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PSRD-MetsOnMars.pdf

Hot Idea May 30, 2008

Meteorites Found on Mars

--- No surprise that there are meteorites on other planets. Now that we've seen them on Mars, what do we know about them and what does their geochemistry tell us about the environment where they landed?

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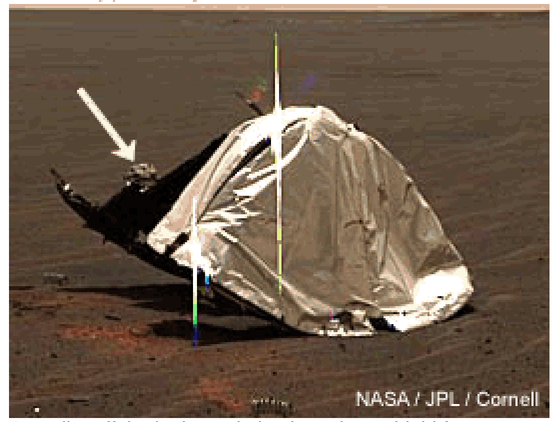
MER Opportunity Heat Shield and Iron Meteorite



Sun glint off the jettisoned aluminum heat shield from MER Opportunity couldn't hide the interesting rock behind it (arrow). Click image for more information.

One meteorite and four possible others, all pieces of asteroids, have been identified since 2005 on the plains and hills of Mars by the Mars Exploration Rover (MER) science team. Christian Schröder (NASA Johnson Space Center) and an international team of cosmochemists and planetary scientists have summarized the investigations of these five rocks. The team reports on the chemistry and mineralogy of the rocks based on data obtained from the suite of instruments onboard the rovers and discusses what these chance discoveries tell us about the Martian environment.

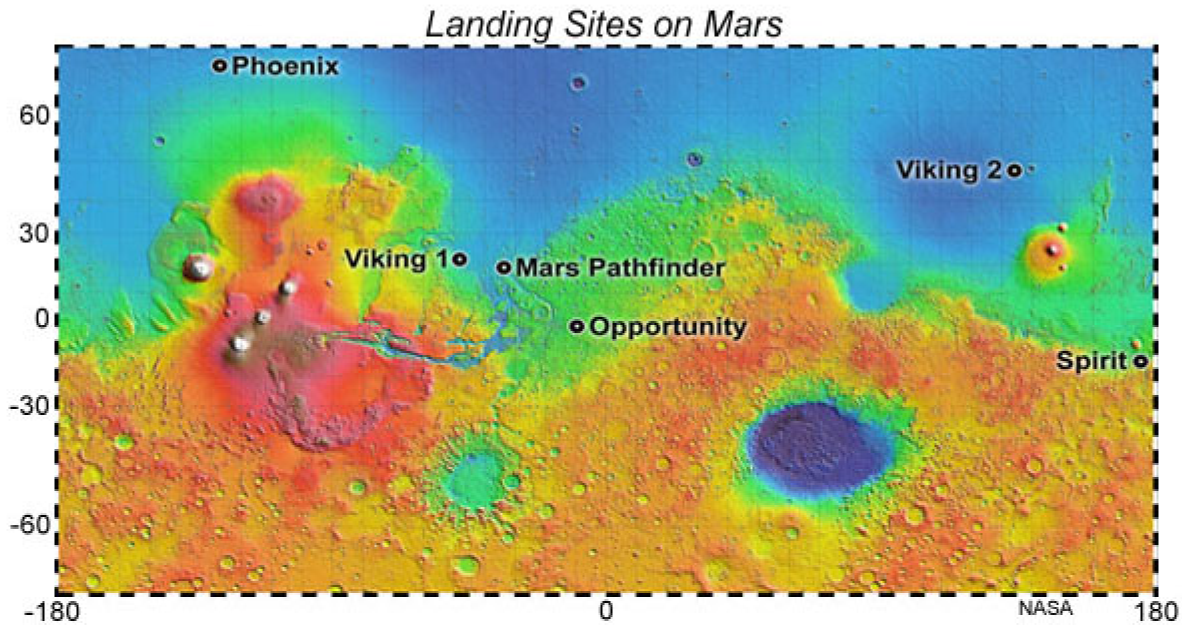
Reference:

- Schröder, C., Rodionov, D. S., McCoy, T. J., Jolliff, B. L., Gellert, R., Nittler, L. R., Farrand, W. H., Johnson, J. R., Ruff, S. W., Ashley, J. W., Mittlefehldt, D. W., Herkenhoff, K. E., Fleischer, I., Haldemann, A. F. C., Klingelhöfer, G., Ming, D. W., Morris, R. V., de Souza, P. A., Squyres, S. W., Weitz, C., Yen, A. S., Zipfel, J., and Economou, T. (2008) Meteorites on Mars observed with the Mars Exploration Rovers, *Journal of Geophysical Research,* v. 113(E6), E06S22, doi: 10.1029/2007JE002990.

