Hot Idea May 8, 2009

Mars Crust: Made of Basalt

--- Chemical analyses of rocks on the Martian surface indicate that the Martian crust was built of basalt lava flows not much different from those on Earth.

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By combining data from several sources, Harry Y. (Hap) McSween (University of Tennessee), G. Jeffrey Taylor (University of Hawai'i) and Michael B. Wyatt (Brown University) show that the surface of Mars is composed mostly of basalt not unlike those that make up the Earth's oceanic crust. McSween and his colleagues used data from Martian meteorites, analyses of soils and rocks at robotic landing sites, and chemical and mineralogical information from orbiting spacecraft. The data show that Mars is composed mostly of rocks similar to terrestrial basalts called tholeiites, which make up most oceanic islands, mid-ocean ridges, and the seafloor beneath sediments. The Martian samples differ in some respects that reflect differences in the compositions of the Martian and terrestrial interiors, but in general are a lot like Earth basalts. Cosmochemistst have used the compositions of Martian meteorites to discriminate bulk properties of Mars and Earth, but McSween and coworkers' synthesis shows that the meteorites differ from most of the Martian crust (the meteorites have lower aluminum, for example), calling into question how diagnostic the meteorites are for understanding the Martian interior.

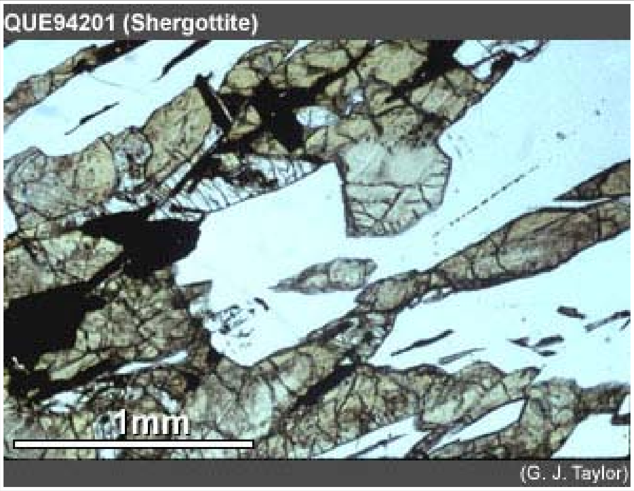
Reference:

- McSween Jr., H. Y., Taylor, G. J., and Wyatt, M. B. (2009) Elemental Composition of the Martian Crust. *Science*, v. 324(5928), p.736-739, doi: 10.1126/science.1165871.

PSRDpresents: Title --Short Slide Summary (with accompanying notes).

A Plethera of Geochemical Data

We now have lots of data on the chemical and mineral composition of Mars. The data come from samples we can hold in our hands, rocks and soils we hold in robot hands and analyze with instruments on the Martian surface, and analyses made from orbit high above the red, dusty surface. Each source provides a unique part of the geochemical puzzle of the Martian crust.



Martian meteorites

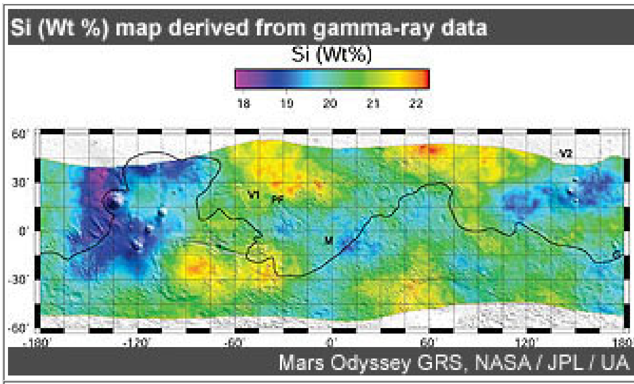
We have about 45 Martian meteorites in our collections on Earth. These have been invaluable in understanding the composition of not only the crust of Mars, but its interior as well. One group, the Shergottites, are clearly lava flows, as shown by the texture of the sample on the left. White is plagioclase feldspar (although transformed by high-pressure shock to glass), dark mineral is pyroxene, and black is titanium-bearing magnetite (iron oxide).

