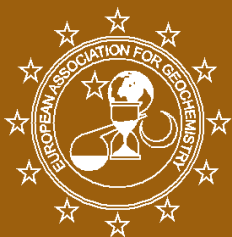
Nine speakers gave presentations to an audience of approximately twenty Earth science and chemistry graduate students from across Europe (Sweden, Great Britain, France, Slovakia, Switzerland, and Germany). After a general introduction, one portion of the talks highlighted cutting-edge experimental techniques used to characterize clay minerals and their interaction with aqueous actinides; methods discussed included EXAFS, XRD, TRLFS, STXM, and X-ray reflective spectroscopy. Another set of talks focused on related modeling tech-



niques: thermodynamic surface complexation modeling, free energy minimization, and atomistic simulation.

Overall, the workshop was conducted in a good-humored atmosphere and provided an excellent forum for discussion and feedback among all participants. The texts of the workshop lectures can be downloaded at: [www.igw.uni-jena.de/ahgeol/Workshops/actinet.html](http://www.igw.uni-jena.de/ahgeol/Workshops/actinet.html)

**Jeffery Greathouse**  
Sandia National Laboratories



www.eag.eu.com

## European Association for Geochemistry

### EAG NEWS AND ANNOUNCEMENTS

#### 16<sup>th</sup> Annual V.M. Goldschmidt Conference 2006



The 2006 V.M. Goldschmidt Conference is to be held 27 August to 1 September at the Melbourne Convention Centre, Melbourne, Australia. This marks the first time this meeting will be held in the Southern Hemisphere. Australia's unique, plate-scale natural laboratory will form the backdrop for the presentation of new ideas on a diverse range of geochemical topics. State-of-the-art conference facilities will provide us with

an unparalleled occasion to enjoy stimulating science, some of the finest wines and dining opportunities, and a gateway to the wealth of Australia's geological record.

Please join us in Melbourne for what promises to be an exciting conference. Information about the meeting can be found at its website [www.goldschmidt2006.org/](http://www.goldschmidt2006.org/)

#### Recent Chemical Geology Special Issues

*Chemical Geology* is the official journal of the European Association for Geochemistry. Members of the EAG can subscribe to *Chemical Geology* at discount member rates. *Chemical Geology* publishes both top-rate manuscripts in all areas of geochemistry and regular special issues on emerging and/or hot topics in our field. Information on the two most recent special issues follows.

**Solid Solutions: From Theory to Experiment**, edited by Udo Becker and Manolo Prieto (volume 225, issue 3–4, pages 173–410, 31 January 2005). The underlying scheme of this special issue is how the combination of computational sciences and laboratory experiments can lead to a comprehensive understanding of thermodynamic, structural and other physicochemical properties of solid solutions. To achieve this goal, contributions were invited from experts in the field to obtain a complementary collection of papers. This special issue explores the shortcomings of the present state of knowledge and outlines the challenges for future research. For example, theoreticians will need more thermodynamic data from experimentalists to verify their computational data, and advances in theoretical work will have to be based on accurate quantum mechanical calculations. Experimentalists studying solid solutions have made great progress in understanding ordering processes at smaller and smaller scales, leading to an exciting future for research in this field.

**Special Issue in Honour of R. K. O'Nions**, edited by Gideon M. Henderson, David R. Hilton and Derek Vance (volume 226, issue 3–4, pages 77–352, 28 February 2006). This volume marks Keith O'Nions' 60<sup>th</sup> birthday and contains contributions from scientists who have worked closely with Keith over the years. The issue presents a suite of sixteen research articles from top international geochemists and focuses on the evolution of geochemical systems ranging from soils to the Earth's mantle.

### THIRD INTERNATIONAL WORKSHOP ON HIGHLY SIDEROPHILE ELEMENT GEOCHEMISTRY



The 3<sup>rd</sup> International Workshop on Highly Siderophile Element Geochemistry will be held at Durham University, UK, 5–7 July 2006. Session themes range from low-temperature processes and

environment/health issues to meteorites, planetary accretion, and core formation. The conference is organised by Ambre Luguet, Graham Pearson and David Selby (Durham), together with Abdelmouhcine Gannoun (The Open University) and Bernhard Peucker-Ehrenbrink (WHOI). For details, see [www.dur.ac.uk/earth.sciences/conferences/](http://www.dur.ac.uk/earth.sciences/conferences/) or e-mail [highly.siderophile@durham.ac.uk](mailto:highly.siderophile@durham.ac.uk)

### EXTENDED ABSTRACTS OF THE 7<sup>th</sup> SYMPOSIUM ON THE GEOCHEMISTRY OF THE EARTH'S SURFACE (GES-7) NOW AVAILABLE

The 103 extended abstracts presented during the 7<sup>th</sup> Symposium on the Geochemistry of the Earth's Surface (GES-7) at Aix-en-Provence, France, August 23–27, 2005 have been published as a special issue of the *Journal of Geochemical Exploration* (volume 88, issue 1–3, January–March 2006). This extended abstract volume was edited by Jean Dominique Meunier, Catherine Keller, Olivier Radakovitch and Jérôme Rose. The GES meetings focus mainly on processes operating at the surface of the Earth rather than on deep crustal geochemical processes. The GES-7 meeting placed particular emphasis on the multiscale environmental

biogeochemistry of the Earth's surface. Abstracts from the meeting cover the following six themes: (1) Environmental impact of waste management; (2) Water cycle and resources: geochemical tracers and contaminants; (3) Biogeochemical processes in soils and ecosystems: from molecular to landscape scale; (4) Weathering: processes, rates and age; (5) Coastal biogeochemistry: from land to continental slope; and (6) Global element cycles and climate change through Earth history (in honor of Prof. Fred Mackenzie). The next meeting in this series (GES-8) will be organised by Mark Hodson and held in England during 2008.

### CALL FOR NOMINATIONS FOR EAG OFFICERS

The European Association for Geochemistry (EAG) is calling for nominations of dynamic, visible, and motivated geochemists for the posts of Councilor and of Vice President. One Vice President and up to five new Councilors will be named this year. The starting term of each post is **1 January 2007**. EAG Councilors normally serve for a three-year term. The post of EAG Vice President is a six-year commitment, the first two serving as Vice President, the second two years as President, and the final two years as Past President. Duties of EAG officers include participating in semi-annual council meetings, developing new programs to serve the European geochemical community, and contributing to EAG committees.

Nominations, including a curriculum vitae of the nominee, should be sent to either **Susan Stipp** ([stipp@geol.ku.dk](mailto:stipp@geol.ku.dk)) or **Philippe Van Cappellen** ([pvc@geo.uu.nl](mailto:pvc@geo.uu.nl)).

## European Geochemical News Briefs

### NEW DANISH RESEARCH PROGRAM APPLYING NANOTECHNOLOGY TO IMPROVE OIL RECOVERY

A new research program, sponsored by the Danish National Advanced Technology Fund, aims at increasing interplay between industrial development and academic research. It recently offered support to a joint venture between Copenhagen University (KU) and Mærsk Olie og Gas AS (Maersk Oil). The five-year effort, with a total research value of 60 million Danish kroner (8 million; \$10 million) will combine investigations of fundamental physical and chemical processes with innovation, with the goal of developing a product or a process that will improve ultimate oil production from chalk reservoirs. The venture, "Improving Oil Recovery through Nanotechnology: A New Approach to an Old Challenge," will combine the expertise of a diverse team, including physicists, chemists, molecular biologists, geologists, mineralogists and engineers. "We have a super group of people and a unique opportunity to apply absolutely fundamental research to a very practical problem," says the project leader Susan Stipp, who describes herself as a NanoGeoScientist.



Oil platform, North Sea, Mærsk Olie og Gas AS

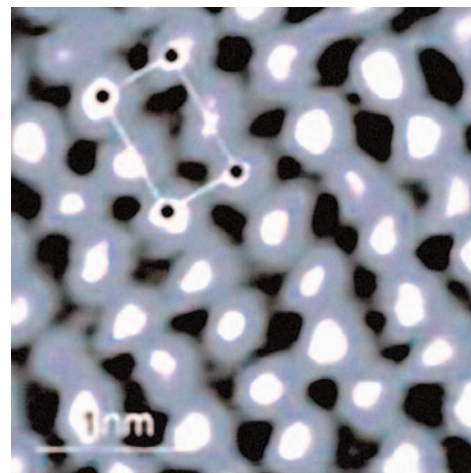
Current methods for extracting oil from chalk leave behind from 25% to as much as 75% of the oil in some oil fields. It remains as small droplets in pore spaces or as thin films on particle surfaces. This oil cannot be recovered at present, but if a method could be developed to extract even some of it, then the economic impact would be significant. "It would give us a few more years of hydrocarbon reserves to allow development of alternative, more sustainable energy forms," says Susan Stipp.



A coccolithosphere is produced by some species of marine algae, in this case, *Emiliania Huxleyi*. These one-celled, photosynthetic organisms cover themselves with disc-shaped coccoliths. Each of the spokes in the wheel is an individual calcite crystal. The sphere is about 10 micrometers in diameter. Chalk is made up predominantly of coccoliths. PHOTO YOUNG AND HENRIKSEN

Trapped oil has driven 30 years of chalk research, and although relationships among residual oil, particle size, wetting, mineral character and sediment compaction are defined, fundamental controls on chalk-oil interaction remain relatively unknown. Nanotechnology is revolutionising our understanding of complex systems in other fields; it also has promising potential for improving oil recovery.

The Nano-Chalk team will attack this old problem with the most advanced methods. Molecular-scale studies of chalk will identify the key parameters defining surface properties, and then nanotechnology will allow design of methods to modify particle surfaces to release more oil. The fundamental understanding of calcite properties is expected to generate spin-off projects on other aspects of calcite behaviour and application. Examples are improved environmental safety with groundwater resources and waste disposal, and more efficient production of fillers and pigments for paper, paint and pharmaceuticals. The work will lead to new paths to follow in the quest for



An atomic force microscope (AFM) image from the end of one of the spokes. The unit cell is  $5 \text{ \AA} \times 8.1 \text{ \AA}$ , indicating a {104} calcite surface. A set of AFM images can be used to define orientation, so we know the spokes are crystals with scalenohedral form. PHOTO HENRIKSEN AND STIPP

understanding biomineralisation, which is a key in designing new treatments for kidney stones, arthritis and osteoporosis.

As a result of the project, facilities will be added to an instrument park and positions will be offered to at least nineteen young scientists, starting from early fall 2006. "The Nano-Chalk venture is a positive, new partnership we have established with Maersk Oil, which I see as important for the broadening of both research and teaching in nanotechnology," says the leader for Copenhagen University's Nano-Science Center, Professor Thomas Bjørnholm.

**Please send any news items for inclusion in future 'European Geochemical News Briefs'**

to Eric Oelkers  
(oelkers@lmtg.obs-mip.fr)

MEMBERSHIP INFORMATION:  
[www.eag.eu.com/membership.html](http://www.eag.eu.com/membership.html)



**August 19 to 24, 2007**  
**Cologne, Germany**  
[www.goldschmidt2007.org](http://www.goldschmidt2007.org)



[www.minsocam.org](http://www.minsocam.org)

## Mineralogical Society of America

### EARLIEST LIFE AND NEW ENERGY SOURCES IN MAY/JUNE AMERICAN MINERALOGIST

The May/June 2006 issue of *American Mineralogist* features "The structure and distribution of carbon in 3.5 Ga Apex chert: Implications for the biogenicity of Earth's oldest putative microfossils," by Bradley T. De Gregorio and Thomas G. Sharp, and "Stabilizing of methane hydrate and transition to a new high-pressure structure at 40 GPa," by Hisako Hirai, Shinichi Machida, Taro Kawamura, Yoshitaka Yamamoto, and Takehiko Yagi, as well as our usual mix of current research on Earth and planetary materials.

If the carbonaceous, microbe-like features preserved within a single chert unit of the 3.5 Ga Apex Basalt are biogenic, then they represent some of the earliest known life on this planet. Until recently, these microbe-like features (along with a few others) have been generally accepted as strong evidence for 3.5 Ga life on Earth. However other researchers have proposed that an as-yet-unidentified organic Fischer-Tropsch-type (FTT) synthesis reaction could have produced the carbon in the microbe-like features abiotically. To shine light on this topic, De Gregorio and Sharp used TEM imaging, diffraction, and EELS to characterize the distribution, structure, and bonding of carbonaceous material in samples of Apex chert to constrain its possible origins.