PSRDpresents: Meteorites Found on Mars --Short Slide Summary (with accompanying notes).

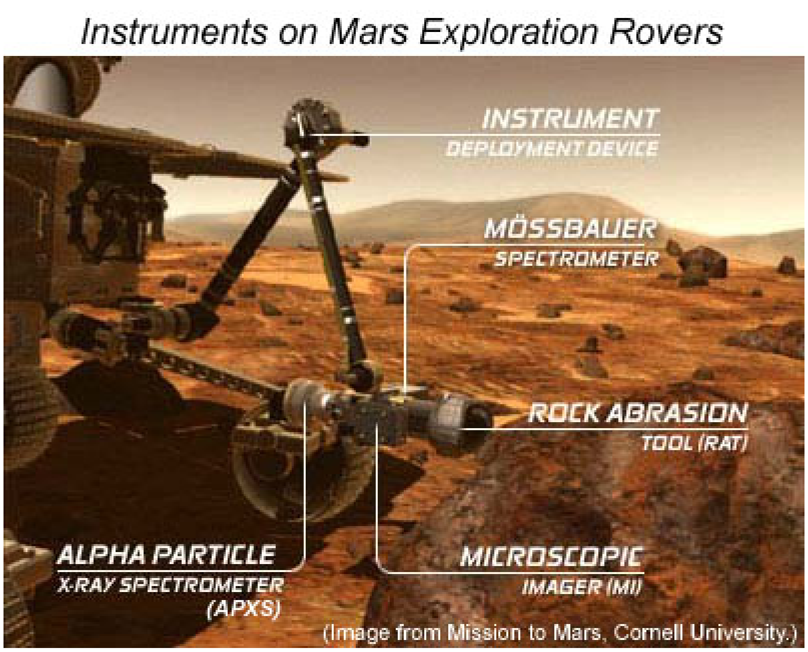
Robots Exploring Mars

Cosmochemists study meteorites from Mars and now, thanks to a couple of exploring rovers, meteorites on the surface of Mars. The two Mars Exploration Rovers (MER), Opportunity and Spirit, are equipped with a payload of cameras and instruments that allow the observation and identification of rocks and soil (no organics implied in the use of this term on Mars). The landing site for Opportunity is in Meridiani Planum, where mineral deposits (hematite) suggest Mars had a wet past and for Spirit it is Gusev Crater, which may have once held a shallow lake (see map below). As scientists navigated the rovers away from their landing sites, analyzing the geology and studying environmental conditions of the regions, the panoramic camera and instruments detected, by lucky chance, a few rocks from space that add something extra to the data bank.



NASA mission landing sites are shown on this base map of Mars topography created by the Mars Orbiter Laser Altimeter (MOLA). Lowlands have colors of blue and green, and highlands are in yellow, orange, red, and white. Viking 1 and Viking 2 landed in 1976. Mars Pathfinder landed in 1997. MERs Opportunity and Spirit landed in 2004 and are still active today. Phoenix landed on May 25, 2008. Instruments on both rovers Opportunity, in Meridiani Planum region, and Spirit, in Gusev Crater, have been used to identify potential meteorites.

The MERs carry sophisticated sets of instruments. Two are used to survey the scene around the rover: The panoramic camera (Pancam) has 13 filters in the visible to near-infrared region. The miniature thermal emission spectrometer (Mini-TES) covers the 5 to 29 um wavelength region. Three additional instruments are mounted on a mechanical arm and can be placed on rock or soil targets for more detailed analyses: The Microscopic Imager (MI) for beautifully detailed images and the Alpha Particle X-ray spectrometer (APXS) for elemental compositions. A Mössbauer spectrometer is used to determine mineralogy of iron-bearing phases. In addition, a set of magnets can be used to attract dust particles and the Rock Abrasion Tool (RAT) removes surface contamination and weathering rinds off the outer layers of rock surfaces.



