PERSPECTIVES: PLANETARY SCIENCE

The Latest News from Mars

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After the recent sad news from Mars, it is refreshing to hear positive news coming from the red planet. On page 1626 (*1*), Bandfield *et al.* interpret data obtained by the Mars Global Surveyor spacecraft, which continues to orbit Mars. The study sheds light on the global surface composition of Mars and suggests that Mars' crust has evolved in a distinctly different way from that of Earth, through processes that we can currently only speculate on.

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Bandfield *et al.* study thermal emission spectrometer (TES) data obtained by the Mars Global Surveyor spacecraft. They concentrate on low-albedo regions, which are presumed to be relatively free of windblown dust. The TES data for these regions show two distinct spectral types. Comparison to terrestrial rock spectra and "mixing" of mineral spectra to fit the TES spectra lead Bandfield and colleagues to conclude that the two spectral types represent silica-poor mafic volcanic rocks such as basalts and more evolved, silica-rich mafic volcanic rocks. The authors refer to the latter as andesite. On Earth, the term andesite immediately conjures up a specific type of uniquely terrestrial rock-forming process, namely volcanism above subducting oceanic lithosphere (*2*). Most andesitic volcanic rocks on Earth occur at such locations. The authors quickly point out that subduction has not occurred on Mars and that the origin of the more evolved rocks on Mars must be different.

Mars, like Earth, is a planet with two distinct types of terrain: an older one at higher elevation and a younger one at lower elevation. (On Earth, the two terrains are the older continental crust and the younger oceanic crust). Unlike Earth, the two terrains on Mars neatly divide the planet in two. The southern hemisphere of Mars is home to the heavily cratered, and thus older, highlands that represent the ancient crust of the planet (*3*). The northern hemisphere contains the lowlands that are covered by younger volcanic units (*3*). The two types of TES spectra broadly correlate with this global dichotomy. The basaltic rocks occur in parts of the southern highlands, whereas vast areas of the northern lowlands contain the more evolved composition [see the figure (*1*)].

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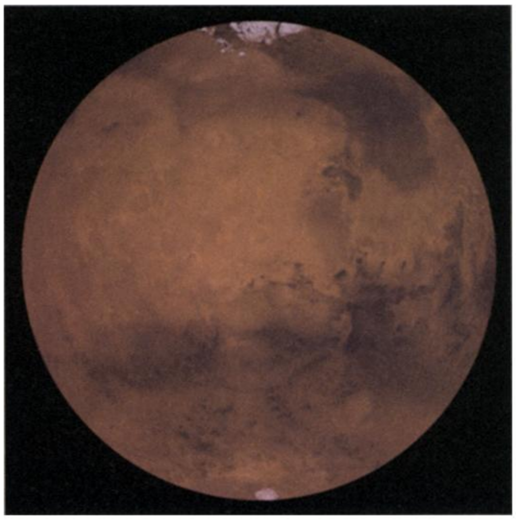
The implications of the TES results are puzzling on several levels. First, one has to wonder why a fundamental change in volcanism occurred on Mars. That the ancient martian crust in the southern highlands contains basaltic material is no great surprise. Basaltic volcanism is perhaps the most common type of igneous activity in the solar system; it has occurred on Earth, Mars, the moon, the asteroid 4 Vesta, and other asteroids that are meteorite parent bodies (*4*). On Earth, basaltic rocks are found throughout the geologic record, and basaltic volcanism is still the reigning type of igneous activity. What may have caused a shift in magmatism on Mars?