Meanwhile Hirai et al. are studying the creation and structure of a possible new energy source. As they explain, knowledge of the stability and structural changes of methane hydrate under a wide range of pressure-temperature conditions is required to overcome humankind's urgent problems of dwindling energy resources and global warming, as well as to answer fundamental questions about the internal structure and evolution of icy planetary bodies. Methane hydrate, called fiery ice, is expected to be a clean and productive energy resource, while methane is a greenhouse gas even more potent than carbon dioxide.

Readers can click on "View Future Titles" on the GeoScienceWorld (GSW) site (<http://ammin.geoscienceworld.org>). Nonsubscribers can view all tables of contents and abstracts and then ask their libraries to join! As the Future Titles list is generated from data the authors input when submitting their material (<http://minsocam.allentrack.org>), please be aware that the simple html code used doesn't show any special characters and that titles and even authors, or the order of authors, may certainly have changed by the time the final version of the article is published.

**Rachel A. Russell**, Managing Editor  
*American Mineralogist*  
[russell@minsocam.org](mailto:russell@minsocam.org)

**VOTE**  
**2006 MSA ELECTIONS**

### NOTES FROM CHANTILLY

- MSA will have electronic balloting for the 2006 election of 2007 MSA officers and councilors. The candidates are: Barb Dutrow for president; Jonathan Stebbins and Peter Heaney for vice president; John M. Hughes for treasurer, and Jay Bass, Klaus Mezger, Jean Morrison, and John Parise for the two councilor positions. Also on the ballot will be the addition of Sustaining Member and Sustaining Fellow Member as new member types. These are open to any new or continuing member or fellow. The cost of a sustaining membership will be the cost of member dues plus an additional amount, to be determined by MSA Council. The additional amount will be a gift to the Society and will be placed in the Society's Endowment Fund.
- MSA members will receive a message containing voting instructions at their current e-mail addresses in May. Make sure MSA has your most recent e-mail address! Those who do not wish to vote online can request a paper ballot from the MSA business office. As always, the voting deadline is August 1.

The individuals elected to office decide on the direction of the Society. Voting is an important job for all MSA members.

- On February 9–12, 2006, the MSA had a booth at the Tucson Gem and Mineral Show, Tucson, AZ. MSA also exhibited at the joint assembly with AGU, Baltimore, MD, on May 24–26, 2006. MSA will have a booth at the GSA meeting, in Philadelphia, PA, on October 22–25, 2006. During that week, MSA will hold its awards lunch, the MSA Presidential Address, a joint MSA-GS reception, its annual business meeting, a council meeting, and breakfasts for the past presidents and associate editors of *American Mineralogist*. This will be the second year that the Roebling Medalist and the MSA Awardee give a lecture at the GSA meeting. This year's Roebling Medalist is Gary Ernst and the MSA Awardee is Daniel Frost. More information is available through the MSA website.

**J. Alex Speer**,  
MSA Executive Director  
[j\\_a\\_speer@minsocam.org](mailto:j_a_speer@minsocam.org)

Mineralogical Society of America – Geochemical Society  
**Short Course**  
**Water in Nominally Anhydrous Minerals**  
Verbania Italy • October 1-4, 2006  
Organizers: Hans Keppler, *Bayerisches Geoinstitut* and Joseph R. Smyth, *University of Colorado*  
an overview of all aspects of water in nominally anhydrous minerals and about water in the interior of the Earth  
For more information about the course and for registration, see <http://www.verbania.bgi.uni-bayreuth.de/>. Registration deadline is June 15, 2006.  
Sponsored by the Bayerisches Geoinstitut, Deutsche Mineralogische Gesellschaft, Geochemical Society, Mineralogical Society of America, and the United States Department of Energy

### IN MEMORIAM

**Eugene C. Robertson** (Life Fellow - 1947)  
**G. D. Robinson** (Life Fellow - 1944)

## ABOUT COPYRIGHT

Authors who publish in Mineralogical Society of America (MSA) publications are asked to assign the copyright to MSA. This applies to *American Mineralogist*, the *Reviews in Mineralogy and Geochemistry*, and, because MSA has the legal responsibility for this magazine at the moment, *Elements*. This requirement appears in the MSA bylaws approved by vote of the membership in 1972. According to notes by H.S. Yoder, the provision was modeled after the American Chemical Society bylaws. However, MSA authors have the right to make a nonprofit or noncommercial use of their work provided they indicate where the writing was first published. Authors who wish to make a profit or authorize for-profit or commercial use of their writing must first obtain the written consent of the Society. Works by government employees done as part of their job cannot be copyrighted.

### Why Does MSA Require the Copyright of an Article?

The most obvious reason for obtaining copyright is so MSA can publish the articles—not only immediately, but also in the future in new ways not yet imagined. Because of this ownership, MSA was able to post back issues of *American Mineralogist* on its website. If MSA had not owned the copyright, it would have had to seek permission for every article from its authors. Aside from the large clerical task of such an undertaking, it is certain that a percentage of the authors could no longer have been located. This means those articles could not have been made available. Additionally some authors would have passed away. MSA would have had the legal challenge of locating the heirs now owning the copyright, many of whom would know little about scientific publishing. They would either deny permission outright because they would not understand what was being asked, or expect lucrative payments. In effect, those publications would be lost to science until the

copyright protection expired. The end result would be gaps in the electronic availability of the journal online. In addition, rather than being free as at present, MSA would need to charge for access to back issues in order to recoup the costs of all the clerical and legal work.

The other reason MSA seeks to own the copyright is as a service to the science. Anyone seeking permission to reproduce an article, figure, table, etc. from MSA publications can simply ask MSA, and we are easy to locate. You can even ask permission online (the "Copyright Permission" link on the MSA homepage). When MSA receives a request, we look to see if the use is reasonable and if MSA actually does own the copyright. In a few cases MSA publishes material from other publications and, while we would have obtained permission to publish the material in question, such permission would not extend to others to do so as well. Once we are satisfied as to the request, we send a letter that the author can provide to his new publisher.

For authors of textbooks or reference works using large amounts of material from MSA publications, MSA's copyright policy makes their work of getting permission much easier. For example, a major amount of material from MSA publications was reproduced in each volume of the new editions of Deer, Howie, and Zussman. It is difficult to imagine the challenge it would have been to locate and correspond with all those authors whose material was used. If authors retained copyright, the obtention of permission to reproduce work for textbooks would have necessitated locating the authors or their heirs. There would certainly be some instances where this would not be possible. This would leave the alternatives of publishing without permission or not using the material at all. The material would be largely lost to science until the copyright expired.

Lately there has been talk of not copyrighting scientific papers at all. The imprudence of this approach would become immediately apparent once someone other than the author makes financially profitable use of the articles, or the article is used in a way the author would not want.

**J. Alex Speer**

## FIFTY- AND TWENTY-FIVE-YEAR MSA MEMBERS

Many MSA members will reach 50 or 25 years of continuous membership in the Society during 2006. Their long support of the Society is appreciated. The members whose names are listed below are recognized and received their 25- or 50-year pins mailed in early January. If you should be on this list and are not, or have not received your pin, please contact the MSA Business Office.

### 50-year members

Dr. Paul B. Barton  
Dr. Werner H. Baur  
Dr. Bruce H. Bryant  
Prof. Carlo Maria Gramaccioli  
Dr. Daniel J. Milton  
Dr. Ernest H. Nickel  
Dr. Hugo Steinfink  
Dr. Ichiro Sunagawa  
Dr. Priestley Toulmin  
Dr. Karl Hans Wedepohl  
Dr. Gunther A. Wolff

### 25-year members

Dr. Lawrence M. Anovitz  
Dr./Prof. Makoto Arima  
Dr. Andrew C. Barnicoat  
Dr. Michael A. Carpenter  
Dr. Christian Chopin  
Mr. John P. Clinkenbeard  
Dr. Mark Cloos  
Dr. Randall T. Cygan  
Dr. Russell J. Hemley  
Dr. Takao Hirajima  
Dr. Anne M. Hofmeister  
Dr. Kurt T. Hollocher  
Dr. Neil E. Johnson  
Mr. Tetsuya Katayama  
Dr. Stanley Korzeb  
Dr. Andreas K. Kronenberg  
Dr. Francisco Lopez-Aguayo  
Prof. Hans-Joachim Massonne  
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Dr. Richard J. Reeder  
Dr. Michael P. Ryan  
Dr. LeeAnn Srogi  
Dr. Helge Stanjek  
Dr. E. Volkmar Trommsdorff



## Medical Mineralogy and Geochemistry

**MSA/GS Short Course  
December 8-10, 2006  
Menlo Park, California**

**Organizers—** Dr. Nita Sahai, University of Wisconsin-Madison, Dr. Martin Schoonen, Stony Brook University.

**Sponsors—** Mineralogical Society of America, Geochemical Society, US Geological Society, National Science Foundation, and US Department of Energy.

More information: [www.minsocam.org/MSA/SC](http://www.minsocam.org/MSA/SC)



www.mineralogicalassociation.ca

## Mineralogical Association of Canada

### NOMINATIONS TO COUNCIL FOR 2006

The Nominating Committee, headed by Dr. Norm Halden, submitted the following slate of candidates for 2006. In accordance with our by-laws, as no additional nominations were submitted, these candidates have been declared elected by acclamation. Their term of office started at the May council meeting. Our heartfelt thanks to outgoing councilors Cliff Shaw and André Lalonde, past president Norm Halden, and long-time treasurer Mati Raudsepp.



#### VICE PRESIDENT

**Peter C. Burns** received a BSc (honours) in geology from the University of New Brunswick in 1988, an MSc in geology from the University of Western Ontario in 1990, and a PhD in geology from the University of Manitoba in 1994. He began his studies of uranium minerals at the

University of New Mexico as a postdoctoral fellow in 1995 and 1996. He joined the faculty of the University of Notre Dame in 1997 and is currently professor and chair of the Department of Civil Engineering and Geological Sciences. Burns has authored or coauthored more than 200 journal papers concerning mineralogy and solid-state chemistry. He was awarded the Hawley Medal of the Mineralogical Association of Canada in 1997, the Young Scientist Award of the Mineralogical Association of Canada in 1998, the Donath Medal of the Geological Society of America in 1999, and the Mineralogical Society of America Award in 2001. He was a council member of the Mineralogical Association of Canada from 1998 to 2005, served as an associate editor of *The Canadian Mineralogist* from 1998 to 2004, served as an associate editor of *American Mineralogist* from 2001 to 2005, is a member of the Advisory Board of *Elements*, and was the editor of *Reviews in Mineralogy* volume 38 in 1999. He is married to Tammy, and they have a son, Kelson Owen, and a daughter, Sarah Victoria.



#### TREASURER

**Martine M. Savard** graduated from Laval University in geological engineering in 1983 and obtained her master's degree in 1986 from Laval University. She received her PhD in 1991 from the University of Ottawa, where she specialized in stable isotope geochemistry. She joined the

Geological Survey of Canada (GSC) in 1990 and applied her expertise in carbonate petrography and geochemistry to the study of dolomitization in the context of carbonate-hosted Pb-Zn deposits. In 1997, she became leader of large projects dealing with environmental issues. These projects concerned the sustainable development of groundwater resources in the St. Lawrence Lowlands of southwestern Quebec and the distinguishing of natural and anthropogenic metal accumulations in the vicinity of smelters using trees as archival systems. Martine is pursuing her research on the sustainable development of groundwater, but recently she has begun working on climate change issues, including paleoclimate reconstruction and evaluation of the impact of atmospheric pollutants on CO<sub>2</sub> uptake by exposed forest stands.



#### SECRETARY

**David Fowle** completed his PhD in 1999 in the field of biogeochemistry at the University of Notre Dame. He then moved on to a postdoctoral fellow position at the University of Wisconsin-Madison from 1999 to 2000. After spending five years at the University of Windsor, where he was appointed Canada Research Chair in biogeochemistry, David moved in 2006 to the Department of Geology at the University of Kansas. David's research interests include quantitative geochemical modeling of bacteria-metal sorption reactions, biomineralization and its effects on contaminant mobility in the subsurface, bioavailability of trace metals in aquatic ecosystems, microbially promoted mineral dissolution, and biogeochemical interactions in wetlands and soil systems.



