Headline Article
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Mineral Abundances in Martian Soils

--- Mineral abundances calculated from a trio of datasets reveal mixtures of unrelated igneous and alteration minerals in Martian dark soils.

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Martian Soil

Gusev Crater, MER Spirit image PIA05116
NASA / JPL / Cornell

Using traditional geochemical calculations with *in situ* Martian cosmochemical data researchers Harry (Hap) McSween Jr. and Ian McGlynn (University of Tennessee) and Deanne Rogers (SUNY at Stony Brook) have developed a method for identifying the major and minor minerals in soils at the Mars Exploration Rovers (MER) landing sites. The team used information from the MER Athena instrument package operating on Mars since January, 2004. They created two models using MiniTES spectra, Alpha Particle X-ray Spectrometer (APXS) data, and Mössbauer spectrometer data to calculate the mineralogy of average dark soils on the Gusev crater plains and on Meridiani Planum, located on opposite sides of Mars. Soils at both locations are similarly composed of minerals derived from the comminution of basalts (about three quarters by weight) and other minerals derived from rocks altered by chemical weathering (about one quarter by weight). This mixture of possibly unrelated materials (primary and altered) might mean that the alteration of soil did not occur in place and that the basaltic and alteration suites of minerals came from different sources. The nearly identical modal mineralogy at two widely-separated locations on the planet supports a previous hypothesis based on comparable chemical compositions that soils have been homogenized, if not globally then at least over large areas of the Martian surface. Yet, global maps of orbital remote sensing data have not shown surface abundances of alteration minerals as high as those in the Martian soils.

Reference:

- McSween, Jr., H. Y., McGlynn, I. O., and Rogers, A. D. (2010) Determining the Modal Mineralogy of Martian Soils, *Journal of Geophysical Research*, v. 115(E00F12), doi: 10.1029/2010JE003582.
- **PSRDpresents:** Mineral Abundances in Martian Soils --**Short Slide Summary** (with accompanying notes).

Taking the Measure of Martian Soils

Much of the Martian surface is covered with soil. It has been defined, for example, by Steven Squyres (MER scientific Principal Investigator) and colleagues as:

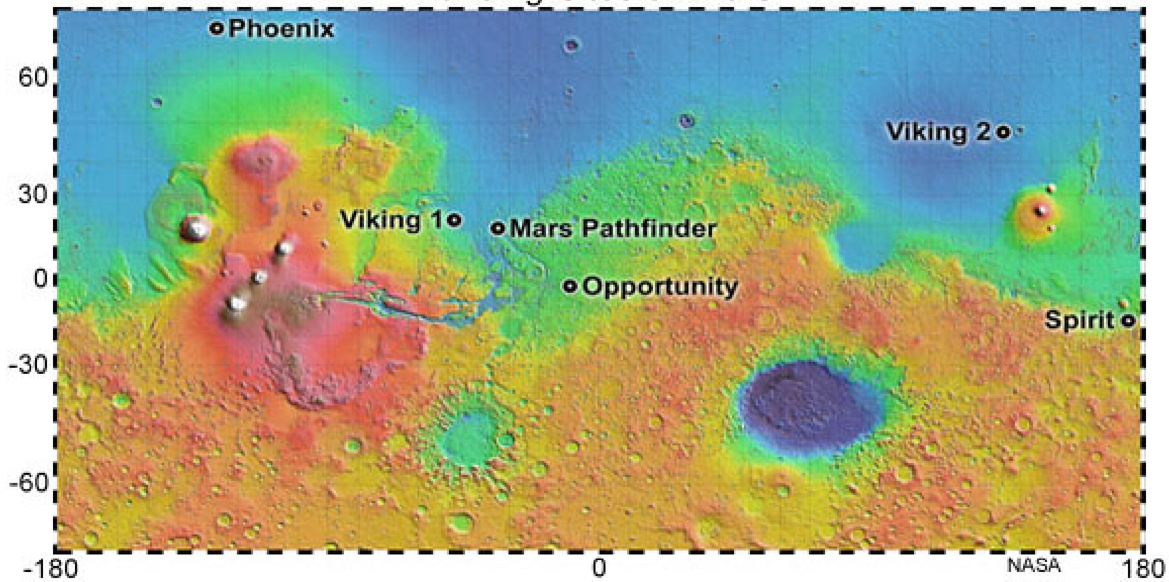
> "Any loose, unconsolidated materials that can be distinguished from rocks, bedrock, or strongly cohesive sediments. No implication of the presence or absence of organic materials or living matter is intended."