Hemispherical view of Mars constructed from Viking Orbiter images. The view is centered on the equator and longitude 90°. The dark region in the northeast of the image is Acidalia Planitia, one of the regions dominated by more evolved, silica-rich rocks. The southern highlands south and just east of Valles Marineris in the center of the image are an area dominated by more basaltic rocks. The four largest and youngest volcanoes on Mars visible on the western side of the image do not fit into the two basic spectra types identified by Bandfield *et al.* (*1*). [Image courtesy of the U.S. Geological Survey]

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Second, it is hard to imagine how the more evolved composition could have formed in apparently vast quantities on Mars. On Earth, substantial quantities of more evolved volcanics erupt in island arcs or along continental margins above sites of subduction of oceanic crust (*2*). As mentioned, this process has not occurred on Mars. Evolved volcanics can also erupt in areas where more primitive, basaltic magmas undergo fractional crystallization and/or assimilation within the crust. Only a fraction of basaltic magma undergoes this process, and basaltic rock is typically extruded on the surface along with only small quantities of the more evolved compositions (*5*). On Earth, fractionation of basaltic magmas at depth more commonly occurs where the crust is thicker. This begs the question of why the process occurred in the northern lowlands where the martian crust is thinner (*6*).

There is some concordance between the TES data and earlier results from Mars. The Mars Pathfinder alpha proton x-ray spectrometer (APXS) measured the major element composition of several large rocks that lay close to the lander. The APXS team concluded that these rocks are evolved, silica- and alumina-rich igneous rocks, similar to terrestrial andesites (*7*). This came as a surprise to many scientists studying the martian crust. The TES results suggest that this may be a characteristic of a large fraction of the martian surface and not a localized phenomenon.

Bandfield and colleagues do not find large regions that match the spectra of the only martian rocks of which we have samples—the martian meteorites (*1*). The martian meteorites are a suite of mostly young igneous rocks (*7*). One exception is Allan Hills 84001, which is roughly 4500 million years old and almost certainly comes from the ancient crust in the southern highlands. ALH 84001 is a rock from deep in the martian crust, and this rock type is probably an insignificant fraction of the exposed bedrock. The remaining martian meteorites are 1300 million years old or younger, and almost half of them are only about 180 million years old (*8*). Attempts to locate possible impact crater launch sites for the martian meteorites show that the most promising sites are in the Tharsis Montes/Olympus Mons regions (*8*, *9*). The TES spectra from these regions apparently do not identify the specific surface rock type (*1*).

Mars shares several general planetological characteristics with Earth, but the TES data suggest that Mars has marched to the beat of a different drummer, producing a distinctly different crustal evolution and surface geology. Refinement of these initial TES results and further observations of Mars should help bring these perplexing results into sharper focus. Particularly important are Mars sample return missions to provide documented specimens of the martian crust that can be subjected to detailed study. This will provide ground truth for the TES and other remote sensing measurements of Mars that cannot be satisfied by the martian meteorites.

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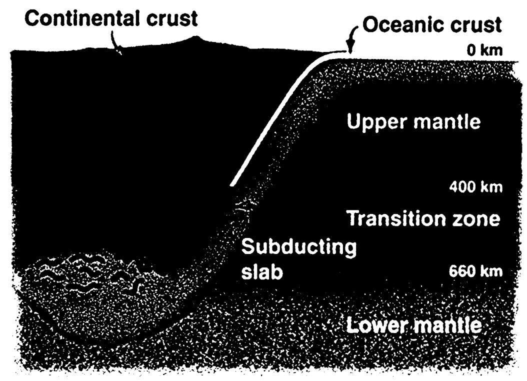
PERSPECTIVES: MANTLE GEOPHYSICS

Clues from a Shocked Meteorite

Masaki Akaogi

Earth's crust contains silicon, aluminum, and alkali metals in higher abundances than in the mantle. In particular, the abundance of sodium and potassium in the crust is one or two orders of magnitude higher than that in the average mantle. It is generally accepted that the crust was formed by transportation of magmas that were produced in the mantle and enriched in the above elements. Feldspars—mineral solid solutions in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$CaAl_2Si_2O_8$—are major hosts of alkali elements and are among the most abundant constituent minerals of Earth's crust. However, little is known about alkali-host minerals in the deep Earth, and behaviors and transport processes of alkali elements to the crust are not well understood. A hollandite-structured phase in the system $NaAlSi_3O_8$-$KAlSi_3O_8$ has been proposed as a likely alkali-host mineral in the transition zone and the lower mantle (*1*), but this phase has never been found in nature. On page 1633 of this issue, Gillet *et al.* (*2*) report the natural occurrence of $NaAlSi_3O_8$-rich hollandite, not in rocks derived from Earth's mantle but in a meteorite from interplanetary space.