#### COUNCILORS

**Marc Constantin** received a BSc and an MSc in geology from Université Laval and obtained a PhD in marine geosciences from the Université de Bretagne Occidentale, France. He was a postdoctoral fellow at the University of Toronto and at Laurentian University and was appointed assistant professor at Université Laval in 2000. His research interests include the petrology, geochemistry, and metallogenesis of magmatic Ni-Cu-PGE deposits in mafic-ultramafic intrusions. He has also worked on the petrogenesis of crustal and mantle rocks at mid-ocean ridges and in ophiolites. He has set up a neutron activation laboratory for the determination of trace amounts of Au, Ir, Ni, Cr, REE, Hf, Ta, Th, and several other elements. Marc was the 2005 president of the Quebec section of the CIMM, where he has been particularly active at providing opportunities for students to interact with professionals from the public and private sectors.



**James Mungall** graduated with a BSc in geology from the University of Waterloo. He did his MSc and PhD in igneous petrology under Robert Martin's guidance at McGill University, studying the petrogenesis of shoshonitic intrusions in the Grenville Province and, later, of peralkaline ocean island rhyolites in the Azores.

Six years of attempting to answer questions about magmatic processes by looking at old rocks convinced him that he should try to understand magma chemistry and physics in the laboratory. After two years of experimental investigations of the transport properties of silicate melts at the Bayerisches Geoinstitut in Germany, Jim found himself back in Canada in the summer of 1996 looking for nickel deposits in northern Quebec. In 1999, Jim found a place where he could combine his passion for field work with experimental petrology and teaching at the University of Toronto.



**Paula Piilonen** received her BSc (Honours) in 1993 from Laurentian University and her PhD (in mineralogy) in 2001 from the University of Ottawa. After her PhD studies, she completed an NSERC-funded postdoctoral fellowship at the Laboratoire des géomatériaux, Université de Marne-la-Vallée, France, in 2002. Paula is currently working as a research scientist in the Mineral Sciences Division at the Canadian Museum of Nature. Her research is focused on the mineralogy, petrology, and geochemistry of alkaline igneous and hydrothermal systems. Paula is a regular sessional lecturer in the Department of Earth Sciences at the University of Ottawa, where she teaches second- and fourth-year mineralogy courses. She is also the New Mineral Editor for *American Mineralogist*, the Canadian representative on the IMA's Commission on Museums, and co-chair of the 2008 Canada-Wide Science Fair Host Committee.



**James Scoates** received his BSc (Honours) from Queen's University in 1987 and his PhD from the University of Wyoming, USA, in 1994. In 1995, he took up a professorship at the Université Libre de Bruxelles in Brussels, Belgium, where he taught for seven years in the Département des Sciences de la Terre et de l'Environnement. Since 2002, James has been an associate professor in the Department of Earth and Ocean Sciences at the University of British Columbia. He also plays a major role in managing the Pacific Centre for Isotopic and Geochemical Research. The research interests of James and his students are focused on better understanding the differentiation processes in silicate magmas and how they affect magma compositional variability, magma dynamics, and mineralization potential.



## THE MINERALS OF CANADA POSTER

The bilingual *Minerals of Canada* poster is the latest outreach project of the Mineralogical Association of Canada. Printed last September, it looks simple enough: a poster with pretty mineral pictures. But in fact, this poster is the result of an extraordinary collaboration of outreach activists and museum curators. Several generations of mock-ups were developed to reach the final version, which shows the minerals surrounding a schematic map of Canada. The project started in 2001 when MAC was encouraged by Jerome Remick III to develop a Canadian minerals poster targeting K-12 school children and their teachers. Jerry had developed a beautiful mineral poster for Quebec a few years before, and he felt that we needed one for Canada and that the Mineralogical Association of Canada was the group to do it. He also encouraged us to submit a proposal for funding to the Canadian Geological Foundation.

Common rock-forming minerals, mineral emblems of the provinces and territories, and attractive well-formed crystals were chosen to illustrate the mineral wealth of Canada. The poster illustrates minerals representative of each province, minerals of economic significance to the provinces, and minerals from key collecting localities. Pictures were provided by the Canadian Museum of Nature, the Royal Ontario Museum, the Ministère des Ressources naturelles et de la Faune du Québec, the Atlantic Geoscience Society, and several companies and individuals. Members of the Canadian Geoscience Education Network (CGEN), museum curators, council members of the Mineralogical Association of Canada, and teachers were consulted extensively to define the content.



Even though nothing will ever replace the excitement of handling real minerals in the classroom (we encourage all teachers to get a mineral collection for classroom activities), we hope that our poster will spark interest and be used as a tool for introducing the unit on rocks and minerals in the classroom.

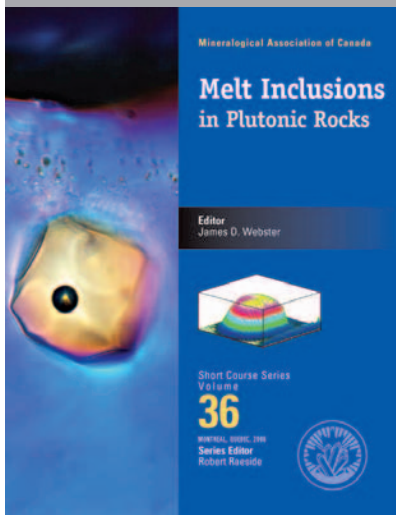
More than 15,000 copies have been distributed to teachers and their students via outreach

groups across the country, such as the EdGEO workshops and the Mining Matters program of the Prospectors and Developers Association. A web page offers complementary information at [www.mineralogicalassociation.ca/poster](http://www.mineralogicalassociation.ca/poster).

**Pierrette Tremblay**

## MELT INCLUSIONS IN PLUTONIC ROCKS

MINERALOGICAL ASSOCIATION OF CANADA SHORT COURSE VOLUME 36



ISBN 0-921294-36-0  
248 pages  
US\$40 (outside Canada)  
CAN\$40 (in Canada)

EDITOR  
**James D. Webster**

Short course volume 36 provides an accurate account of the current state of knowledge about melt inclusions in plutonic rocks. The volume discusses means to ensure high-quality melt inclusion research, provides practical methods to evaluate and investigate melt inclusions, describes important new analytical techniques and useful examples of their application to natural systems, and summarizes current understanding of plutonic systems ranging from basaltic to rhyolitic in composition.

### Table of Contents

- Melt inclusions in plutonic rocks: Petrography and microthermometry – R.J. Bodnar, J. Student
- Application of secondary ion mass spectrometry to the determination of traditional and non-traditional light stable isotopes in silicate melt inclusions – G.D. Layne
- In situ* laser ablation-ICP-MS chemical analysis of melt inclusions and prospects for constraining subduction zone magmatism – T. Pettke
- Melt inclusion record of magmatic immiscibility in crustal and mantle magmas – V.S. Kamenetsky
- Crystallized melt inclusions in gabbroic rocks – I. Veksler
- Parental magmas of plutonic carbonatites, carbonate-silicate immiscibility and decarbonation reactions: Evidence from melt and fluid inclusions – I. Veksler, D. Lentz
- Magmatic processes and volatile phase generation in porphyry-type environments: A laser ablation – ICP-MS study of silicate and sulfide melt inclusions – W.E. Halter and C.A. Heinrich
- Silicate melt inclusions in felsic plutons: A synthesis and review – J.W. Webster, R. Thomas
- Understanding pegmatite formation: The melt and fluid inclusion approach – R. Thomas, J.W. Webster, P. Davidson
- Fluid and melt inclusions in the subvolcanic environments from volcanic systems: Examples from the Neapolitan area and Pontine Islands, Italy – B. De Vivo, A. Lima, V.S. Kamenetsky, L.V. Danyushevsky

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www.iagc.ca

## International Association of Geochemistry

### CHANGES AT THE TOP

Dr. John Ludden, the IAGC's current president, has announced that he intends to step down from this position due to his recent appointment as director of the British Geological Survey, a post he will take up this summer. The IAGC would like to thank John for his guidance in the past two years and wish him well in this prestigious position.

Another recent change has been the retirement, due to health reasons, of Dr. Robert A. Berner as Chairman of the IAGC Working Group Geochemistry of the Earth's Surface. Bob has asked that Prof. Sigurður Gíslason (sigrg@raunvis.hi.is), University of Iceland, take over the position.

**Mel Gascoyne**, Manager,  
IAGC Business Office Manager & Newsletter Editor

### THE IAGC'S 40<sup>th</sup> BIRTHDAY!

Next year, the IAGC will be 40 years old, having been founded in 1967 by Earl Ingerson and others. Our history and early beginnings were described in detail by past Secretary and Vice President Brian Hitchon (*Applied Geochemistry*, volume 1, pp. 7–14).

Plans are afoot to recognise the birthday in conjunction with the Goldschmidt Conference, to be held in Cologne, Germany, 19–24 August 2007. It has been decided that medal awards planned for 2006 will be deferred to this Goldschmidt meeting. Watch this space in the next issue of *Elements* for more details.

### UPCOMING IAGC-SPONSORED MEETINGS

#### Goldschmidt Conference

The 16<sup>th</sup> Annual Goldschmidt Conference will take place in Melbourne, Australia, from 27 August to 1 September, 2006. The IAGC is a cosponsor of this meeting, which is convened by the Geochemical Society and the European Association for Geochemistry. Conference themes include geochemical techniques, mineral deposits, the solar system, constraints on timescales, biogeochemistry, aquatic geochemistry, surface processes and ocean chemistry. Full details can be found at [www.goldschmidt2006.org](http://www.goldschmidt2006.org). Please note the following deadlines:

**30 June 2006** – Speaker registration deadline

**30 June 2006** – Early registration cut-off date

Through sessions organized by various committees, the Melbourne 2006 Goldschmidt Conference will provide a forum for open discussion of important issues. The conference should help us acquire fresh perspectives on future scientific requirements, set specific achievable goals, and discuss research opportunities. For a detailed summary of each theme, please refer to the website, [www.goldschmidt2006.org](http://www.goldschmidt2006.org)

**LOOK OUT FOR THE IAGC BOOTH  
AT GOLDSCHMIDT IN MELBOURNE!**

**COME BY AND PUT YOUR NAME IN FOR THE PRIZE DRAWS!**

### ISEG-7

The 7<sup>th</sup> International Symposium on Environmental Geochemistry is to be held (*note date change*) on 24–27 September, 2006, in Beijing, China. IAGC support is being provided for this meeting. The main themes at the conference will be geochemical records of change and contamination, geochemistry and health, fragile habitats (e.g. karsts), organic pollutants, coal, water resources, environmental management and analytical geochemistry. Advance registration must be made by 31 July 2006.

### IAGC-Sponsored Sessions at GSA 2006

The following thematic sessions have been proposed for the next Geological Society of America (GSA) meeting to be held in Philadelphia, 22–25 October 2006: "Geochemical Modeling Applications in Ground Water Systems," chaired by June Mirecki and Russell Harmon, and "Sources, Transport, Fate and Toxicology of Trace Elements in the Environment," chaired by LeeAnn Munk, David Long and W. Berry Lyons. Watch for details at the GSA website ([www.geosociety.org](http://www.geosociety.org)) later in the summer.

### APPLIED GEOCHEMISTRY UPCOMING PAPERS



Below are titles of some of the new papers that will appear in *Applied Geochemistry* in the next few months.