Martian soil is formed by the breakup and chemical alteration of rocks through a variety of processes including: physical weathering (by wind, water, ice, changes in temperature), mechanical breakup due to impact cratering, cosmic ray irradiation, reduction/oxidation, and aqueous chemical weathering. It contains a record of the planet's environmental conditions and geologic history that we have been piecing together for at least the past thirty years of exploration using spacecraft flybys, orbiters, robotic landers, and rovers. Some of the soil could have formed early in Martian history when the Red Planet had wetter and warmer conditions, more Earthlike than we see on it today. And perhaps, we may someday find evidence that Martian rock weathering and soil development included biological processes. (Some say we already have!) For all these reasons, characterizing the soil in detail is a critical undertaking. What with all the data gathered on the geology and atmosphere on Mars, scientists are still trying to determine any chemical and mineralogical coupling between soils and the surface rocks beneath them, which previous work has shown to be dominantly **basalt**. (For a review see the **PSRD** article: **Mars Crust: Made of Basalt**.) McSween, McGlynn, and Rogers looked carefully at soil data from two locations on opposite sides of the planet visited by the MER rovers not only to identify the minerals but also to quantify the mineral assemblages to better understand similarities and differences, and how they can be used to understand the Martian crust.

Tracks from the MER Opportunity rover cross the soil-covered Martian surface near Victoria Crater (on the horizon) in Meridiani Planum. This approximately-true-color scene was obtained by the rover's panoramic camera (Pancam) in May, 2007. Click image for more information.

Seven years ago this month, the MER Spirit rover landed in Gusev crater and MER Opportunity rover landed in Meridiani Planum carrying instruments able to, among many other things, directly identify various minerals in the soils. *In situ* mineral detection markedly enhanced the bulk chemical data obtained for soils from previous landed missions (e.g. **Viking** in 1976, **Mars Pathfinder** in 1997) and the chemical and mineralogical data obtained from orbit (e.g. **Mars Global Surveyor** in 1997, **Mars Odyssey** in 2001).

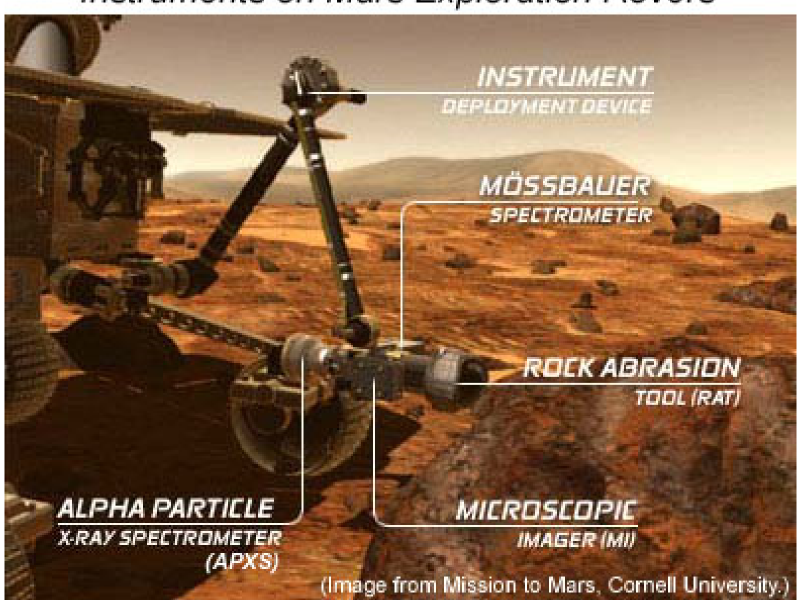
Landing Sites on Mars



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 in Meridiani Planum and Gusev crater, respectively. Note that Opportunity and Spirit landed 180^{o} apart. Phoenix landed in 2008.

The MER instruments of particular interest in the study by McSween and colleagues are the Miniature Thermal Emission Spectrometers (MiniTES), Alpha Particle X-ray Spectrometers (APXS), and Mössbauer spectrometers.

Instruments on Mars Exploration Rovers



This artist's rendition shows instruments on the MERs. The MiniTES is not shown in this view but is mounted at the bottom of the rover's mast, just off the top left corner of this picture. Scanning mirrors reflect light down to it. The APXS sensor head and Mössbauer Spectrometer, which are small enough to fit in the palm of your hand, are placed against rock and soil targets for analyses.