Many meteorites show evidence for high-velocity collisions of parental asteroids. Shock compression at the collision produces very high pressure and temperature, in some cases in excess of 50 GPa and 2000°C, inducing phase transitions and melting of minerals. Dense silicate minerals such as ringwoodite, majorite, ilmenite, and perovskite, which Earth scientists accept as constituent minerals of the transition zone (at depths of 400 to 660 km) and the lower mantle (660 to 2900 km), have been discovered in shocked meteorites (*3*). Hence, shocked meteorites can serve as a window to look down into Earth's deep interior.



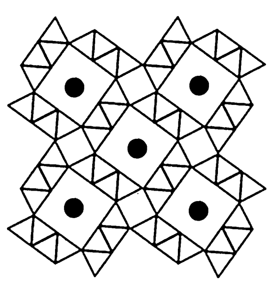
Deep down inside Earth. Hollandite can be stable in subducted crustal materials in the transition zone and the upper part of the lower mantle (red).

Gillet *et al.* (*2*) have identified the hollandite phase in the heavily shocked Sixiangkou meteorite by micro-Raman spectroscopy and x-ray microdiffraction. Tomioka *et al.* (*4*) have also reported the occurrence of the same structured mineral in the shocked Tenham meteorite by analytical transmission electron microscopy.

Gillet *et al.* (*2*) tightly constrained the peak pressure and temperature in the shock synthesis processes of the hollandite, based on high-pressure experiments (*1*, *5*). The absence of calcium ferrite–structured $NaAlSiO_4$ and stishovite indicates a peak pressure of about 23 GPa. This pressure corresponds to the interface between the transition zone and the lower mantle. An assemblage of majorite-garnet solid solution and magnesiowüstite observed in the shock veins constrained the temperature to 2000° to 2300°C. This very high synthesis temperature is consistent with the stability field of $NaAlSi_3O_8$-rich hollandite suggested by high-pressure experimental studies (*1*).

Hollandite has a unique structure (see the figure to the right), consisting of edge-sharing $(Si,Al)O_6$ octahedra, eight members of which form large tunnels, with Na and K occupying the sites in the tunnels. Compared with feldspars, which have a framework of $(Si,Al)O_4$ tetrahedra, hollandite in the system $NaAlSi_3O_8$-$KAlSi_3O_8$ is about 40 to 50% higher in density. In spite of its dense structure, hollandite can accommodate large mono- and divalent cations, including Na, K, Rb, Sr, and Ba (*6*). It is generally accepted that these elements, except for Na, are "incompatible" elements, which are incorporated preferentially in melt rather than in coexisting minerals, when partial melting occurs in the upper mantle. However, hollandite can be a host mineral of these "incompatible" elements with large cation sizes.

The identification of $NaAlSi_3O_8$-rich hollandite in a natural material has important implications for the behavior and processing of alkali elements in Earth's deep mantle (see the figure above). It is widely accepted that oceanic crust and sediments are subducted into the transition zone and presumably into the lower mantle (*7*). A part of the continental crust can also be subducted into the deep mantle. These crustal materials can be returned to Earth's surface as components of magmas derived from the mantle. Because the subducted crustal materials have high abundances of Na, K, Si, and Al, the hollandite phase in the system $NaAlSi_3O_8$-$KAlSi_3O_8$ is likely to form in the depth range of the transition zone and the upper part of the lower mantle. In low-temperature regions of subducting slabs, $KAlSi_3O_8$-rich hollandite would be stable, whereas $NaAlSi_3O_8$-rich hollandite could reside in high-temperature regions such as ascending plumes. It is recognized that the subduction of oceanic crust and sediments introduces large amounts of water as hydrous minerals into the upper mantle, the transition zone, and presumably the lower



Crystal structure of hollandite. Large alkali cations (circles) are accommodated in the large tunnels of the structure.

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