Artist's rendition showing instruments onboard the MERs. The PanCam and Mini-TES are not shown in this view.

Unexpected Discoveries

This is the first meteorite found on another planet. Its maximum dimension is 31 centimeters. Click image for more information. There were two meteorites found on the Moon.

In January 2005, the Opportunity rover used its panoramic camera to image its surroundings on Meridiani Planum near the remnants of the lander's heat shield, which had been cast off after serving to protect the rover from temperatures of up to 2,000 ^{o}F during its plung through the Martian atmosphere. A close-by rock seen in the images showed a smooth surface covered by depressions somewhat like regmaglypts (small depressions on meteorite surfaces caused by ablation during descent through the atmosphere.)

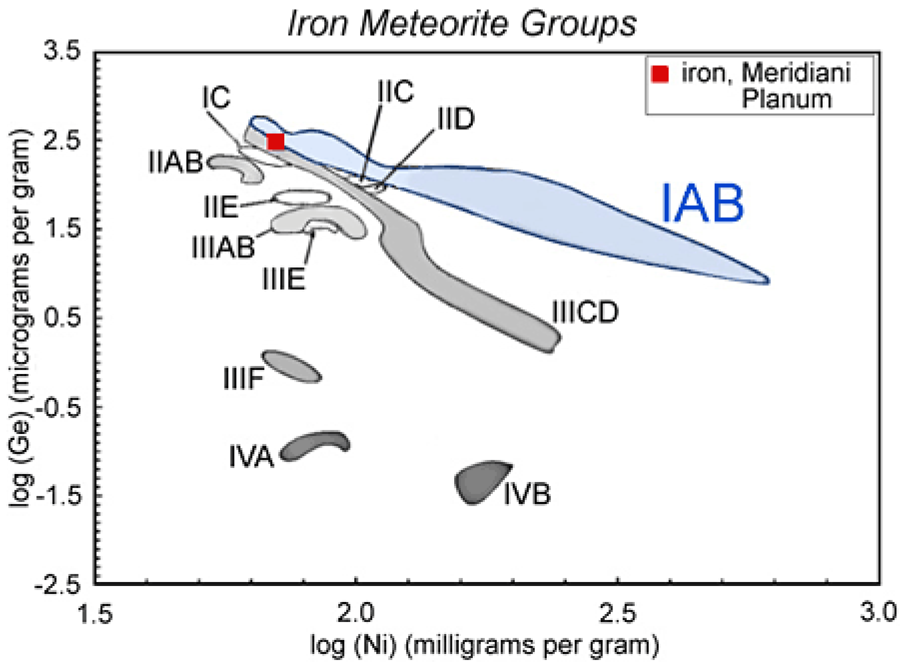
As summarized by Schröder and colleagues, spectra obtained by the Mini-TES of the rock showed features akin to the Martian atmosphere, which meant it was highly reflective at mid-infrared wavelengths, a characteristic of metals. This led to the logical thought that the rock was an iron meteorite. Further classification of the meteorite was allowed by the onboard instruments: APXS, Mössbauer, MI, and the RAT.

- **Alpha Particle X-ray Spectrometer** - The APXS-derived bulk elemental composition of Meridiani Planum meteorite is 93% iron, 7% nickel, ~300 ppm germanium, and <100 ppm gallium.

- **Mössbauer Spectrometer** - Spectra from the RAT-brushed surface show 94% of the iron is in a metal phase. On the basis of the iron/nickel ratio, this phase was assigned to kamacite (an iron-nickel mineral with low nickel content). Mössbauer spectra of both the "as is" and the RAT-brushed surface show ~5% of the iron is in the ferric state (Fe^{3+}). Schröder and colleagues suggest some of the iron may have been oxidized during the meteorite's fall through the Martian atmosphere.

This meteorite was officially approved on October 10, 2005 with the name "Meridiani Planum" and remains the only approved meteorite on Mars. It is classified as a IAB complex iron meteorite.