Surface Soils up close

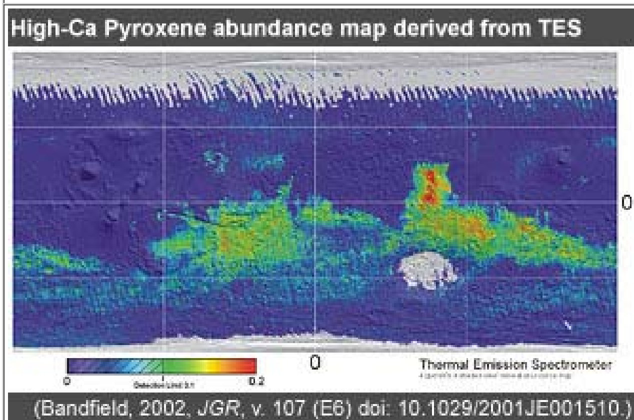
This high-resolution image from the panoramic camera (PanCam) on the Mars Exploration Rover Spirit shows the region containing the patch of soil at Gusev Crater. Using the alpha-particle-X-ray spectrometer (APXS) mounted on Spirit's robot arm, cosmochemists were able to determine the chemical composition of the soil here and in other places. The soils provide an average of local rocks mixed with fine, dusty materials produced locally, regionally, and even globally. Chemical data are also available for the Viking and Pathfinder landing sites.

Fresh rocks

This image was taken by the Mars Exploration Rover Spirit's panoramic camera during the rover's grinding of the rock nicknamed "Mazatzal." Both Spirit and Opportunity came equipped with brushing and grinding tools to remove dust and weathered material to allow access by the APXS to the fresh, unaltered interior. The grinder was called the "rock abrasion tool," or RAT. The picture shows the rock after the rover drilled 3.8 millimeters. The dark grey material around and in the left circular RAT hole is the underlying basaltic rock. The RAT hole is 4.5 cm in diameter.



Chemical analysis from orbit
The Mars Odyssey spacecraft, launched in April 2001, has been collecting data from a 500-km orbit since early 2002. One of its instruments is the Gamma-Ray Spectrometer (GRS), a remarkable device that allows us to measure global elemental concentrations of silicon (see map at left), iron, calcium, aluminum, potassium, thorium, chlorine, and hydrogen. It probes the surface to a depth of a few tens of centimeters (a foot and a half or so), but has a spatial resolution of about 500 km.



Mineral analyses from orbit
The Thermal Emission Spectrometer (TES) flew on the Mars Global Surveyor spacecraft, which entered Martian orbit in September 1997. After an arduous voyage to circularize its orbit using the atmosphere as a brake, it began its scientific mapping in April 1999 and continued to return fascinating data until late 2006. TES data can be used to determine the abundances of the major minerals on the Martian surface, such as the map of the abundance of high-calcium pyroxene shown at left. The mineral abundances can also be converted to chemical analyses. TES senses only the upper 100 micrometers or so, but it does so at a spatial resolution of about 1 km.

Each of these measurements has unique characteristics and provides different information. We can study Martian meteorites in excruciating detail in labs here on Earth, using state-of-the-art instruments. Lab analyses of meteorites are highly accurate and can detect low concentrations of elements and isotopes. However, we do not know where on Mars a specific meteorite comes from, so we cannot readily put them into the context provided by orbital imaging and spectroscopic data coupled with geologic mapping.

The measurements made by landers and rovers at landing sites provide information at known locations, but the analyses have greater uncertainty than do meteorite analyses, and landed instruments cannot detect low concentrations of elements. Nevertheless, the measurements of soil composition are highly informative, and have gotten better with each mission.