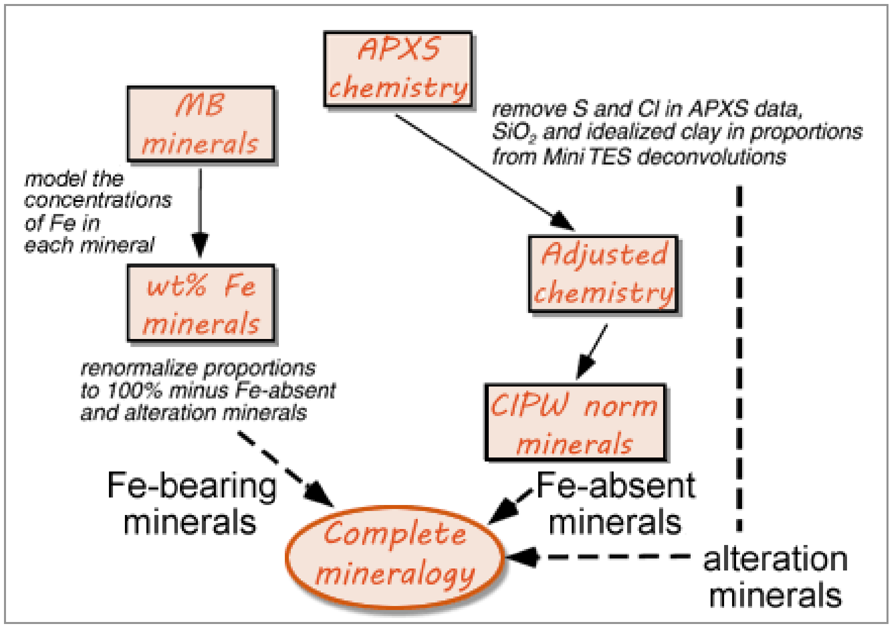
MiniTES acquires remote measurements of emitted thermal infrared energy (in the spectral range 5-29 μm) of the rocks and soils surrounding the MER rovers. Researchers use the data to determine the mineralogy of

Martian surface materials, including silicates, carbonates, sulfates, phosphates, oxides, and hydroxides. In 2008 Deanne Rogers and Oded Aharonson modeled the MiniTES spectra of sands on the Meridiani plains, and found an olivine basaltic composition plus a small amount of amorphous silica and sulfate. Their results (summarized in the right hand column of the table below) were consistent with data from other MER instruments and with prior orbital data acquired from Mars Global Surveyor's thermal emission spectrometer (**TES**). McSween, McGlynn, and Rogers completed a new, comparable MiniTES study of Gusev soils (shown in the table's middle column). Igneous minerals (olivine, pyroxenes, and feldpsars) dominate the miniTES-derived mineral abundances (in wt%) of the soils at both locations.

MiniTES-derived Mineral Abundances in wt% for Martian Soils		
Mineral	Gusev soil	Meridiani soil
Olivine	22 ± 4	17 ± 3
High-Ca Pyroxene	0	7 ± 4
Low-Ca Pyroxene	37 ± 10	23 ± 8
Feldspars	23 ± 9	25 ± 8
Sulfates	7 ± 2	8 ± 5
Silica	8 ± 4	10 ± 4
Clays	4 ± 4	5 ± 3
Other	0	4 ± 1
(From McSween *et al.* (2011) *JGR*, v. 115(E00F12), doi: 10.1029/2010JE003582.)		