Iron meteorites are made, almost completely, of iron-nickel metal. Cosmochemists group them according to the abundances of trace elements such as germanium and gallium, as well as nickel. Initially, irons were classified into four groups and were identified by Roman numerals I, II, III, and IV. Today twelve groups are recognized and designated further by letters A through F according to concentrations of siderophile ("iron-loving") trace elements. When the concentration of a trace element is plotted against overall nickel content on a logarithmic plot, the iron meteorites cluster into groups. Iron meteorites that do not fit into the groups are called ungrouped. For example, the figure below shows where the meteorite Meridiani Planum plots in relation to the IAB and IIICD groups on the logarithmic plot of germanium versus nickel.

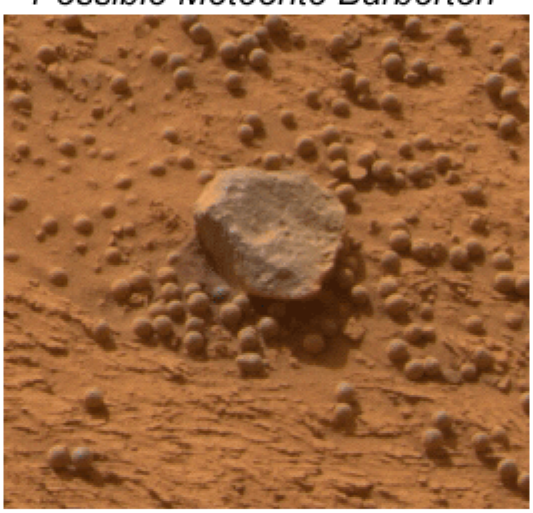


(Adapted from Schröder *et al.*, 2008, *JGR*, Fig. 3, doi: 10.1029/2007JE002990.)

This is a logarithmic plot of the concentrations of germanium versus nickel in iron meteorites based on many years of analytical work by cosmochemists. Fields for the 12 groups are shown. Meridiani Planum has Ge-Ni characteristics within the ranges of Ni-poor IAB and IIICD irons.

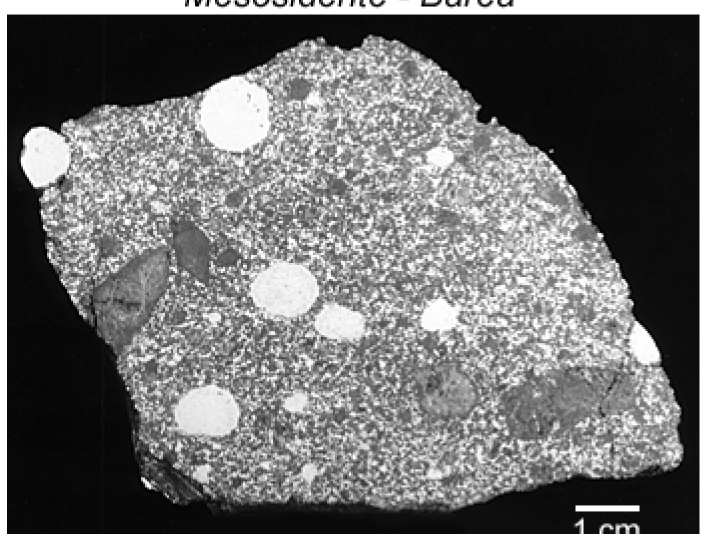
The second rock proposed by the MER Opportunity team to be a meteorite is a 3 centimeter-sized pebble at the rim of Endurance crater and unofficially named Barberton. It was found on sulfate-rich bedrock in the midst of basaltic soil and a hematite spherule lag deposit (see image below, left).

Possible Meteorite Barberton



(From Schröder *et al.*, 2008, *JGR*, Fig. 5b, doi: 10.1029/2007JE002990.)