The orbital measurements by the TES and GRS instruments provide a global view of the chemical and mineralogical composition of the Martian surface. They see things differently, however. TES measures the spectrum of energy emitted in infrared wavelengths. From the measured spectra, which are pictures of the ground in boxes 3 x 6 kilometers in size, spectroscopists can determine the main minerals present. TES spectra can be modeled using minerals with known spectra and chemical compositions. Once the mineral abundances are calculated, the mineral chemistry can be used to figure out the chemical composition of the surface. However, the emitted energy comes from the upper 10 to 100 micrometers of surface grains, so even mild alteration by water can change the sensed mineralogy, hence change the inferred chemical composition.

In contrast, the gamma rays detected by the GRS, which are produced by nuclear reactions of cosmic rays with surface materials, come from the upper few tens of centimeters, much deeper than the source of the TES signal. On the other hand, the GRS has blurry eyesight--its spatial resolution is larger than the state of Arizona (which is about the size of Equador). The gamma-ray data are binned into grid points 5 degrees on a side (roughly 500 kilometer squares).

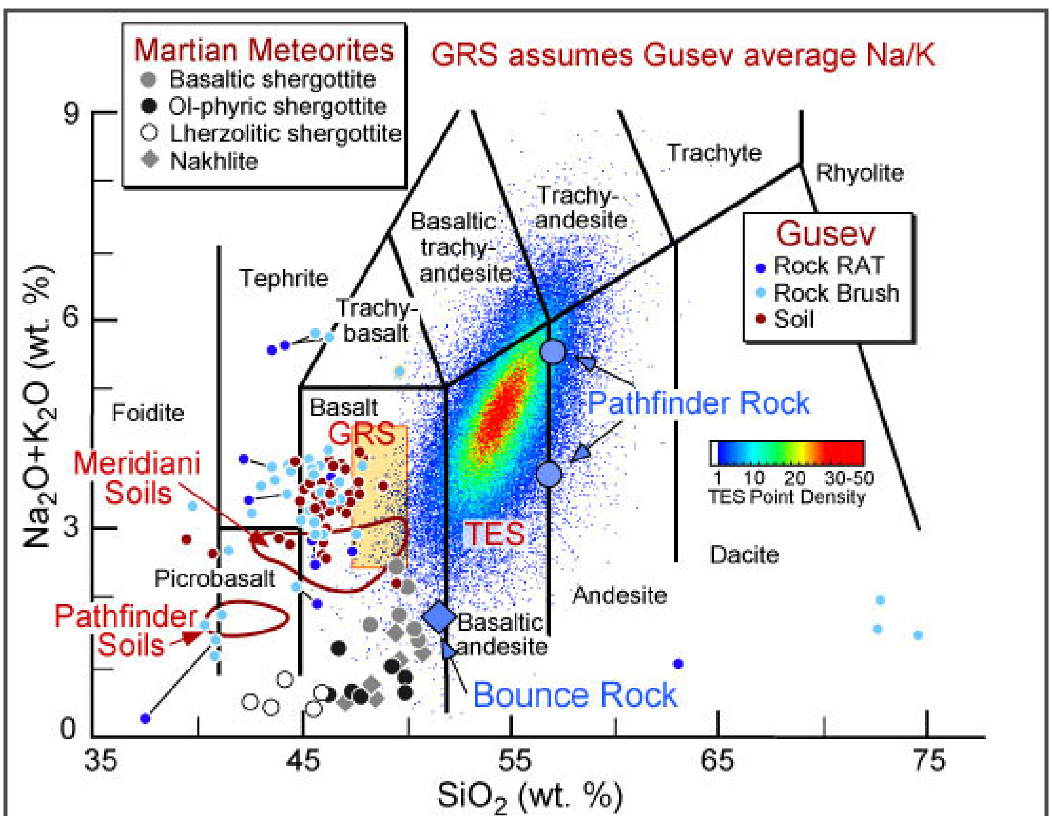
McSween and colleagues combine all these geochemical data to determine what type or types of igneous rock makes up the surface of Mars.