Also carried on the MER Spirit and Opportunity rovers were the APXS, which measures abundances of rock-forming elements by direct contact with a rock or patch of soil. The instrument emits and measures backscattered alpha particles and x-rays from the target material. Another MER spectrometer placed directly against a rock or soil sample is the Mössbauer Spectrometer. It is especially designed to determine the composition and abundance of iron-bearing minerals, both igneous and those formed in watery environments. Previous work by McSween and colleagues in 2008 used a combination of APXS and Mössbauer data to quantify the total mineralogy of basaltic rocks in Gusev crater. But the mineral assemblages of Martian soils are more complex than those of Martian basaltic rocks, with the soils containing not only minerals derived by physical weathering of the basalts but also other minerals derived from rocks altered by chemical weathering. So McSween, McGlynn, and Rogers extended the previous methodology using APXS and Mössbauer data to the dark soils at both MER landing sites. The input chemical data included the average of 28 basaltic soils from Gusev and the average of 12 basaltic soil from Meridiani. Their mineral calculation procedure is illustrated in the flowchart shown below, for iron-bearing minerals (left side) and iron-absent minerals (right side). The calculations included corrections for the abundances of alteration minerals (notably sulfate, chloride, silica, clays) in the soils. McSween and coauthors used two different assumptions about the alteration phases involving sulfur and chlorine. Their Model 1 calculates the measured sulfur and chlorine as sulfate and chloride salts. This is consistent with TES and Mini-TES results. Their Model 2 assumes that the sulfur and chlorine are incorporated into or adsorbed onto fine-grained iron oxide minerals (schwertmannite and akaganeite) known to be present in the soils. This model is consistent with Mössbauer measurements.

Calculating the Complete Mineralogy of Soils at MER Landing Sites: Gusev Crater and Meridiani Planum

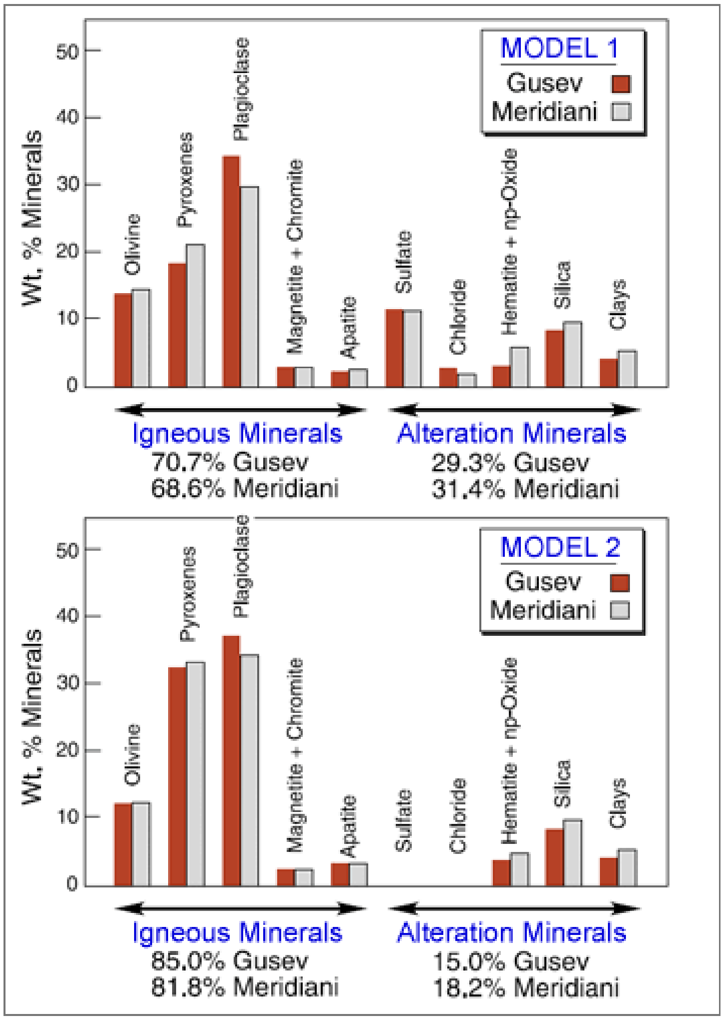


(Adapted from McSween *et al.*, 2010, *JGR*, v. 115(E00F12, doi:10.1029/2010JE003582.)

Diagram showing the method used by McSween and coauthors to calculate the complete mineralogy of soils from Gusev and Meridiani, Mars. Following the colored boxes from the top shows how Mössbauer (MB) data were used for iron-bearing minerals, APXS for iron-absent minerals, and MiniTES for silica and clays. The notes accompanying the boxes give more details and the reader is referred to the *JGR* research paper for complete details of the method.