1. Spectroscopic investigation on the chemical forms of Cu during the synthesis of zeolite X at low temperature – R. Terzano, M. Spagnuolo, L. Medici, F. Tateo, B. Vekemans, K. Janssens, P. Ruggiero
2. Sources of groundwater nitrate revealed using residence time and isotope methods – K. B. Moore, B. Ekwurzel, B. K. Esser, G. B. Hudson, J. E. Moran
3. Estimation of potential pollution of waste mining dumps at Peña del Hierro (Pyrite Belt, SW Spain) as a base for future mitigation actions – A. Romero, I. González, E. Galán
4. Behaviour of boron and strontium isotopes in groundwater-aquifer interactions in the Cornia Plain (Tuscany, Italy) – M. Pennisi, G. Bianchini, A. Muti, W. Kloppmann, R. Gonfiantini
5. Elemental sulfur in drain sediments associated with acid sulfate soils – E. D. Burton, R. T. Bush, L. A. Sullivan
6. Fate of organic matter during aquifer storage and recovery (ASR) of reclaimed water in a carbonate aquifer – J. L. Vanderzalm, C. Le Gal La Salle
7. Evidence of precursor phenomena in the Kobe earthquake obtained from atmospheric radon concentrations – Y. Yasuoka, G. Igarashi, T. Ishikawa, S. Tojonami
8. Transport of Cd, Cu and Pb in an acid soil amended with phosphogypsum, sugar foam and phosphoric rock – C. G. Cambell, F. Garrido, V. Illera, M. T. García-González
9. Apparent seasonal variations in iron photoreduction in acidic discharge from a former pyrite mine, Oakland, California – T. W. Butler, J. C. Seitz
10. The applicability of accelerated solvent extraction (ASE) to extract lipid biomarkers from soils – B. Jansen, K. G. J. Nierop, M. C. Kotte, P. de Voogt, J. M. Verstraten
11. Partitioning and mobility of trace metals in the Blesbokspruit: Impact assessment of dewatering of mine waters in the East Rand, South Africa – A. N. Roychoudhury, M. Starke
12. Modelling spatial and temporal variations in temperature and salinity during stratification and overturn in Dexter Pit Lake, Tuscarora, Nevada, U.S.A. – L. S. Balistrieri, R. N. Temple, L. L. Stilings, L. A. Shevenall

**Ron Fuge**, Executive Editor  
*Applied Geochemistry*



[www.geochemsoc.org](http://www.geochemsoc.org)

## Geochemical Society

### NEWS AND NOTES FROM SAINT LOUIS

#### *Goldschmidt 2007 – Cologne, Germany*

19–24 August 2007

Preparations for next year's Goldschmidt Conference are already underway. Dr. Herbert Palme ([herbert.palme@uni-koeln.de](mailto:herbert.palme@uni-koeln.de)) is the conference organizer.

#### *Goldschmidt 2010?*

The GS Board of Directors will be examining North American bids for the 2010 Goldschmidt Conference during the 2006 annual board meeting on August 26, in Melbourne, Australia. If you, your university, or your city are interested in submitting a bid, please contact the GS business office at [gsoffice@geochemsoc.org](mailto:gsoffice@geochemsoc.org)

#### *GS Logo Contest*

Thank you to everyone who participated in the GS Logo Contest. We received nearly 140 entries. As of this writing, the selection committee has been narrowing down the field.

#### *GS at GSA Meeting & Exposition*

The GS Program Committee will be organizing a number of sessions at the 2006 GSA Meeting and Exposition to be held in Philadelphia, PA, from 22 to 25 October 2006. GS members qualify for discounted registration. GS will also have a booth at the exhibition.

#### *Elsevier Publication Discount*

Through an agreement with Elsevier, Geochemical Society members can take advantage of a 25% discount to the company's full line of books, including the paperback edition of the *Treatise on Geochemistry*. Order forms can be found either in *Geochemical News* or online at <http://gs.wustl.edu/join/elsevierbooks.pdf>

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### GEOCHEMICAL SOCIETY – RELATED QUESTIONS OR COMMENTS?

Send them to the Geochemical Society Business Office:

**Seth Davis**

Geochemical Society Business Manager

Washington University/EPSC

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### GOLDSCHMIDT 2006 – MELBOURNE AUSTRALIA

27 AUGUST–1 SEPTEMBER 2006

[WWW.GOLDSCHMIDT2006.ORG/](http://WWW.GOLDSCHMIDT2006.ORG/)

The Melbourne Goldschmidt Conference is fast approaching! The early registration deadline is **June 30, 2006**. Remember that GS and EAG members qualify for a substantial registration discount. If you are not already a member of GS or EAG, then please join before you register to take advantage of this member benefit.

With support from the National Science Foundation, the Geochemical Society will be awarding \$40,000 (US) in student travel grants for the Melbourne Goldschmidt Conference. Recipients will be recognized in the August issue of *Elements*.



### MEET THE GS MEDAL WINNERS

Preview Melbourne Goldschmidt

Have you ever wondered what happens to old tires?

Find out in the April issue of G.N.

### 2006 GEOCHEMICAL SOCIETY AWARD RECIPIENTS ANNOUNCED

#### V.M. Goldschmidt Medal

Susan Solomon (US National Oceanic & Atmospheric Administration, Boulder) [1]

#### F.W. Clarke Medal

Alexis Templeton (University of Colorado) [2]

#### C.C. Patterson Medal

Fred Mackenzie (University of Hawaii, Manoa) [3]

#### GS/EAG Fellows

William H. Casey (University of California, Davis) [4]

Bor-ming Jahn (Institute of Earth Sciences, Taipei) [5]

Brian N. Popp (University of Hawaii, Manoa) [6]

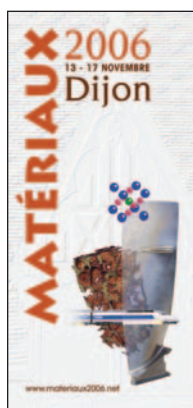
Jacques Schott (Laboratoire des Mécanismes et Transferts en Géologie, Toulouse) [7]





[www.sfmc-fr.org](http://www.sfmc-fr.org)

## Société Française de Minéralogie et de Cristallographie



### MATÉRIAUX 2006

The Société Française de Minéralogie et Cristallographie is one of a number of scientific societies in France. It has developed links with several of them and regularly participates in joint meetings where it sponsors symposia.

As a member of the Fédération Française des Matériaux (FFM), composed of 24 societies in materials sciences and physics, SFMC will participate in the **Matériaux 2006** meeting in Dijon, France, November 13–17, 2006 ([www.materiaux2006.net](http://www.materiaux2006.net)).

The SFMC is responsible for the organization of the following two sessions:

### Radiation Effects in Materials and Minerals

MICHEL BEAUVY (GFC), ETIENNE BALAN (SFMC), JEAN-LOUIS BOUTARD (SF2M)

This symposium aims to provide a better understanding of radiation effects in materials and minerals and their applications. Technological, experimental, and theoretical aspects will be addressed. Radiation effects are important in a particularly large number of research fields, including dating methods in Earth sciences and archeology, the generation of nuclear power (present and future nuclear plants, nuclear waste disposal), the design of nanostructured materials, and radiation dosimetry. Many different varieties of radiation can be used, corresponding to particles of various types and energy. Irradiated materials can be crystalline (ceramics, metals, etc.) or amorphous (glasses), and include inorganic and organic compounds. Because the effects of radiation damage range from the most subtle (low concentration of point defects) to the most devastating (amorphization), their investigation makes use of extremely diverse experimental and theoretical tools. The aging of the materials used in the core of nuclear power plants typically requires multiscale modeling methods. The symposium will also include an important contribution from the CPR project SMIRN (Simulation of Materials of Nuclear Plants and Installations) funded by EDF, CEA, and CNRS; subjects will range from the *ab initio* calculation of radiation-induced point defects to the crystal plasticity of Zr alloys and ferritic steels.

### Amorphous Materials: Properties, Structure and Durability

DANIEL NEUVILLE (SFMC), LAURENT CORMIER (SFMC), AND JEAN PHALIPPOU (GFC)

Glasses and melts play an important role in the formation and evolution of the Earth, in glass processing, and in the storage of nuclear wastes. The structure and properties of glasses and silicate melts are well known but some aspects remain poorly understood, such as the glass transition, glass durability, and the links between short- and medium-range order. Contributions to this symposium are invited on diverse aspects of glasses and melts, including their properties, structure, dynamics, and durability.

### RÉUNION DES SCIENCES DE LA TERRE 2006

SFMC is also the co-organizer, together with the Société Géologique de France, of the **Réunion des Sciences de la Terre (RST) 2006** meeting, in Dijon, December 4–8, 2006.

The RST meetings are usually attended by 500 to 800 scientists, including PhD students, postdocs, and experienced researchers. Originally, they were dedicated to the francophone scientific community. However, because of their enduring success, the audience has grown, so that nowadays, RST meetings are renowned opportunities for scientists from all over the world to meet and discuss their results and hypotheses. Furthermore, these meetings offer to young geologists the chance to meet industrial partners and find job opportunities.

The following sessions are organized by the SFMC:

### Hydrothermalism and Fluid–Rock Interactions

MARTINE BUATIER (UNIVERSITÉ DE BESANÇON), ANNE-MARIE KARPOFF (CNRS–UNIVERSITÉ LOUIS PASTEUR)

This session is open to contributions on the mineralogical and geochemical study of natural rocks, fluids and sediments, and on experimental data and modeling of continental and oceanic hydrothermal systems. Presentations dealing with the relations between (1) magmatic activity and hydrothermalism, (2) fluid flow and fluid–rock interaction, and (3) biology and hydrothermalism are welcome.

### Magmatic Processes

MONIQUE SEYLER (UNIVERSITÉ DE LILLE) AND PIERRE BARBEY (UNIVERSITÉ DE NANCY)

Heat and mass transfers originating in the convective mantle are important processes in the deep Earth. This session, organized around invited talks and oral and poster presentations, aims to bring together petrologists, analysts, and experimentalists to discuss recent progress in the field of kinetics of magmatic processes, from partial melting to magma emplacement at various levels in the crust.

Emphasis is on the following topics:

1. Characterization of natural phases (structures, physical properties, chemical gradients from crystal to outcrop scales, glass inclusions); quantitative approaches and new analytical techniques (in situ analysis, EBSD, image processing, etc.)
2. Experimental simulation (very low degrees of melting; nucleation and growth; deformation of magmatic suspensions) and extraction of thermodynamic data (equilibrium and non-equilibrium element partitioning, diffusion coefficients, etc.)
3. Numerical modeling of magmatic and eruptive processes and of thermal and seismic properties of partially melted material.

### Planets and Primitive Earth

FRANÇOIS COSTARD (CNRS–UNIVERSITÉ DE PARIS SUD) AND OLIVIER GRASSET (UNIVERSITÉ DE NANTES)

Comparative planetology requires complementary approaches, such as geophysics, petrology, sedimentology, geochemistry, climatology, and astronomy. The goal of this session is to gather people from these different fields in order to share recent discoveries and set up new scientific projects using a complementary approach. Planetary surface studies (morphotectonics, surface mineralogy, etc.), numerical modeling, and experimental work (climates, internal structures and dynamics, cosmochemistry) in relation to recent and ongoing space missions will be presented. Mars and Titan show similarities with primitive Earth. Thus, special attention will be given to studies related to the paleoenvironment of Earth and Mars and to the surface–interior interactions on Titan.

The full program of RST 2006 can be found on the meeting website:

<http://www.u-bourgogne.fr/RST-DIJON>



www.ima-mineralogy.org

## International Mineralogical Association



### FROM THE PRESIDENT

#### NEXT STOP KOBE

This issue of *Elements* will be the last before our 19<sup>th</sup> General Meeting in Kobe. It is a matter of great sadness that one of our longest-serving and most distinguished Councillors, Werner Schreyer, has recently died. A fitting tribute to Werner by Walter Maresch is published on this page.

The Kobe programme will, as usual, include two meetings of the council and two business meetings at which national representatives will be able to make their views known on the performance and future of IMA. Even in the four years since the last general meeting in Edinburgh, enormous changes have occurred in the way communication occurs between the members of scientific organizations. Scientific publishing is in a state of considerable turmoil. For IMA, *Elements* presents an unprecedented opportunity. Council has had preliminary discussions, by e-mail, on a number of initiatives to strengthen IMA in this fast-changing world. Some of these ideas are listed below, and we would welcome the input of IMA members in general.

A new position of Communications Officer should be created in Council, responsible for providing copy to *Elements* and for obtaining news material from member societies, commissions and working groups.

An IMA medal recognizing distinction in mineralogy should be instituted, with the aim of becoming the most prestigious international mineralogical award.

Commissions and working groups have contributed to the mineralogical community mainly by sponsoring sessions at meetings. Currently they are composed solely of individuals nominated by the national societies. We should consider opening membership to all members of IMA and making them in part international, electronically active newsgroups.

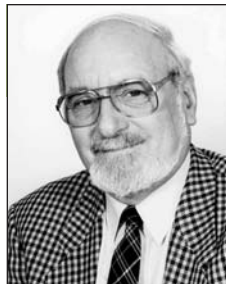
We need to consider co-organization of meetings with other mineralogical and geochemical organizations and to have a long-range meetings plan.