The Basalts of Mars

There has been a debate about the composition of igneous rocks on the surface of Mars. It all began soon after TES began probing the surface from its perch on Mars Global Surveyor. In 2000, Josh Bandfield, Vicky Hamilton, and Phil Christensen (Principal Investigator for and the inspiration behind the TES instrument) showed that the TES spectra for the northern plains of Mars differed significantly from the southern highland. The two regions had mineral abundances similar to basalt (Surface Type 1, in the south) and andesite (Surface Type 2, in the north), two common volcanic rock types on Earth. Andesite has more silicon than does basalt, giving rise to a distinctive mineralogy. More important, andesite is produced in large amounts by plate tectonics on Earth, although it can be made by crystallization of water-bearing basalt, too.

Cosmochemists had mixed reactions to the possibility of andesite on Mars, greeting the news with fascination, consternation, or skepticism. Cosmochemists Mike Wyatt, then a graduate student at the University of Tennessee, and Hap McSween took a different view of the TES results (see **PSRD** article The Tricky Business of Identifying Rocks on Mars). They used a different set of minerals in fitting the TES spectra, including minerals made by weathering of basalt. Their results show that weathered basalt also matches the spectral properties of Surface Type 2. The fundamental issue was whether the rocks contain igneous glass with a high concentration of SiO_2 or are coated with a coating of amorphous silica (almost pure SiO_2) produced by water-rock interactions. Analysis of rocks at the Spirit landing site in Gusev Crater shows that many rocks have such a silica coating, and that the inside of the rocks (revealed by the rock abrasion tool) is unaltered igneous rock. In addition, TES and other spectral instruments show that the dominant minerals on the surface of Mars are pyroxene, plagioclase, and olivine, the minerals that make up basalt.

The chemical compositions of rocks are a useful way to classify them. Geochemists are particularly enthusiastic about using the plot of total alkalis versus silica, as shown in the diagram below. On this diagram, the Gusev soils and rocks plot mostly in the basalt field, with a few containing less SiO_2. The soils at the Meridiani site (where the rover Opportunity landed) are similar, but contain a little less alkalis. Martian meteorites also plot in the basalt field, but have low alkalis.



(From McSween *et al.*, 2009, *Science*, v. 324, doi: 10.1126/science.1165871.)

Geochemists make frequent use of this diagram, which plots the total concentration of alkali elements sodium and potassium (expressed as oxides) versus SiO_2. Rocks are classified by where they plot on this diagram. Data for Martian meteorites, analysis of rocks and soils at landing sites, and the GRS data (global average in the center of the box, with one standard deviation marking the edges) cluster around the basalt field, indicating that the crust of Mars is dominated by basalt. The Martian meteorites have lower alkalis, suggesting that they are not abundant in the Martian crust. On the other hand, the TES data suggest basaltic andesite. TES data have been converted to oxide concentrations and plotted as a contoured cloud of points, with the red region having the most points and the blue area having the least number. Pathfinder rock (two estimates of its dust-free composition) also plots near the andesite field. The best bet is that the TES data and Pathfinder rock have been affected by interactions with water. If great expanses of the surface were composed of rocks with more than 50 wt% SiO_2, the GRS data would be shifted to the right.