McSween and coauthors' calculated mineral abundances are shown in the charts below. Results of Model 1 (on top) and model 2 (on the bottom) show that there are more igneous minerals (about 70-85% depending on the model) in the soils at each location than alteration minerals (about 15-30%). The authors note that the models may actually bracket the actual mineral abundances. The igneous minerals are olivine, pyroxenes, plagioclase, magnetite, chromite, and apatite. The alteration minerals are sulfate, chloride, hematite, nanophase oxide, silica, and clays. They propose that the presence of alteration phases in association with minerals like olivine and phosphate, which are easily weathered in the Martian acidic environment, suggests that the soils are physical mixtures of unrelated materials. The mere presence of olivine in the soils suggests limited exposure to water and aqueous alteration. The nearly identical modal mineralogy at two locations on opposite sides of the planet supports a prior hypothesis based on similar chemical compositions that soils have been homogenized, at least over large areas of the crust.

Model-Derived Mineral Abundances
of Average Gusev and Meridiani Soils

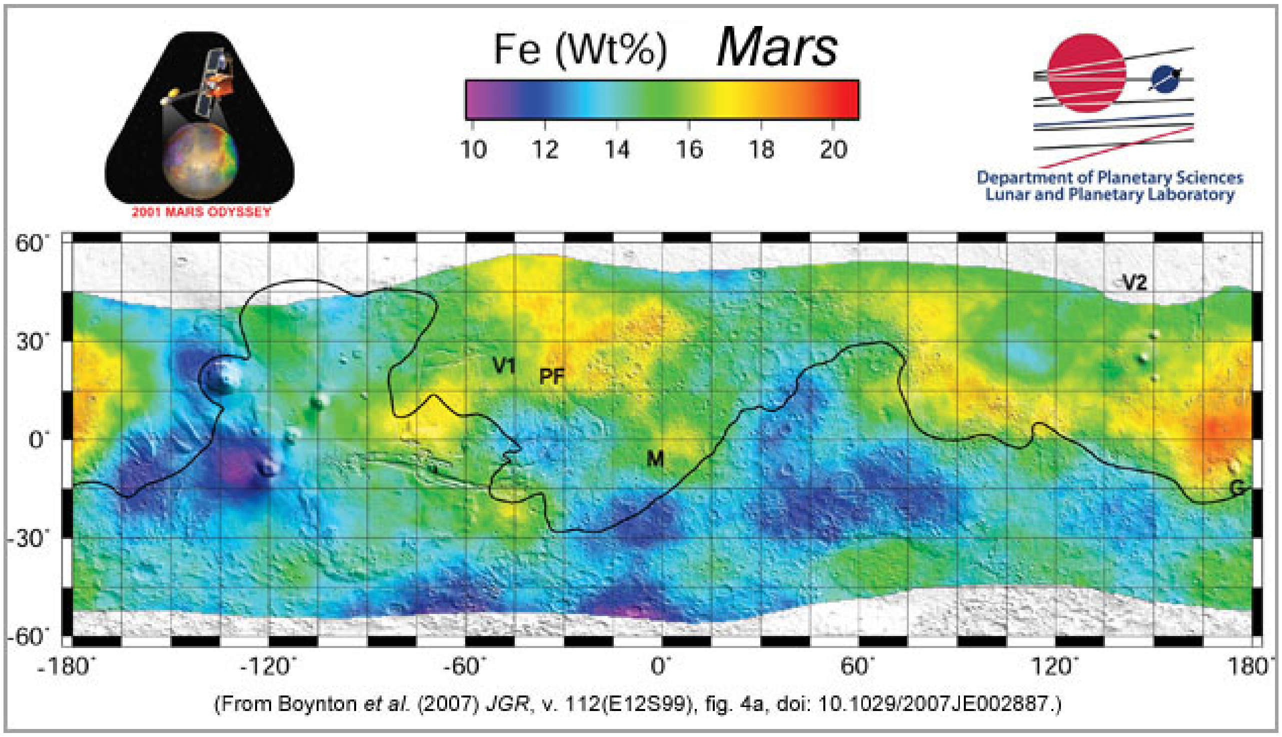


(From McSween *et al.*, 2010, *JGR*, v. 115(E00F12,
doi:10.1029/2010JE003582.)

Calculations of the mineralogy of average dark soils from Gusev crater and Meridiani Planum show a predominance of minerals derived from basaltic rocks, about 70-85% depending on the model. The remainder are alteration phases. Results of the two models by McSween and coauthors likely bracket the actual mineralogy of the soils.