We must solve our problems with setting and collecting membership dues, a topic I discussed at length in *Elements* in February 2006.

In the long term, after our 2010 meeting in Budapest, we need to break the tradition that the chairman of the organizing committee of the general meeting automatically becomes president. The four-year period of presidency is too long. Before the meeting the president-elect is very busy and has little time to learn the ways of IMA. Afterwards, the new president relaxes, exhausted. I speak with personal experience here. The president of IMA should be a distinguished mineralogist, elected by the international community, and the position should not simply be an outcome of the success of a national bid to run a general meeting.

Please let me have your views on any of these topics. If IMA is supported by your national mineralogical organization, *IMA is your society*. I look forward to meeting some familiar faces in Kobe, and I wish the organizers the best of success in what promises to be an outstanding meeting.

**Ian Parsons**  
President



### IN MEMORIAM

#### Werner Schreyer (1930–2006)

IMA councilor Werner Schreyer passed away on February 12, 2006, after battling a particularly virulent type of cancer for a number of months. Werner calmly accepted the reality and the consequences of his illness. He drew solace from the fact that his life had been filled to the brim with the excitement of science, the pleasures of classical music and the company of his family, his friends and his colleagues he enjoyed so much. Werner is survived by his wife, Marianne, and their two sons, Andreas and Christoph.

From the very beginning of his professional career, Werner Schreyer viewed mineralogy from an international perspective. He was the first German fellow to join the Carnegie Institution in Washington after the war. His key role some 20 years later in the establishment of the Bayerisches Geoinstitut in Germany can be viewed as his tribute to this institution and its importance in the geosciences. Werner was a member of the IUGS Commission on Experimental Petrology at High Pressures from 1971 to 1992 and its chairman from 1971 to 1984. He was a member (1972–1984) and chairman (1976–1984) of the German National Committee for IUGS and IMA national representative for Germany (1990–1994). Werner took on the role of IMA councilor in 1994.

Werner Schreyer was an outstanding scientist of international stature. The presentation of the Roebling Medal by Peter J. Wyllie and the acceptance by Werner Schreyer (*American Mineralogist* 88: 936-939, 2003) provide wonderful and eloquent testimony to this. Originally trained in Munich as a hard-rock petrographer in the classical German tradition, Werner became one of the pioneers of experimental petrology in Germany after his fellowship at the Carnegie Institution. Big hammers, big samples and astute observation were his trademarks in the field. He combined his uncanny powers of perception and intimate knowledge of field relationships with precisely planned laboratory experiments to open new avenues of research. His approach must be considered the optimum marriage of field and laboratory work. Werner's impressive list of more than 250 publications spans a wide spectrum, including classical field work in structural geology and petrography, theoretical and experimental aspects of metamorphic petrology, and detailed crystal chemistry and mineral physics of a wide range of minerals and their experimental analogs. Many of these articles are seminal introductions to new directions in these fields. Those who read "Mr. Cordierite's" early papers on this mineral will note concepts of geospeedometry far ahead of their time. His early work in the MASH system later evolved into the foundations of ultrahigh-pressure metamorphism.

Werner Schreyer was a respected, effective and exciting teacher. With determination and energy, he and his team made the Institute of Mineralogy in the newly created Ruhr-University of Bochum one of the world's most distinguished departments. Werner expected hard work from those around him but led the way himself. More than ten of his graduates and co-workers have gone on to professorships elsewhere. Above all, Werner Schreyer was not only an exceptional scientist and teacher, but also a friend and a stimulating colleague.

Over the years, Werner's outstanding work has been recognized by many. He was particularly proud of the Roebling Medal awarded to him in 2002 by the Mineralogical Society of America, and considered this award to be a crowning tribute to his career. Prior to this, the German, Austrian and Belgian mineralogical societies had bestowed their corresponding highest honour on him as well. Honorary doctorates were awarded by the Universities of Hanover and Liège. Werner Schreyer was a member of six scientific, learned academies and Honorary Fellow of five international geoscience societies.

Werner was in the midst of a prolific and successful second career as emeritus professor. We will miss his youthful enthusiasm and his eagerness to learn. Mineralogy has lost one of its most prestigious post-war scientists.

**Walter Maresch**  
IMA National Representative for Germany



<http://aipea.org>

## International Association for the Study of Clays

*Association internationale pour l'étude des argiles*  
*International Association for the Study of Clays*  
*Internationale Vereinigung zum Studium der Tone*  
*Международная ассоциация по изучению глины*



David L. Bish

It is a great pleasure to join the increasing number of societies participating in *Elements*, and I hope this forum will foster increased collaboration between us. AIPEA is an international association consisting of the national clay societies of the world. It acts as an umbrella organization to coordinate and facilitate international activities and collaborations relating to clay mineralogy (much like IMA). AIPEA represents clay mineral societies from France, Czech Republic, Brazil, Mexico, Italy, Israel, South Korea, South Africa, Belgium, The Netherlands, Japan, Russia, Poland, Hungary, India, Spain, Romania, Australia, Columbia,

Yugoslavia, Turkey, Bulgaria, the United Kingdom and Ireland, Sweden, China, Germany, Portugal, and the USA. Broadly speaking, the aim of AIPEA is the worldwide promotion of international cooperation in clay research and technology. AIPEA accomplishes this by sponsoring the International Clay Conference (ICC) every four years. A full report on our recent annual meeting, held last August in Tokyo, Japan, with

396 participants from 36 countries, was published in the December 2005 issue of *Elements* (volume 1: 313-314).

AIPEA also produces an annual newsletter that contains information on the activities of our national clay society members, together with information on upcoming meetings and grant programs. Our awards program recognizes and encourages young and not-so-young clay scientists. The Bradley Award is given to a young clay scientist based on a research paper, and the 2005 award winner was Dr. Javiera Cervini-Silva of the University of California at Berkeley, USA. In her Bradley Award presentation, she discussed the effects of iron redox cycling and the hydration properties of smectites on the Brønsted basicity of adsorbed water. The AIPEA Fellowships and Medals are given to honor active clay scientists for their contributions to clay science. The 2005 AIPEA Fellowships were awarded to Dr. José Julien Fripiat (France) and Dr. José Serratos (Spain). AIPEA Medals for excellence in clay science, sponsored by the Asociación Española des Arcillas, were given to Dr. Eduardo Ruiz-Hitzky (Spain) and Dr. Stephen Guggenheim (USA).

The Nomenclature Committee of AIPEA has established a consistent clay terminology, and we will shortly place nomenclature discussions of the past 30 years on the AIPEA website (<http://aipea.org/>). Over the next four years, the Teaching Committee will investigate ways to expand clay science teaching, not only to clay scientists but also to those in the materials and chemistry fields who work with clay materials in their research.

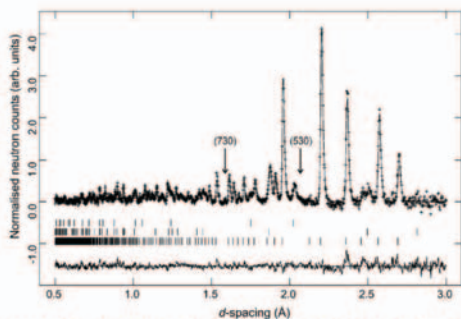
AIPEA will meet next at the Euroclay Conference in 2007 in Portugal, at which time the AIPEA council will hold formal meetings. The next International Clay Conference will be held June 20–26, 2009, and is being organized by Dr. Saverio Fiore of Italy. Plans are already well advanced, and a detailed scientific proposal will be put forward at the Euroclay meeting in 2007.

AIPEA officers for 2005–2009 are Prof. David Bish, Indiana University (president); Prof. Takabumi Sakamoto, Chiba Institute of Science (vice president); Prof. Robert A. Schoonheydt, Katholieke Universiteit Leuven (past president); Dr. J. Theo Kloprogge, Queensland University of Technology (secretary general); and Dr. Jeanne B. Percival, Geological Survey of Canada (treasurer). The AIPEA council consists of Dr. Peter Komadel (Slovak Academy of Sciences), Dr. Atsuyuki Inoue (Chiba University), Dr. N. Clauer (Centre de Géochimie de la Surface), Prof. Saverio Fiore (Consiglio Nazionale delle Ricerche, Potenza), Dr. Celso S.F. Gomes (Universidade de Aveiro), Dr. Daisy Barbosa Alves (Petroleo Brasileiro S.A.), Prof. Darrell G. Schulze (Purdue University), and Prof. Stephen Guggenheim (University of Illinois at Chicago).

**David L. Bish**  
 President, AIPEA

### Mineralogical Society of America and Geochemical Society Short Course

## NEUTRON SCATTERING IN EARTH SCIENCES



Final refinement profile for katoite at 9.42 GPa from Lager et al. (2005) *American Mineralogist* 90: 639-644.

December 7-8, 2006

Holiday Inn-Bay Bridge, Emeryville, CA 94608

Hans-Rudolf Wenk, University of California-Berkeley, and Nancy Ross, Virginia Polytechnic Institute, Convenors

Student Support Available

Supported partly by DOE-BES, COMPRES, LANSCE and SNS

More information and registration: <http://www.minsocam.org/msa/sc>

# Environmental Geochemistry

## Treatise on Geochemistry, volume 9<sup>1</sup>

Volumes of review articles tend to make a lot of promises, whether explicit or implied, e.g. comprehensive coverage of a subdiscipline, appropriate for everyone from advanced undergraduates to cutting-edge researchers. However, it is not always easy to deliver the goods. In practice, most of the time we end up with a hodgepodge of whatever the authors come up with by the submission deadline—if the editors are lucky, that is. This is not to say that such volumes are useless. On the contrary, they often include some very valuable chapters. But as a whole, they seldom deliver the sort of comprehensive coverage and accessibility for which one would hope.

*Environmental Geochemistry*, the ninth volume of the award-winning *Treatise on Geochemistry* series published by Elsevier, comes with the same set of promises. The website for the series ([www.treatiseongeochemistry.com](http://www.treatiseongeochemistry.com)) claims that it “seeks to present a comprehensive, integrated summary of the present state of geochemistry,” and quotes reviews that tout it as “essential” for “undergraduates through professionals.” The difference between this volume and many others is that it delivers on those promises remarkably well. It really does consider the broad sweep of environmental geochemistry in a way that is useful to professionals and yet accessible to advanced undergraduates. The volume editor (Barbara Sherwood Lollar) and the series executive editors (H. D. Holland and K. K. Turekian) have accomplished an extraordinary feat that should be emulated by others putting together similar collections.

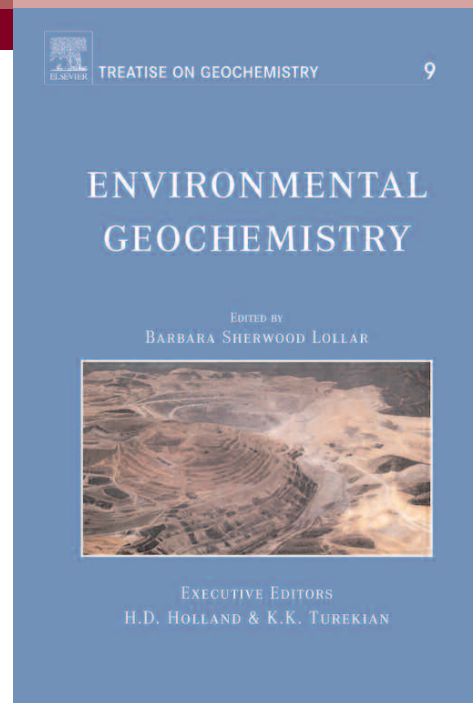
Here is how it seems to have been done. First, the editors clearly defined the scope of the volume within reasonable limits. Only local- and regional-scale processes were considered, since global-scale, atmospheric processes have been treated in other volumes of the series. Second, the editors developed a clear vision of how the topics to be considered should be organized. While some chapters deal with environmental problems where both natural and anthropogenic contaminant sources are important, others deal exclusively with anthropogenic sources. Beyond that, the editors did remarkably well at separating topics to be covered into convenient packages.