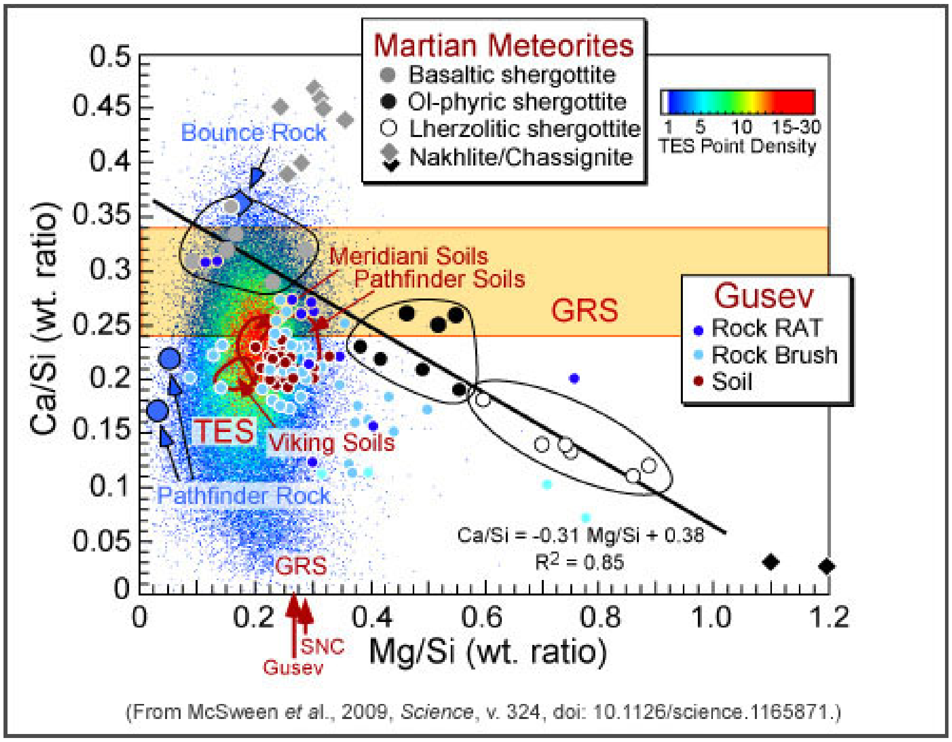
The GRS data are consistent with alkali-rich basalts being abundant on Mars. However, it did take some finagling to plot the GRS data on this diagram. We first converted the data to be on a volatile-free basis to get rid of the effects of weathering so we could see the igneous rock composition. We used our analysis of H (expressed as H_2O) and chlorine, and calculated sulfur from the sulfur to chlorine ratio at the landing sites (about 5). We had to estimate the Na2O concentration to plot the GRS data on this diagram because the GRS does not measure Na. We assumed that the Na/K ratio was the same as in Gusev rocks and soils. The result is that GRS data plot squarely in the basalt field.

The compositions derived from TES data and the inferred compositions of rocks at the Pathfinder site plot to the right of the other data, indicating rocks higher in SiO_2, which geochemists call basaltic andesites and andesites. (The Pathfinder "rock" is actually a calculated soil-free composition. The Pathfinder mission did not carry a RAT, so we have to contend with dust on the rock surfaces and the likely presence of a weathered zone.) We interpret the offset of the TES data and the Pathfinder rock from everything else as the effect of weathering. TES and the calculation procedure for estimating the soil-free rock at the Pathfinder site reflect the composition of the uppermost surface. Note that the Pathfinder soils fall in the basalt field.

The Martian crust appears to be made of basalt. But what kind of basalt?