Global Significance

If the soils at Gusev crater and Meridiani Planum are representative of the Martian crust, then in the simplest case, relatively unweathered basalts comprise about three-quarters (by weight) of the surface of Mars and older, aqueously altered rocks comprise the rest. The results of the models by McSween and coauthors seem to support the idea of a widespread surface soil layer having a uniform composition. How widespread? While Martian dust is moved globally by dust storms, the sand-sized and larger grains in soils would more likely be transported for kilometers at most. Soil homogenization may be occurring over regional areas, not necessarily over the entire globe. Do the orbital maps support these results? Yes and no. Mars Global Surveyor **TES** data and Mars Odyssey Gamma Ray Spectrometer (**GRS**) data show regional-scale variations in mineralogy and chemistry, respectively, including basaltic components. A map of iron concentrations in the mid-latitude region of Mars, shown below, is one example of GRS orbital data. Iron is among the most abundant elements on the surfaces of both Mars and Earth. This map clearly shows global variations in iron, but interestingly, the Meridiani (labeled M) and Gusev crater (G) landing sites lie in areas with similar iron concentrations.



This map of the iron concentrations in the mid-latitude region of Mars was determined from Mars Odyssey Gamma Ray Spectrometer data. A 0-kilometer elevation contour line is shown in black for reference. Landing sites are marked by letters. The map shows the global variations and regional patterns in iron concentrations. The Meridiani (M) and Gusev crater (G) landing sites are located in regions with similar iron concentrations.

Yet, global maps of orbital remote sensing data have not shown surface abundances of alteration minerals as high as those identified in the soils by McSween and coauthors. They offer three possible answers. The areal extents of sulfate and clay deposits have not been fully identified from orbit or they have been buried by younger volcanic flows or they have been preferentially weathered and mixed into soils in proportions not representative of the whole surface.

Continued mapping by the ESA Mars Express and the NASA Mars Reconnaissance Orbiter (**MRO**) missions will address this soil compositional disconnect. A big step will be taken by the NASA Mars Science Laboratory (**MSL**) rover mission, to be launched in late-2011. MSL will carry an APXS and a Laser Induced Breakdown Spectrometer for chemical analyses (see the **PSRD** article: **LIBS: Remote Chemical Analysis**), and a X-ray diffraction instrument for identifying minerals and their abundances using a different technology than used on the MER rovers. So we begin this new year contemplating the soils on Mars with data obtained by a host of advanced instruments *in situ* and in orbit, and anticipating the new discoveries that will be revealed during the next missions exploring the Red Planet and continued studies of Martian meteorites.

Additional Resources

Links open in a new window.

- **PSRDpresents:** Mineral Abundances in Martian Soils --**Short Slide Summary** (with accompanying notes).

- **Athena instrument package** on the Mars Exploration Rovers.
- Boynton. W. V. and 27 others (2007) Concentration of H, Si, Cl, K, Fe, and Th in the Low- and Mid-latitude Regions of Mars, *Journal of Geophysical Research*, v. 112(E12S99), doi: 10.1029/2007JE002887.
- McSween, Jr., H. Y., McGlynn, I. O., and Rogers, A. D. (2010) Determining the Modal Mineralogy of Martian Soils, *Journal of Geophysical Research*, v. 115(E00F12), doi: 10.1029/2010JE003582.
- McSween, Jr., H. Y. et al. (2008) Mineralogy of Volcanic Rocks in Gusev Crater, Mars: Reconciling Mössbauer, Alpha Particle X-Ray Spectrometer, and Miniature Thermal Emission Spectrometer Spectra, *Journal of Geophysical Research*, v. 113(E06S04), doi: 10.1029/2007JE002970.
- Rogers, A. D. and Aharonson, O. (2008) Mineralogical Composition of Sands in Meridiani Planum Determined from Mars Exploration Rover Data and Comparison to Orbital Measurements, *Journal of Geophysical Research*, v. 113, E06S14, doi: 10.1029/2007JE002995.
- Soderblom, L. A. and 43 others (2004) Soils of Eagle Crater and Meridiani Planum at the Opportunity Rover Landing Site, *Science*, v. 306(5702), p. 1723-1726, doi: 10.1126/science.1105127.
- Taylor, G. J. (2009) Mars Crust: Made of Basalt, *Planetary Science Research Discoveries*, **http://www.psrd.hawaii.edu/May09/Mars.Basaltic.Crust.html**.
- Yen, S. and 35 others (2005) An Integrated View of the Chemistry and Mineralogy of Martian Soils, *Nature*, v. 436, p. 49-54, doi: 10.1038/nature03637.

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