Some chapters (e.g. chapter 9.02, “Arsenic and Selenium,” and chapter 9.03, “Heavy Metals in the Environment”) are divided among elements that exhibit similar chemical behavior, while others (e.g. chapter 9.15, “The Geochemistry of Pesticides”) treat particular classes of contaminant compounds. Still others (e.g. chapter 9.09, “Salinization and Saline Environments,” and chapter 9.16, “The Groundwater Geochemistry of Waste Disposal Facilities”) address problems associated with particular types of natural and engineered environments.

This convenience in packaging would normally carry the price of considerable overlap among chapters, but once again the editors have done a remarkable job of avoiding this pitfall, as far as possible. For example, several of the chapters discuss sorption on mineral surfaces in the context of contaminant fate and transport, but only one (chapter 9.09, “Environmental Geochemistry of Radioactive Contamination”) goes into any depth, addressing the utility of surface complexation models for estimating how distribution coefficients will change under various geochemical conditions.

On the other hand, minimizing overlap would normally carry another price. That is, many scientists will not read every chapter in such a volume, so a lack of depth in any chapter might be detrimental. However, not only are the various chapters in the volume cross-referenced to one another, showing an exceptional degree of collaboration between editor and authors, but the volume has an index. In an age when any decent word processor can practically create an index on its own, there is no excuse for neglecting to include one. Unfortunately, too many collections of review articles fail in this respect, as well.

The authors of the chapters included in *Environmental Geochemistry* should also be commended for coming through with accessible, yet comprehensive and cutting-edge treatments of their topics. Reading through the volume, I was rewarded with many insights about where significant problems have yet to be solved and how my own, somewhat narrow, area of expertise might be brought to bear. At the same time, I never got the sense that the students in my undergraduate geochemistry class would have any trouble following most of the chapters, at least after the first half of my course. There is no larding with equations or abuse of overly technical language. Chapters in the volume could easily be used as supplemental reading for advanced undergraduate classes, and in fact, this semester I plan to have my students



read the chapter on radioactive contamination in preparation for a field trip to the Hanford Site.

My one problem with the entire *Treatise on Geochemistry* series is the price of the hard-bound editions (\$5450 for the ten-volume set.) This absurdly high price will certainly do nothing to appease those university librarians who have begun a movement to boycott high-priced Elsevier journals. Luckily, most of the volumes in the series are now available in paperback editions for \$89 each, which is much more reasonable.

Therefore, I highly recommend *Environmental Geochemistry* as a nearly ideal review volume for advanced undergraduates, graduate students, and professionals. However, obtaining a free copy by doing a short book review is even more highly recommended.

**Barry Bickmore**  
Brigham Young University

<sup>1</sup> Barbara Sherwood Lollar, editor (2005) *Environmental Geochemistry, Treatise on Geochemistry 9*, Elsevier, ISBN 0-08-044643-4, US\$89; 8 0

## 2006

**June 18–21** Chinese International Conference on Continental Dynamics and Environmental Change of the Tibetan Plateau, Xining, Qinghai Province, PRC. Web page: [www.geosociety.org/meetings/index.htm](http://www.geosociety.org/meetings/index.htm)

**June 20–23** 5<sup>th</sup> Annual Meeting of Consortium for Materials Properties Research in Earth Sciences (COMPRES), Snowbird, Utah, USA. Web page: [www.compres.stonybrook.edu/](http://www.compres.stonybrook.edu/)

**June 25–29** First International Congress on Ceramics, Toronto, Canada. Details: Dr. Stephen Freiman, tel.: 301-975-5658, or Mark Mecklenborg, ACerS Staff Director, Technical Publications and Meetings, tel.: 614-794-5829. E-mail: [stephen.freiman@nist.gov](mailto:stephen.freiman@nist.gov) or [mmecklenborg@ceramics.org](mailto:mmecklenborg@ceramics.org); web page: [www.ceramics.org/?target=/meetings/icc/home.asp](http://www.ceramics.org/?target=/meetings/icc/home.asp)

**June 25–30** Gordon Research Conference: Research at High Pressure, University of New England, Biddeford, Maine, USA. Web page: [www.grc.uri.edu/programs/2006/highpres.htm](http://www.grc.uri.edu/programs/2006/highpres.htm)

**July 2–6** Meeting of Young Researchers in Earth Sciences (MYRES) II: Dynamics of the Lithosphere, Verbania, Italy. E-mail: [info@myres.org](mailto:info@myres.org); web page: <http://myres.org/meetings.html>

**July 2–6** Australian Earth Sciences Convention, Melbourne, Australia. Details: Australian Earth Sciences Convention, c/o The Meeting Planners, 91-97 Islington Street, Collingwood, Victoria, Australia 3066; tel.: +61 3 9417 0888; fax: +61 3 9417 0899; e-mail: [earth2006@meetingplanners.com.au](mailto:earth2006@meetingplanners.com.au); website: [www.earth2006.org.au](http://www.earth2006.org.au)

**July 4–5** Biomineralisation and Environmental Mineralogy 2006 Workshop, École Nationale de Géologie de Nancy, Nancy, France. E-mail: [biomin2006@limos.uhp-nancy.fr](mailto:biomin2006@limos.uhp-nancy.fr)

**July 9–15** 18<sup>th</sup> World Congress of Soil Science, Philadelphia, PA, USA. E-mail: [wcss@colostate.edu](mailto:wcss@colostate.edu); web page: [www.colostate.edu/programs/IUSS/18wcss/index.html](http://www.colostate.edu/programs/IUSS/18wcss/index.html)

**July 10–12** Granulites and Granulites 2006, University of Brasilia, Brazil. Details: Michael Brown, e-mail: [mbrown@geol.umd.edu](mailto:mbrown@geol.umd.edu); web page: [www.geol.umd.edu/pages/meetings/granulites2006.htm](http://www.geol.umd.edu/pages/meetings/granulites2006.htm)

**July 10–19** American Crystallographic Association Summer Course on Small Molecule Crystallography, Indiana University of Pennsylvania, Indiana, PA, USA. E-mail: [lake@iup.edu](mailto:lake@iup.edu); web page: [www.hwi.buffalo.edu/ACA/ACA2006SummerCourse.html](http://www.hwi.buffalo.edu/ACA/ACA2006SummerCourse.html)

**July 16–21** Zeolite '06, 7<sup>th</sup> Meeting of the International Natural Zeolite Association, Socorro, New Mexico, USA. Details: Dr. Robert Bowman, e-mail: [bowman@nmt.edu](mailto:bowman@nmt.edu); web page: <http://cms.lanl.gov/zeo2006.html>

**July 22–27** American Crystallographic Association (ACA) Annual Meeting, Honolulu, HI, USA. Details: Judith Kelly, 113 Uncle Sam Rd., Phippsburg, Maine 04562. Tel.: 207-389-9058; fax: 860-486-4331; e-mail: [judith.kelly@uconn.edu](mailto:judith.kelly@uconn.edu); web page: [www.xray.chem.ufl.edu/aca2006/index.html](http://www.xray.chem.ufl.edu/aca2006/index.html)

**July 23–28** Gordon Research Conference: Origin Of Life, Bates College, Lewiston, Maine, USA. Details: Janet Siefert or Robert M. Hazen. Web page: [www.grc.uri.edu/programs/2006/origin.htm](http://www.grc.uri.edu/programs/2006/origin.htm)

**July 23–28** 19<sup>th</sup> International Mineralogical Association (IMA) Meeting, Kobe, Japan. Details: Dr. Kiyoshi Fujino, e-mail: [2006ima@congre.co.jp](mailto:2006ima@congre.co.jp) or [2006imapro@congre.co.jp](mailto:2006imapro@congre.co.jp); web page: [www.congre.co.jp/ima2006](http://www.congre.co.jp/ima2006)

**July 30–Aug 2** International Symposium on Zeolites and Microporous Crystals (ZMPC2006), Yonago, Tottori Prefecture, Japan. E-mail: [zmpc2006@chem.tottori-u.ac.jp](mailto:zmpc2006@chem.tottori-u.ac.jp); web page: [www.chem.tottori-u.ac.jp/~zmpc2006](http://www.chem.tottori-u.ac.jp/~zmpc2006)

**July 30–August 4** Gordon Research Conference: Biomineralization, Colby-Sawyer College, New London, NH, USA. Web page: [www.grc.uri.edu/programs/2006/biomin.htm](http://www.grc.uri.edu/programs/2006/biomin.htm)

**August 4–5** Workshop on PENELOPE and Modelling Secondary Fluorescence in Electron Microprobe Analysis, Madison, Wisconsin, USA. Details: John Fournelle, e-mail: [johnf@geology.wisc.edu](mailto:johnf@geology.wisc.edu); web page: [www.geology.wisc.edu/~johnf/penelope](http://www.geology.wisc.edu/~johnf/penelope)

**August 4–6** Satellite Conference to ECM23 on Mathematical and Theoretical Crystallography, Leuven, Belgium. E-mail: [mathcryst.satellite@lcm3b.uhp-nancy.fr](mailto:mathcryst.satellite@lcm3b.uhp-nancy.fr); web page: [www.lcm3b.uhp-nancy.fr/mathcryst/leuven2006.htm](http://www.lcm3b.uhp-nancy.fr/mathcryst/leuven2006.htm)

**August 6–11** 69<sup>th</sup> Annual Meeting of the Meteoritical Society, ETH Zürich, Switzerland. Details: Rainer Wieler, ETH Zürich, Isotope Geology, CH-8092 Zürich, Switzerland. Tel.: +41 44 632 37 32; fax: +41 44 632 11 79; e-mail: [Wieler@erdw.ethz.ch](mailto:Wieler@erdw.ethz.ch); website: [www.metsoc2006.ethz.ch](http://www.metsoc2006.ethz.ch)

**August 6–11** 23<sup>rd</sup> European Crystallographic Meeting (ECM23), Leuven, Belgium. Details: Organizing Secretariat, Momentum, Grensstraat 6, B-3010 Leuven, Belgium. Tel.: +32 16 40 45 55; fax: +32 16 40 35 51; e-mail: [info@momentum-pco.be](mailto:info@momentum-pco.be); website: [www.ecm23.be](http://www.ecm23.be)

**August 6–11** Gordon Research Conference: Organic Geochemistry, Holderness School, Plymouth, New Hampshire, USA. Details: Steve Larter or Katherine H. Freeman; web page: [www.grc.uri.edu/programs/2006/orggeo.htm](http://www.grc.uri.edu/programs/2006/orggeo.htm)

**August 13–18** Gordon Research Conference: Ceramics, Solid State Studies in Optimization of Performance through Microstructural Design, Proctor Academy, Andover, New Hampshire, USA. Details: John E. Blendell or Robert F. Cook; web page: [www.grc.uri.edu/programs/2006/ceramics.htm](http://www.grc.uri.edu/programs/2006/ceramics.htm)

**August 21–24** IAGOD Symposium: 12<sup>th</sup> Quadrennial International Association on the Genesis of Ore Deposits, Moscow, Russia. Details: Dr. Sergei Cherkasov, Executive Secretary 12<sup>th</sup> IAGOD, Vernadsky SGM RAS, 11-2 Mokhovaya str., Moscow, 125009 Russia. Tel.: +7-(095)-203-4667; fax: +7-(095)-203-5287; e-mail: [iagod@sgm.ru](mailto:iagod@sgm.ru); web page: [www.rags.ru/about.shtm](http://www.rags.ru/about.shtm) (in Russian); or [www.iagod.sgm.ru/](http://www.iagod.sgm.ru/)

**August 26–27** GIA Gemological Research Conference, San Diego, California USA. Details: Dr. James E. Shigley, tel.: 760-603-4019; e-mail: [gemconference@gia.edu](mailto:gemconference@gia.edu); web page: [www.gia.edu/gemsandgemology/30609/2006\\_gia\\_gemological\\_research\\_conference.cfm](http://www.gia.edu/gemsandgemology/30609/2006_gia_gemological_research_conference.cfm)

**August 27–29** International Gemological Symposium (IGS), San Diego, CA, USA. Details: Gemological Institute of America, The Robert Mouawad Campus, 5345 Armada Drive, Carlsbad, CA 92008. E-mail: [igs@gia.edu](mailto:igs@gia.edu); website: [www.symposium.gia.edu](http://www.symposium.gia.edu)