Mesosiderite - Barea



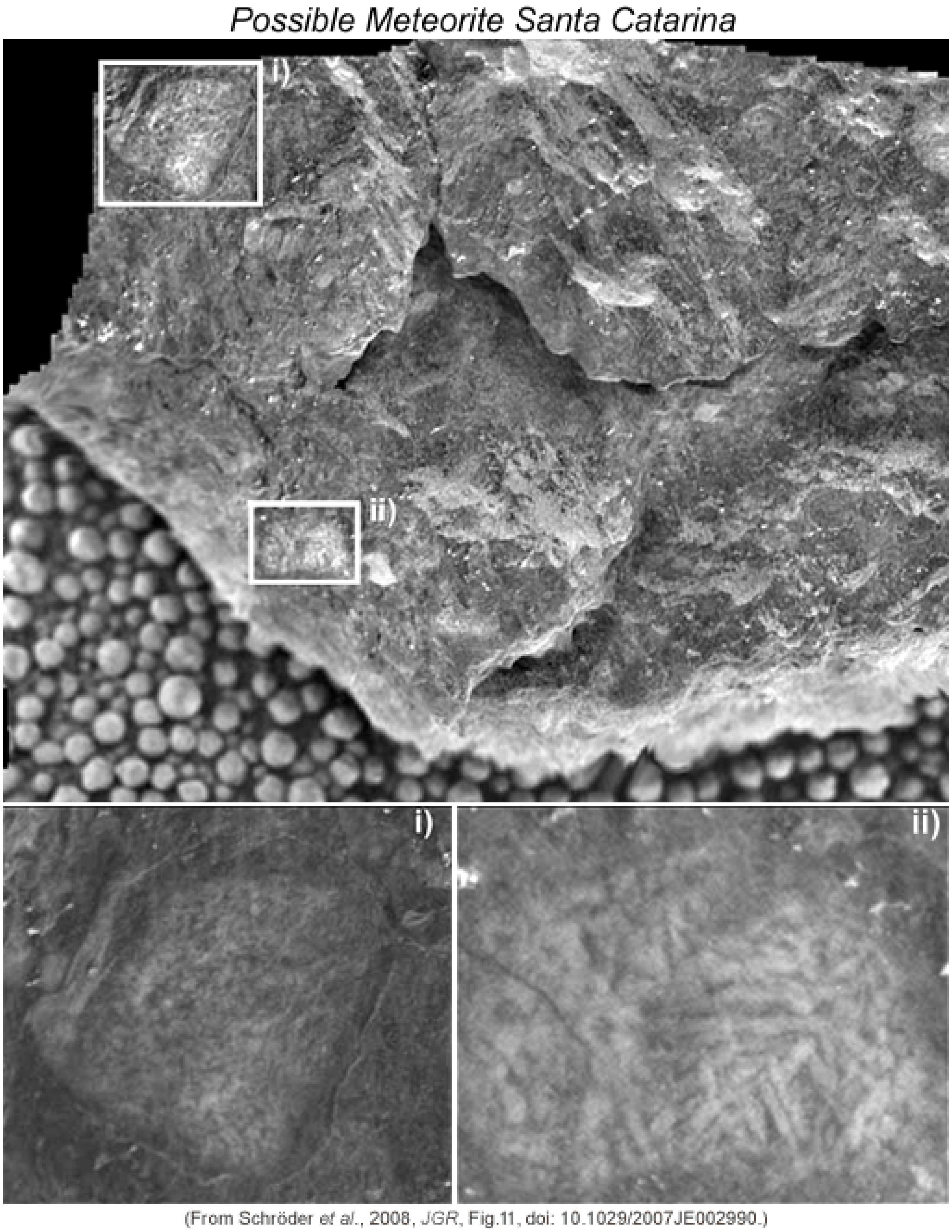
(Photo courtesy of Ed Scott.)

[LEFT] This is an approximate true color Pancam image of the reddish dust and ~3 centimeter pebble, Barberton (center), found by the Opportunity rover at the rim of Endurance crater in Meridiani Planum. The smaller beads in the scene form the hematite spherule lag deposit. **[RIGHT]** For comparison, this is a cut face of a mesosiderite, Barea, an observed fall in Spain in 1842. Barea is a brecciated stony-iron meteorite containing nearly equal shares of silicate rock fragments in various sizes (dark areas) and metal (white areas). The silicates are dominantly igneous rock fragments.

Schröder and colleagues report Barberton was analyzed with the Microscopic Imager, the APXS, and the Mössbauer Spectrometer, but it was too small to be brushed or abraded with the RAT. Some of the surrounding soil was also analyzed for comparison. Barberton is olivine-rich and contains metallic iron in the form of kamacite, suggesting a meteoritic origin. However, Schröder and coauthors also report that although it is unique among samples investigated at Meridiani Planum, Barbarton's high magnesium and nickel contents and low aluminum and calcium contents would also be consistent with an ultramafic rock of Martian origin. Though it cannot yet be proven that Barberton is a meteorite, if true, then cosmochemists say it is similar in Mg/Si, Ca/Si, and Al/Si ratios to howardites and diogenites (rocks formed from basaltic magmas), but enriched in S/Si, Fe/Si, and Ni. The authors suggest Barberton, then, is chemically most consistent with a mesosiderite silicate clast with some additional metal and sulfide.