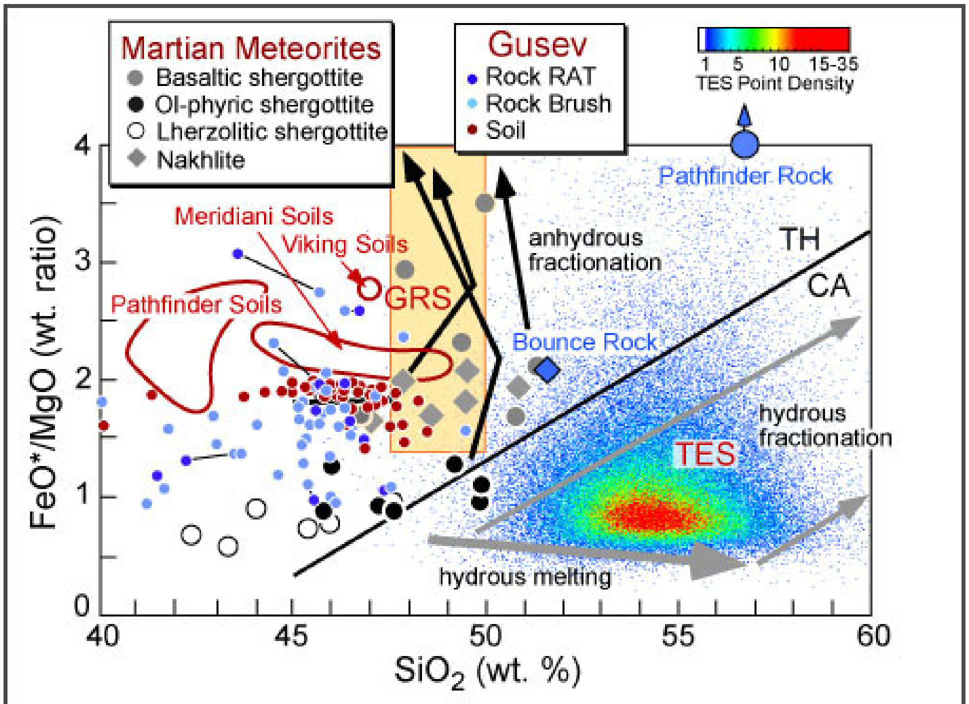
What Kind of Basalt?

Terrestrial calc-alkaline rocks and typical basalts (called tholeiites) form distinctive trends on diagrams such as the ratio of FeO to MgO versus SiO_2. To use our GRS data for this, we had to do another compositional trick because GRS does not measure magnesium. (The main reason is that the housing for the GRS detector is made largely of magnesium, so the background is too high to determine the concentration on the Martian surface.) Hap McSween came up with the trick, shown in the diagram below, a plot of Ca/Si versus Mg/Si, which has been used extensively to classify Martian meteorites. He noticed that the GRS range for Ca/Si intercepted a well-defined trend for the shergottite group of Martian meteorites. The average Ca/Si for GRS data intersects the shergottite line at a Mg/Si value of 0.29. Because we know the Si value for each GRS analysis, we can determine the Mg. As a check, the Gusev (Spirit landing site) rocks and soils has a mean Mg/Si of 0.27, indistinguishable from 0.29 (the uncertainty is about 0.1).



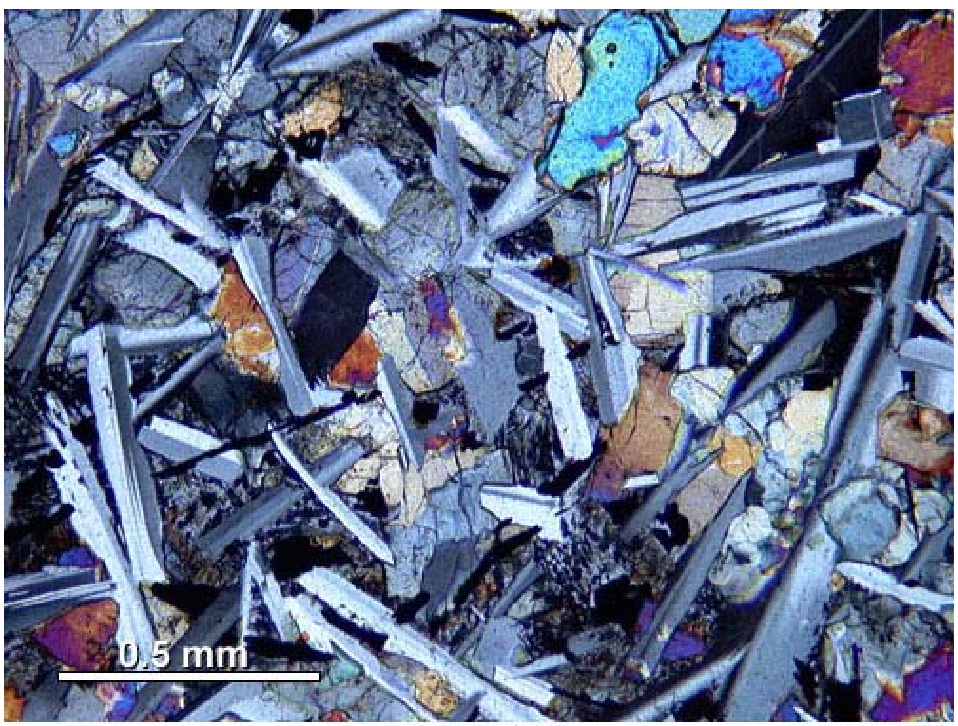
Ca/Si vs Mg/Si diagram used to classify Martian meteorites. The GRS data intersect the well-defined line for shergottites (the most common type of Martian meteorite), indicating a mean Mg/Si of 0.29. This is close to the average of soils and rocks at the Gusev crater site, 0.27 (see red arrows along the Mg/Si axis).