**August 27–September 1** 16<sup>th</sup> Annual V.M. Goldschmidt Conference, Melbourne, Australia. Details: Goldschmidt 2006 Conference Managers, GPO Box 128, Sydney NSW 2001, Australia. E-mail: [goldschmidt2006@tourhosts.com.au](mailto:goldschmidt2006@tourhosts.com.au); website: [www.goldschmidt2006.org](http://www.goldschmidt2006.org)

**August 27–September 1** 17<sup>th</sup> International Mass Spectrometry Conference (IMSC), Prague, Czech Republic. Details: CZECH-IN, spol. s r.o., 17<sup>th</sup> IMSC Conference Secretariat, Prague Congress Centre, 5. května 65, CZ-140 21 Prague, Czech Republic. Tel.: +420 261 174 305; fax: +420 261 174 307; e-mail: [imsc2006@czech-in.cz](mailto:imsc2006@czech-in.cz); website: [www.imsc2006.org](http://www.imsc2006.org)

**August 27–September 1** 17<sup>th</sup> International Sedimentological Congress, Fukuoka, Japan. E-mail: [isc2006-ec@or.knt.co.jp](mailto:isc2006-ec@or.knt.co.jp); website: [www.isc2006.com](http://www.isc2006.com)

**September 3–8** Gordon Research Conference: Rock Deformation, Big Sky Resort, Big Sky, MT, USA. Details: Mark Jessell, UMR 5563, Laboratoire des Mécanismes et Transferts en Géologie, Université Paul Sabatier, 31400 Toulouse, France. E-mail: [mjessell@lmtg.obs-mip.fr](mailto:mjessell@lmtg.obs-mip.fr); web page: [www.grc.uri.edu/programs/2006/rockdef.htm](http://www.grc.uri.edu/programs/2006/rockdef.htm)

**September 3–8** Gordon Research Conference: Magnetic Nanostructures, The Queen's College, Oxford, UK. Details: Jagadeesh S. Mooder or Stefan Bluegel; web page: [www.grc.uri.edu/programs/2006/magnano.htm](http://www.grc.uri.edu/programs/2006/magnano.htm)

**September 4–8** European High Pressure Research Group (EHPRG) 44<sup>th</sup> International Conference, Prague, Czech Republic. Details: Agency Carolina Ltd. (Project Manager: Ivana Bittarova), Albertov 7/3a, POB 45, 128 01 Prague 2, Czech Republic. Tel.: +420 224 990 827; fax: +420 224 918 681; e-mail: [ehprg06@fzu.cz](mailto:ehprg06@fzu.cz); web page: <http://kfes-80.karlov.mff.cuni.cz/EHPRG>

**September 4–10** Volcano International Gathering, "Volcano: Life, Prosperity, and Harmony," Yogyakarta, Indonesia. Details: Secretariat, Faculty of Mineral Technology, UPN "Veteran" Yogyakarta, Jl. SWK 104 (Lingkar Utara) Condongcatu, Yogyakarta 55282, Indonesia. Tel.: +62-274-486733, ext. 309; fax: +62-274-487814; e-mail: [saribk@plasa.com](mailto:saribk@plasa.com); website: <http://vig2006.recent.or.id>

**September 6–10** Engineering Geology for Tomorrow's Cities: The 10<sup>th</sup> IAEG Congress, Nottingham, United Kingdom. E-mail: [contact@iaeg2006.com](mailto:contact@iaeg2006.com); web page: [www.iaeg2006.com](http://www.iaeg2006.com)

**September 10–12** Uranium: Athabasca Deposits and Analogues, Saskatoon, Saskatchewan, Canada. Field conference organized by the CIM Geological Society. Website: [www.saskuranium2006.ca](http://www.saskuranium2006.ca)

**September 10–13** International Symposium on Experimental Mineralogy, Petrology and Geochemistry (EMPG XI), Bristol, UK. Details: Bernard Wood; e-mail: [helpdesk@empg2006.org](mailto:helpdesk@empg2006.org); website: [www.empg2006.org](http://www.empg2006.org)

**September 10–14** American Chemical Society 232<sup>nd</sup> National Meeting, Atlanta, GA, USA. Details: ACS Meetings, 1155, 16th Street NW, Washington, DC 20036-4899. Tel.: 202-872-4396; fax: 202-872-6128; e-mail: [natlmgtg@acs.org](mailto:natlmgtg@acs.org); web page: [www.chemistry.org/portal/a/c/s/1/acdisplay.html?DOC=meetings/sanfrancisco2006/home.html](http://www.chemistry.org/portal/a/c/s/1/acdisplay.html?DOC=meetings/sanfrancisco2006/home.html)

**September 13–15** Ferrom Meeting of the Geological Society: "Minerals, Magmas and Megastructures", London, UK. Web page: [www.huxley.ic.ac.uk/research/Basins/MDSG/display.php?ID=21](http://www.huxley.ic.ac.uk/research/Basins/MDSG/display.php?ID=21)

**September 18–22** Third Mid-European Clay Conference (MECC'06), Opatija, Croatia. Details: Mr. Vanja Bisevac (MECC06), Mineralosko-petrografski zavod PMF-a, Horvatovac bb, HR-10000 Zagreb, Croatia; tel.: +385 (0)1 4605999; fax: +385 (0)1 4605998. E-mail: [mecc06@gfz.hr](mailto:mecc06@gfz.hr); website: <http://mecc06.gfz.hr>

**September 18–29** Modular Course in Mineral Exploration in Volcanic Terrains (Field-Based), Sudbury, Ontario, Canada. Details: Harold Gibson, Mineral Exploration Research Centre, Department of Earth Sciences, Laurentian University, Willet Green Miller Centre, 933 Ramsey Lake Road, Sudbury, ON, Canada, P3E 6B5. Tel.: 705-675-1151 ext. 2371; fax: 705-675-4898; e-mail: [hgbison@laurentian.ca](mailto:hgbison@laurentian.ca); website: <http://earthsciences.laurentian.ca>

**September 24–28** Crystallization 2006: Eighth International Symposium on Crystallization in Glasses and Liquids, Jackson Hole, WY, USA. Details: Dr. Mark J. Davis, e-mail: [mark.davis@us.schott.com](mailto:mark.davis@us.schott.com); web page: [www.acers.org/meetings/crystallization/home.asp](http://www.acers.org/meetings/crystallization/home.asp)

**September 25–30** 7<sup>th</sup> International Symposium on Environmental Geochemistry (7<sup>th</sup> ISEG), Beijing, China. Details: Dr. Cong-Qiang Liu, State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, 46 Guanshui Road, Guiyang, Guizhou Province, 550002, P. R. China. E-mail: [iseg2006@vip.skleg.cn](mailto:iseg2006@vip.skleg.cn) or [liucongqiang@vip.skleg.cn](mailto:liucongqiang@vip.skleg.cn); website: [www.iseg2006.com](http://www.iseg2006.com)

**October 1–4** Water in Nominally Anhydrous Minerals, MSA/GS Short Course, Verbania, Italy. Details: Hans Keppler, Bayerisches Geoinstitut, Bayreuth, Germany and Joseph Smyth, University of Colorado, Boulder, CO, USA; web page: [www.minsocam.org/MSA/SC](http://www.minsocam.org/MSA/SC)

**October 1–6** Society of Exploration Geophysicists 76<sup>th</sup> Annual Meeting and International Exposition, New Orleans, Louisiana, USA. Details: PO Box 702740, Tulsa, OK 74170-2740, USA.



Tel.: 918-497-5500; fax 918-497-5557;  
e-mail: meetings@seg.org; web page:  
http://seg.org/meetings

**October 2-6 Fourth International Conference on Mars Polar Science and Exploration**, Davos, Switzerland. Details: Stephen Clifford, Lunar and Planetary Institute; tel.: 281-486-2146; e-mail: clifford@lpi.usra.edu; web page: http://www.lpi.usra.edu/meetings/polar2006

**October 15-19 Materials Science & Technology 2006 (MS&T '06)**, Cincinnati, OH, USA. Contact: TMS Meetings Services, 184 Thorn Hill Road, Warrendale, PA 15086, USA. Tel.: 724-776-9000, ext. 243; e-mail: mtgserv@tms.org; web page: www.matscitech.org

**October 22-25 Geological Society of America Annual Meeting**, Philadelphia, Pennsylvania, USA. Details: GSA Meetings Dept., PO Box 9140, Boulder, CO 80301-9140, USA. Tel.: 303-447-2020; fax: 303-447-1133; e-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings/index.htm

**October 23-24 Martian Sulfates as Recorders of Atmospheric Fluid-Rock Interactions**, Houston, Texas, USA. Details: Jim Papike, jpapike@unm.edu or Elizabeth Waggoner; tel.: 281-486-2164; fax: 281-486-2125; e-mail: waggoner@lpi.usra.edu

**November 5-8 AAPG 2006 International Conference and Exhibition**, Perth, Australia. Details: AAPG Conventions Department, PO Box 979, Tulsa, OK 74101-0979, USA. Tel.: 918-560-2679; e-mail: convene2@aapg.org; web page: www.aapg.org/perth/index.cfm

**November 14-15 Material, Minerals, & Metal Ecology 2006**, Cape Town, South Africa. Details: Dr Barry Wills, Minerals Engineering International, 18 Dracaena Ave, Falmouth, Cornwall TR11 2EQ, UK. Tel.: +44 7768 234121; e-mail: bwills@min-eng.com; web page: www.min-eng.com/mmme06/index.html

**November 18-19 Theoretical Crystallography and Materials Science**, Satellite Conference of the AsCA'06 / CrSJ meeting, Tsukuba, Japan. E-mail: mathcryst.satellite@lcm3b.uhp-nancy.fr; web page: http://www.lcm3b.uhp-nancy.fr/mathcryst/asca2006.htm

**November 20-23 Joint Conference of the Asian Crystallographic Association (AsCA) and the Crystallographic Society of Japan (CrSJ)**, Tsukuba, Japan. Details: Secretariat, Realize AT Limited, Ohtsuka 3cho-me Bldg., 3-11-6 Ohtsuka, Bunkyo-ku, Tokyo 112-0012, Japan. Tel.: + 81-3-5940-7640; fax: + 81-3-5940-7980; e-mail: satomi@realize-at.jp; web page: www.realize-at.jp/AsCA2006/AsCA2006-CrSJ.htm

**November 27-December 1 Materials Research Society Fall Meeting**, Boston, MA, USA. Details: Materials Research Society, 506 Keystone Drive, Warrendale PA 15086-7573, USA. Tel.: 724-779-3003; e-mail: info@mrs.org; web page: www.mrs.org/s\_mrs/sec\_mtgdetail.asp?CID=6073&DID=167209

**December 2006 7<sup>th</sup> European Meeting on Environmental Chemistry**, Brno, Czech Republic. Details: Dr. Josef Caslavsky, Institute of Analytical Chemistry, Czech Academy of Science, Veveri 97, 61142 Brno, Czech Republic. E-mail: caslav@iach.cz

**December 4-8 Earth Science Meeting, Société Française de Minéralogie et de Cristallographie**, Dijon, France. Details: Bruno David; e-mail: bruno.david@u-bourgogne.fr; web page: www.u-bourgogne.fr/RST-DIJON

**December 6-15 Modular Course in Exploration Geochemistry**, Sudbury, Ontario, Canada. Details: Steve Piercey, Mineral Exploration Research Centre, Department of Earth Sciences, Laurentian University, Willet Green Miller Centre, 933 Ramsey Lake Road, Sudbury, ON, Canada, P3E 6B5. Tel.: 705-675-1151 ext. 2364; fax: 705-675-4898; e-mail: spiercey@laurentian.ca; website: http://earthsciences.laurentian.ca

**December 7-8 MSA/GS Short Course: Neutron Scattering Applied to Earth Sciences**, Emeryville, CA, USA. Details: Rudy Wenk, University of California, Berkeley, California, and Nancy L. Ross, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. E-mail: wenk@seismo.berkeley.edu; web page: www.minsocam.org/MSA/SC/Neutron\_descrptn.html

**December 8-10 MSA/GS Short Course: Medical Mineralogy and Geochemistry**, USGS, Menlo Park, CA, USA. Details: Nita Sahai, University of Wisconsin, Madison, Wisconsin, and Martin A. Schoonen, State University of New York,

Stony Brook, New York. E-mail: sahai@geology.wisc.edu; web page: www.minsocam.org/MSA/SC/MedMin\_descrptn.html