Mesosiderites (see example in photo, above right) are one of two main types of stony-iron meteorite (the other type is called pallasite). Mesosiderites are complex mixtures (roughly 50:50) of smashed up volcanic rock (silicates) and iron-nickel metal. These meteorites have been brecciated by impacts and metamorphosed by burial.

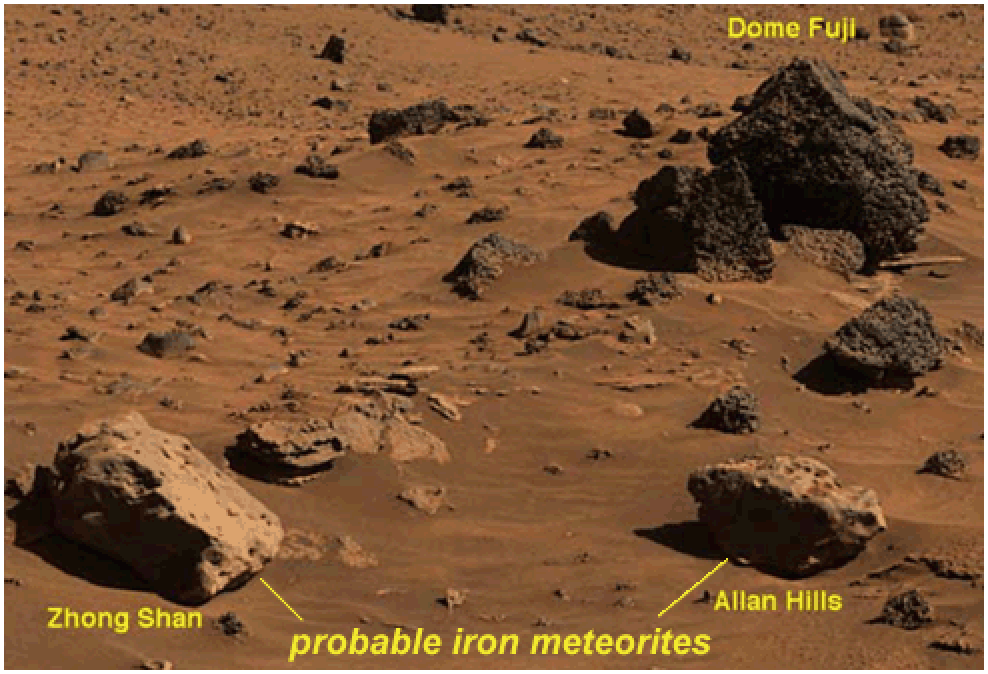
A 14-centimeter long cobble, dubbed Santa Catarina, is the third possible meteorite found by the Opportunity rover team. Schröder and colleagues describe Santa Catarina as a fractured, brecciated rock containing some clasts with possible igneous quench textures in olivine minerals (see images below). The cobble could not be abraded or brushed because of its geometry, but it was analyzed with the instrument suite of Microscopic Imager, APXS, and Mössbauer Spectrometer. Santa Catarina has an ultramafic composition with unusually high nickel. Schröder and team say that compared to other materials analyzed in Meridiani Planum, Santa Catarina is most similar to Barberton. Element ratios of Mg/Si, Ca/Si, Al/Si, S/Si, and Fe/Si are all very close to soil-corrected values obtained for Barberton. According to the authors, the iron-bearing mineralogy is, as in Barberton, dominated by Fe^{2+} in the minerals olivine (52%) and pyroxene (26%). Santa Catarina is more oxidized than Barberton with 14% of the iron as nanophase ferric oxide--a weathering product. Schröder and colleagues identified 7% troilite (iron sulfide) in the Mössbauer spectrum, but no kamacite (as had been found in Barberton or Meridiani Planum meteorite).



The Microscopic Imager onboard MER Opportunity acquired these detailed images of possible meteorite Santa Catarina sitting atop smaller beads of the hematite spherule lag deposit. The top image (about 5 centimeters high) shows the fractured surface and several individual clasts (outlined and shown in greater detail). Box (i) shows details of a clast consisting of light-toned crystals in a darker matrix. Box (ii) reveals what Schröder and team say might be an igneous quench texture in olivine.