Iron, magnesium, and silicon behave in different ways when magmas are formed by partial melting in a planetary interior and during fractional crystallization of magmas holding chambers beneath volcanoes. This is shown clearly in the graph below, which plots FeO/MgO versus SiO_2. Two distinct trends are shown. The gray lines shows the calc-alkaline trend, which really means melting and crystallization of magma formed in a water-rich interior. The heavy gray line shows the trend during melting and the thinner gray lines show how magmas evolve during crystallization, from two different starting compositions. The other trend is shown by the black lines in which SiO2 does not change much, but the FeO/MgO ratio changes significantly. All the rocks and soils, and most of the meteorite points, plot in that area of the diagram. This is consistent with the type of magma called tholeiite, which makes up the basalt seafloor and oceanic islands on Earth. It appears that the Martian crust is made mostly of basalt like tholeiite.



(From McSween *et al.*, 2009, *Science*, v. 324, doi: 10.1126/science.1165871.)

FeO/MgO vs silica diagram used for distinguishing dry thoreiitic (TH) from wet calc-alkaline (CA) rocks. (The asterisk on FeO* denotes that the plot uses total iron expressed as FeO, hence not distinguishing ferrous from ferric iron.) All the Martian samples, including the global GRS data, plot in the tholeiite field. Arrows represent melting and magma evolution trends in terrestrial magmas. The TES data plot with the calc-alkaline rocks, but McSween and coworkers argue that this reflects surface weathering, not internal igneous processing.