**December 11-15 American Geophysical Union Fall Meeting**, San Francisco, California, USA. Details: E. Terry, AGU Meetings Department, 2000 Florida Avenue NW, Washington, DC 20009, USA. E-mail: eterry@agu.org; web page: www.agu.org/meetings

**December 13-15 9<sup>th</sup> Australasian Environmental Isotope Conference and 2<sup>nd</sup> Australasian Hydrogeology Research Conference**, Adelaide, South Australia, Australia. E-mail: cgs@groundwater.com.au; web page: http://groundwater.com.au/07-A3-Brochure-135399.pdf

## 2007

**February 24-28 2<sup>nd</sup> International Conference and Exhibition on Geo-Resources in the Middle East and North Africa (GRMENA-2)**, Cairo University, Egypt. Details: Prof. Dr. Ali Sadek; tel.: 00202-3446411; fax: 00202-3448573; e-mail: alisadek@mail.eun.eg; website: www.grmena.com.eg

**February 25-March 1 2007 TMS Annual Meeting & Exhibition**, Orlando, FL, USA. Details: TMS Meetings Services, 184 Thorn Hill Road, Warrendale, PA 15086. Tel.: 724-776-9000, ext. 243; e-mail: mtgserv@tms.org; web page: www.tms.org

**March 25-29 American Chemical Society 233<sup>rd</sup> National Meeting**, Chicago, IL, USA. Details: ACS Meetings, 1155-16<sup>th</sup> St NW, Washington, DC 20036-489. Tel.: 202-872-4396; fax: 202-872-612; e-mail: natlmtgs@acs.org; web page: www.chemistry.org/portal/a/c/s/1/acsdisplay.html?DOC=meetings%5Cfuture.html

**April 1-4 American Association of Petroleum Geologists and Society for Sedimentary Geology (SEPM) Joint Annual Meeting**, Long Beach, California, USA. Details: AAPG Conventions Department, PO Box 979, 1444 S. Boulder Ave., Tulsa, OK 74101-0979, USA. Tel.: 918-560-2679; fax: 918-560-2684; e-mail: convene@aapg.org

**April 9-12 Materials Research Society Spring Meeting**, San Francisco CA, USA. Web page: www.mrs.org/s\_mrs/sec.asp?CID=4750&DID=164575

**May 6-10 10<sup>th</sup> European Workshop on Modern Developments and Applications in Microbeam Analysis (EMAS 2007)**, Antwerp, Belgium. Details: EMAS Secretariat, c/o University of Antwerp, Dept. of Chemistry, Campus Drie Eiken, Universiteitsplein 1, BE-2610

Antwerp-Wilrijk, Belgium. Tel.: 32 3 820 23 43; fax: 32 3 820 23 43; e-mail: Luc.Vantdack@ua.ac.be

**May 23-25 Geological Association of Canada and Mineralogical Association of Canada Joint Meeting (GAC-MAC): Yellowknife 2007 - For a Change in Climate**, Yellowknife, Canada. Web page: www.nwtgeoscience.ca/Yellowknife2007

**June 2-7 44<sup>th</sup> Annual Meeting of the Clay Minerals Society**, Santa Fe, New Mexico, USA. Details: to be announced.

**June 17-20 10<sup>th</sup> International Conference and Exhibition of the European Ceramic Society**, Berlin, Germany. Details: Deutsche Keramische Gesellschaft e.V., Am Grotz 7, D-51147 Köln Tel.: +49-2203-96648-0; fax: +49-2203-69301; e-mail: ecers2007@dkg.de; website: www.ecers2007berlin.de

**June 25-30 Combined Societies' Meeting: MinSoc, MSA and MAC: Frontiers in Mineral Sciences 2007**, Cambridge UK. Details: M.A. Carpenter, e-mail: mc43@esc.cam.ac.uk; web page: www.minsoc.org/pages/meetings/frontiers/index.html

**July 2-13 International Union of Geodesy and Geophysics (IUGG) 2007 General Assembly**, Perugia, Italy. E-mail: secretary@IUGG2007perugia.it; website: www.iugg2007perugia.it

**July 9-13 11<sup>th</sup> Congress of the International Society of Rock Mechanics**, Lisbon, Portugal. Contact: Sociedade Portuguesa de Geotecnia, LNEC, Av. do Brasil, 101, 1700-066 Lisboa, Portugal. Tel.: +351 218443321; fax: +351 218443021; e-mail: spg@inec.pt; website: www.isrm2007.org

**July 22-27 Euroclay 2007**, Aveiro, Portugal. Details: Prof. Fernando Rocha or Prof. Celso Gomes; e-mail: cgomes@geo.ua.pt; web page: www.ing.pan.pl/ecga.js/confer1.htm

**August 12-17 15<sup>th</sup> International Zeolite Conference (15<sup>th</sup> IZC)**, Beijing, China. Contact: Prof. Shilun Qiu, Organizing Secretary, 15<sup>th</sup> IZC, State Key Laboratory of Inorganic Synthesis and Preparative Chemistry, Jilin University, Linyuan Road 1788, Changchun 130012, China. Tel.: +86-431-5168590; fax: +86-431-5168614; e-mail: izzc@jlu.edu.cn; website: www.15izc.org.cn

The meetings convened by the societies participating in *Elements* are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol. To get meeting information listed, please contact Andrea at Andrea.Koziol@notes.udayton.edu

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Waterloo Hydrogeologic Inc./Schlumberger	168
Yale University	192

# The Mighty Works of Finn MacCumhail



The Causeway itself. The regular columns of the colonnade contrast with the irregular fracture patterns on the surface of rounded blocks from the entablature.

Pierrette and I ended volume 1, issue 5, entitled "Large Igneous Provinces", with some parting shots of the island of Staffa, in the Scottish Hebrides. By a happy chance I recently visited its Northern Irish equivalent, the Giant's Causeway, which, whatever misguided geologists tell you, was actually constructed by the giant Finn MacCumhail (Finn McCool) on his way to a trial of strength with his Scottish equivalent. The Causeway is a much-visited tourist attraction which I last saw many years ago as a student, and having knocked around the world a bit since then I was prepared to be disappointed. When you leave the car park you cannot see the Causeway or the cliffs behind it, but when it suddenly comes into view around a corner it is all truly impressive. Not quite the gasp produced by the Grand Canyon or Lake Louise, but a sharp intake of breath nonetheless.

The Causeway is enclosed in an amphitheatre of high cliffs of piled, well-jointed basalt flows, the thickest around 30 m, with one brilliant red bole horizon to remind us that Ulster was sub-tropical in the early Tertiary. The



Basalt flows and bole horizon above the Giant's Causeway

Causeway that Finn constructed extends from the base of these flows and slopes gradually away under the waters between Scotland and Ireland. It is built of around 40,000 marvellously regular polygonal basalt columns with an average diameter of 0.45 m, mostly hexagonal but with some 4-, 5-, 7- and 8-sided columns. Many columns have surface grooves, at right angles to the long axis, known as chisel marks. As with many lava flows, this well-jointed colonnade is capped by an irregularly jointed entablature, very conspicuous on our picture of Fingal's Cave. Large boulders from the entablature have rolled down into the waters surrounding the Causeway.

The origin of jointing in basalts has been ascribed to contraction during cooling since the 19<sup>th</sup> century, and two recent papers have expanded on the details. Reiter et al. (1987) showed how the process could be modelled by the propagation of fractures from the upper and lower surfaces as successive layers become elastic, and successfully modelled the chisel marks, each of which represents an incremental fracturing episode. Two physicists, Jagla and Rojo (2002), who do not reference Reiter et al. (perhaps they didn't type 'columnar jointing' into MinAbs Online!), confirmed their conclusions and fascinatingly showed how the distribution of polygons with the observed variable number of sides can be predicted if the ordered fracture pattern develops from an initially disordered one 'at the surface of the rock'. Their hypothetical disordered fracture pattern looks to me remarkably like the surface of the blocks of entablature that Finn left lying beside his masterwork, but Jagla and Rojo do not mention this. Perhaps the entablature-colonnade boundary is an order-disorder phase transition, not something I expected to encounter when I started on this little piece!

Jagla EA, Rojo AG (2002) Sequential fragmentation: The origin of columnar quasi-hexagonal patterns. *Physical Review E* 65: 026203 1-7

Reiter M, Barroll MW, Minier J, Clarkson G (1987) Thermo-mechanical model for incremental fracturing in cooling lava flows. *Tectonophysics* 142: 241-261

**Ian Parsons**



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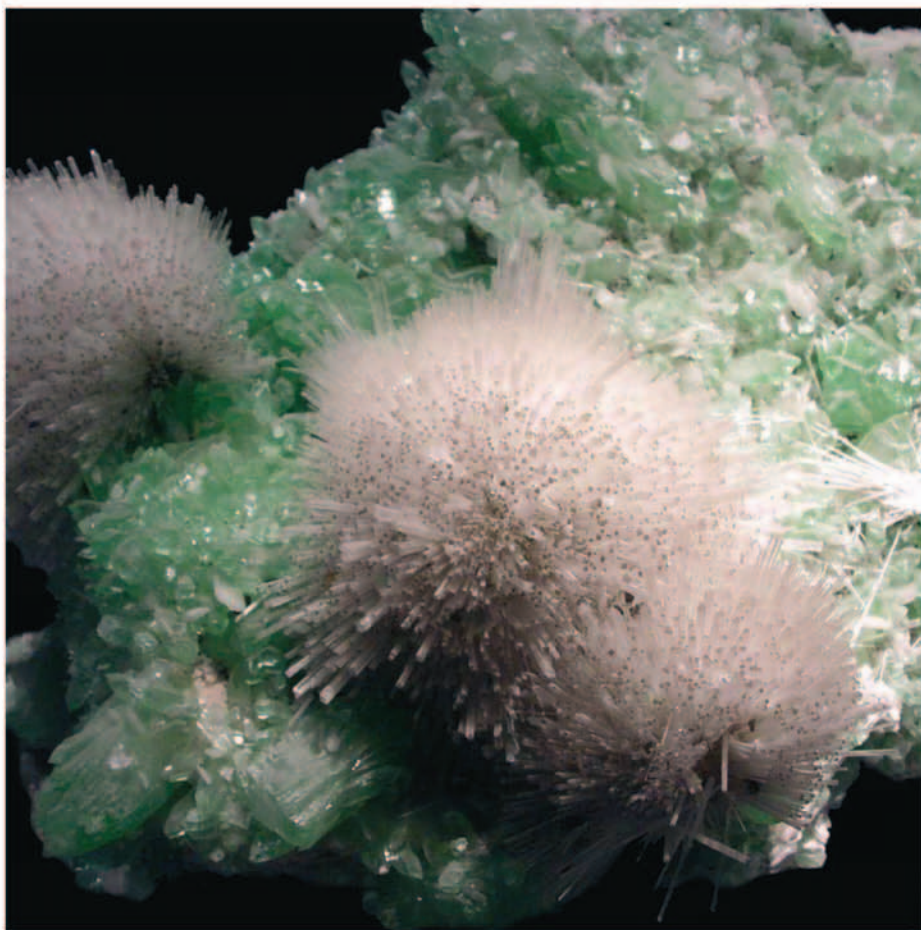
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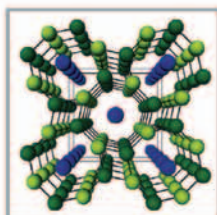
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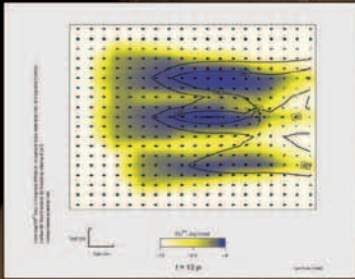
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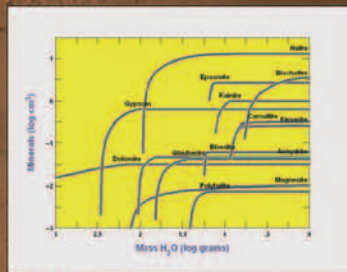


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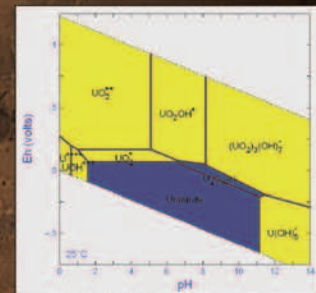


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