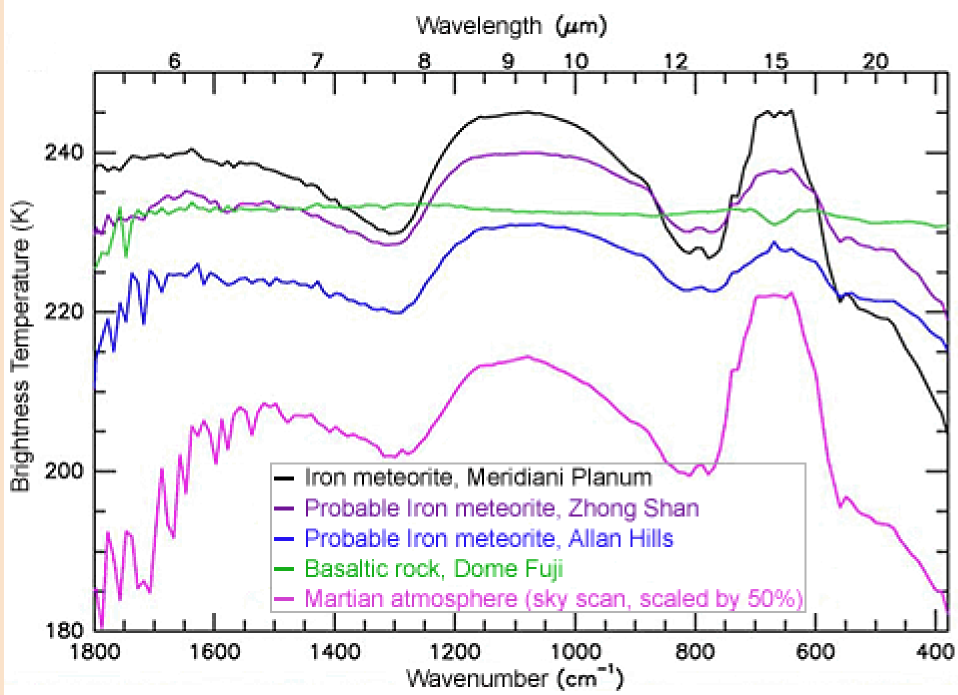
The fourth and fifth possible iron meteorites were identified based on MER Spirit's remote sensing instruments in the Columbia Hills inside Gusev Crater. They are 25- to 30-centimeter boulders, named Zhong Shan and Allan Hills (see image below). Schröder and colleagues show the Mini-TES thermal infrared characteristics of these possible meteorites are similar to the Meridiani Planum meteorite (see diagram below). All three rocks display spectral characteristics similar to the Martian atmosphere because metallic iron is highly reflective in thermal infrared (as well as visible) wavelengths. But because these rocks lie on steep terrain and were discovered after the failure of Spirit's right front wheel, detailed investigations with the rover's Microscopic Imager, APXS, and Mössbauer Spectrometer were not possible.

Two Probable Iron Meteorites in Gusev Crater



(From Schröder *et al.*, 2008, *JGR*, Fig.14b, doi: 10.1029/2007JE002990.)

Comparison of Known and Probable Meteorites on Mars



(From Schröder *et al.*, 2008, *JGR*, Fig.14a, doi: 10.1029/2007JE002990.)

Spectra of rocks on Mars obtained by mini-TES on both MER rovers. The spectrum of the known iron meteorite, Meridiani Planum (black) displays the spectral characteristics of the Martian atmosphere (pink) because of the highly reflective nature of metallic iron in thermal infrared wavelengths. The rocks called Zhong Shan (purple) and Allan Hills (blue) found in Gusev Crater by the Spirit rover have similar textural and spectral characteristics to meteorite Meridiani Planum. A nearby rock called Dome Fuji has a completely different spectrum from the others (green). It is a Martian basaltic rock.

Five Samples - Many Questions

In the true sense of what scientific discovery is all about, answering one question usually stimulates more questions. So is finding an iron meteorite and a handful of other rocks that could be meteorites on Mars. Why did we find iron and possibly stony iron meteorites and not other types? Why isn't the iron meteorite rusted? When did it fall? Did it make a crater when it hit the surface?