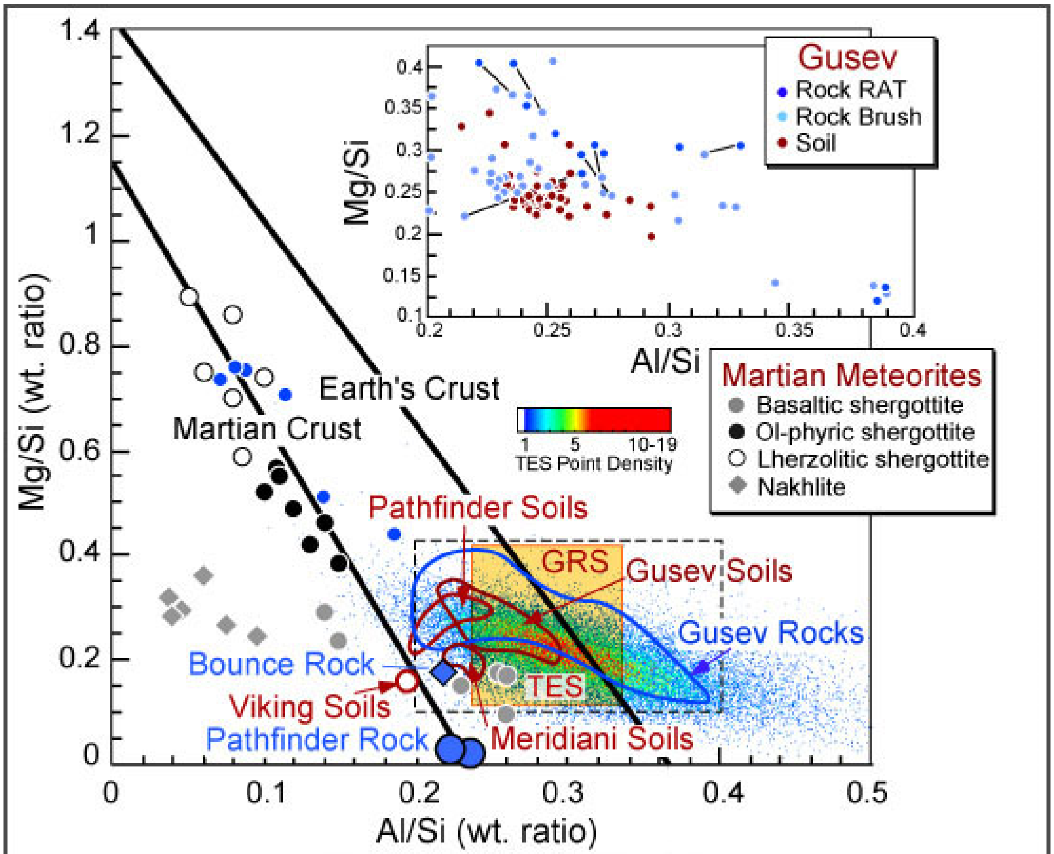


Hawaiian Basalt (G. J. Taylor)

In a thin section, the typical Martian basalt might look like this one from Hawai'i, if viewed in polarized light. The gray mineral is plagioclase, bluish green to blue grains near the top are olivine, and the remainder is mostly high-Ca pyroxene.

So What's With the Meteorites?

Cosmochemists have attached a lot of importance to the compositions of Martian meteorites, including using them as the basis for determining the bulk composition of Mars. However, in the diagrams shown above, the meteorites seem to be different from the rocks and the global GRS data. This is reinforced in the diagram below, in which we plot Mg/Si versus Al/Si. All the rock and soil, GRS, and even TES data plot along a line defined by rocks in the Earth's crust. The Martian meteorites are offset from this line, to lower Al/Si.



(From McSween *et al.*, 2009, *Science*, v. 324, doi: 10.1126/science.1165871.)

This Mg/Si versus Al/Si diagram has been used to discriminate between Mars and Earth rocks, when Martian meteorites represented all we knew about Mars rocks. The Martian meteorites were distinctly lower in aluminum. Gusev and GRS data, however, do not show this depletion in Al and plot along the same line as do Earth rocks.

Mars clearly has a complicated, heterogeneous interior. Melting inside Mars can produce rocks not dissimilar from those on Earth and rocks like the Martian meteorites. In fact, the Martian meteorites are a diverse group of samples that come from numerous separate places in the Martian mantle. On the other hand, Mars rocks are different in some respects from Earth rocks. The biggest difference is that Mars basalts, as shown by the meteorites and by GRS analyses of the surface, have more FeO in them than do Earth rocks (16 to 18 wt% versus about 10 wt% on Earth). Nevertheless, these two planets produced similar types of basalts, dominated by tholeiites.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** Title --Short Slide Summary (with accompanying notes).

- Bandfield, J. L., Hamilton, V. E., and Christensen, P.R. (2000) A Global View of Martian Surface Compositions from MGS-TES. *Science*, v. 287(5458), p. 1626-1630, doi: 10.1126/science.287.5458.1626.
- McSween Jr., H. Y., Taylor, G. J., and Wyatt, M. B. (2009) Elemental Composition of the Martian Crust. *Science*, v. 324(5928), p.736-739, doi: 10.1126/science.1165871.
- Wyatt, M. B. and McSween Jr., H. Y. (2002) Spectral Evidence for Weathered Basalt as an Alternative to Andesite in the Northern Lowlands of Mars. *Nature*, v.417(6886), p. 263-266, doi: 10.1038/417263a Letter.