Based on the populations of meteorites observed to fall on Earth, stony meteorites outnumber irons. The statistics are 94% stony meteorites (mainly chondrites), 5% irons, and 1% stony irons. The same could be expected on next-door Mars. Previous work by Albert Yen (Jet Propulsion Lab) and colleagues using nickel abundances measured by the APXS indicates that the Martian soil and certain sedimentary rocks contain 1% to 3% contamination from meteorite debris. So why haven't stony (chondritic) meteorites been identified in the MER data? Schröder and coauthors suggest chondrites may be too weak to survive impact at current atmospheric densities. Or maybe MERs Opportunity and Spirit just happened to move through strewn fields of irons. Maybe more of the cobbles on the Martian plains and hills are stony meteorites that just haven't been recognized.

Rocks in Meridiani Planum indicate there was water present in the past. And we know iron will rust when in contact with water and oxygen. So the apparently almost-rust-free metallic surface of iron meteorite Meridiani Planum is consistent with the current dry, cold environment of Mars where alteration rates are extremely slow. The presence of olivine (a mineral easily altered by water) in possible meteorites Barberton and Santa Catarina also points to dry conditions since these rocks landed. But maybe the rust was sandblasted away. Or maybe rust is present on the meteorite but simply obscured by dust.

Of course this brings the next question, when did the meteorites fall? If iron meteorite Meridiani Planum fell long ago, perhaps millions of years ago, it was probably buried. But we don't know if it was buried by sand moved by water or wind or for how long. Perhaps the meteorite was only recently exposed on the surface by the winds that we know have also exposed bedrock and the hematite spherules that make up the lag deposits. We don't know when the meteorites fell.

If Meridiani Planum meteorite, Barberton or Santa Catarina created impact craters, we don't see them. If they fell in the past, a denser atmosphere might have decelerated the pieces enough to prevent hypervelocity impacts. If they fell recently through the existing, thin Martian atmosphere, they could be fragments of larger meteoroids that never made craters. Or if craters were made, they could have been erased by wind erosion. Schröder and coauthors also suggest the possibility that Barberton and Santa Catarina, because they were found on the rims, could be pieces of the impactors that formed Endurance crater and Victoria crater, respectively.

Searching for meteorites was not, and is not, a primary objective of the MER missions, though their serendipitous discoveries show the flexibility and achievement of the team to investigate unusual rocks and identify them. If more meteorites are identified and classified on Mars, then we just might find types not yet seen in our meteorite collections on Earth. And fundamentally, finding meteorites on other planetary surfaces stimulates new ideas in cosmochemistry and planetary science.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** Meteorites Found on Mars --Short Slide Summary (with accompanying notes).

- Athena Science Payload instruments onboard the two MERs.
- Malin, M. C., Edgett, K. S., Posiolova, L. V., McColley, S. M., and Noe Dobrea, E. Z. (2006) Present-Day Impact Cratering Rate and Contemporary Gully Activity on Mars, *Science*, v. 314(5805), p. 1573-1577, doi: 10.1126/science.1135156.

- Mars Exploration Rover Mission.
- Meteorite found on Mars: Meridiani Planum, data from the Meteoritical Bulletin Database.
- Meteorites found on the Moon, data from the Meteoritical Bulletin Database.
- Schröder, C., Rodionov, D. S., McCoy, T. J., Jolliff, B. L., Gellert, R., Nittler, L. R., Farrand, W. H., Johnson, J. R., Ruff, S. W., Ashley, J. W., Mittlefehldt, D. W., Herkenhoff, K. E., Fleischer, I., Haldemann, A. F. C., Klingelhöfer, G., Ming, D. W., Morris, R. V., de Souza, P. A., Squyres, S. W., Weitz, C., Yen, A. S., Zipfel, J., and Economou, T. (2008) Meteorites on Mars observed with the Mars Exploration Rovers, *Journal of Geophysical Research*, v. 113(E6), E06S22, doi: 10.1029/2007JE002990.
- Scott, E., Yang, J., and Goldstein, J. (2007) When Worlds Really did Collide. *Planetary Science Research Discoveries*, http://www.psrd.hawaii.edu/April07/irons.html. [Cosmochemical studies and dynamical models of protoplanetary collisions suggest a new origin for iron meteorites.]
- Yen, A. S., et al. (2006) Nickel on Mars: Constraints on Meteoritic Material at the Surface, *Journal of Geophysical Research*, v. 111(E12S11, doi: 10.1029/2006JE002797.

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