Headline Article

October 26, 2012

Exploring the Mantle of Mars

--- Cosmochemistry and geophysics experts meet to discuss what we know and do not yet know about the composition, structure, and evolution of the Martian mantle.

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About 65 Mars specialists met at the Lunar and Planetary Institute in Houston, Texas, September 10-12, 2012, to discuss what we know about the mantle of Mars from meteorites, high-pressure experiments, geophysical and remote sensing data, and theory. The valuable but incomplete meteorite record shows clearly that Mars melted and **differentiated** into a dense iron-rich core and rocky mantle 4.5 billion years ago. This event produced chemically distinct regions of the mantle that finally melted hundreds of millions of years ago to make the magmas that produced the meteorites. Other melting events produced the older portions of the crust, most of which formed before 3.5 billion years ago. Still unknown are how many distinctive source regions formed, when they melted to form magmas, how they melted, the vigor of mantle convection and how the distinctive regions were preserved during convection, and whether the mantle has mineralogical changes with depth. Planetary scientists hope that additional meteorite samples, the current Curiosity rover mission, the geophysical InSight mission, and the future Mars Sample Return mission will give them crucial information to answer these questions.

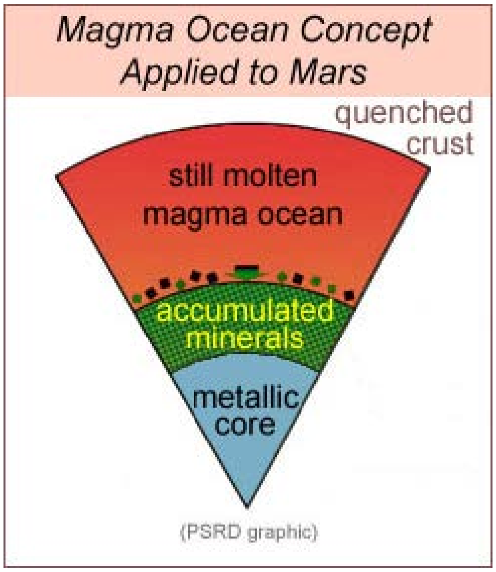
Reference:

- *The Mantle of Mars: Insights from Theory, Geophysics, High-Pressure Studies, and Meteorites,* Meeting from September 10-12, 2012, LPI Contribution No. 1684. Lunar and Planetary Institute, Houston. This meeting was convened by Mars experts Jim Papike and Charles Shearer (University of New Mexico) and Dave Beaty (Jet Propulsion Laboratory). [**Meeting website**]

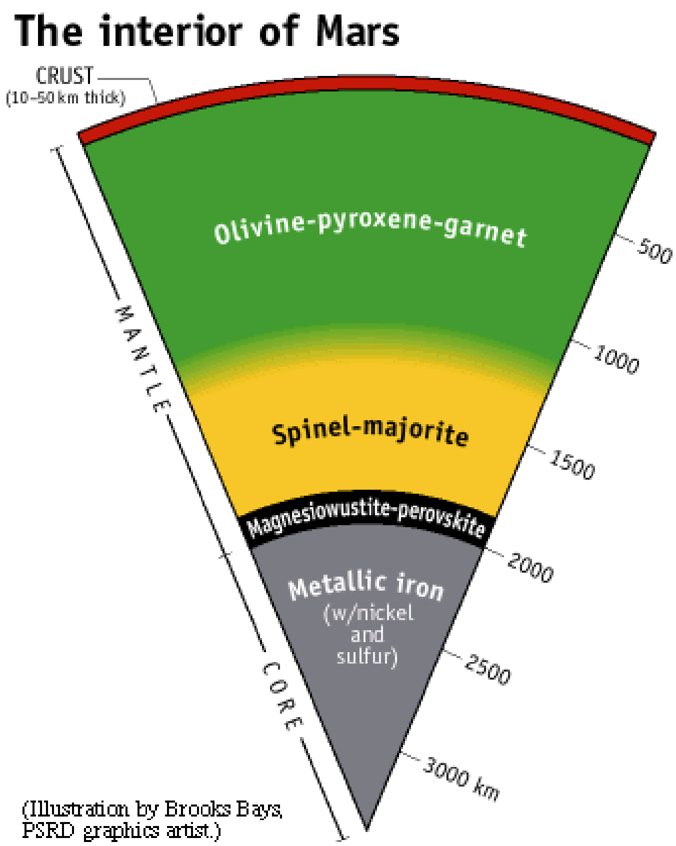
Melting, Crystallization, Rearrangement, Cooling, Crust Formation, and Who Knows What Else?

There is nothing easy about figuring out a planet's chemical and mineralogical composition, the formation of its crust and concomitant evolution of its mantle, and its present thermal state and structure. But it's an irresistible challenge at the core of planetary science.

The Martian bulk chemical composition (the composition of the entire planet, from metallic core to red surface) is centrally important to understanding how planets **accreted** from countless planetesimals. Understanding its primary differentiation into core, mantle, and perhaps primitive crust allows us to compare to the larger Earth and smaller Moon and Mercury. (Cosmochemists have shown that it is likely that the Moon and terrestrial planets began in a molten state, each surrounded by an ocean of magma.) Knowing how a slowly-moving mantle transports material from depth and back down again (a process called convection) and the timing and speed of this process is intimately tied to understanding the history of magmatism in Mars and formation of its crust. The challenge is to unravel all this.



The magma ocean concept, originally devised to explain the composition of the lunar highlands crust, has been applied to Mars as well. The concept is that Mars began molten and then crystallized, with denser minerals sinking to the bottom or crystallizing there initially. But in contrast to the Moon, low-density minerals did not form on Mars until quite late in the crystallization sequence, so no floatation crust formed. The chief evidence for a magma ocean on Mars is the ancient ages for mantle source regions (see below).



(Illustration by Brooks Bays, PSRD graphics artist.)

Experiments done by C. Bertka and Y. Fei (Carnegie Institution of Washington) give us one possible view of the interior of Mars. In this picture, the uppermost mantle of Mars consists of olivine and pyroxene, with a small amount of garnet (shaded green). These are common minerals on Earth, the other planets, the Moon, and asteroids. However, at a depth of about 1100 km, the olivine begins to convert to a more dense form, called gamma-spinel, without changing its chemical composition. The conversion is complete by 1300 km. Along with the conversion of olivine to a spinel crystal structure, garnet and pyroxene convert to a mineral called majorite, which has a crystal structure like garnet, but is close to pyroxene in chemical composition (shaded yellow). At higher pressures, hence deeper, there is a relatively abrupt transition at 1850 km (shaded black) to a mixture of perovskite (itself a mixture chemically of $MgSiO_3$ and $FeSiO_3$) and magnesiowustite (a mixture of FeO and MgO). The metallic core (shaded gray) begins at about 2000 km depth and continues to the center at a depth of 3390 km. This useful view is by necessity simplified as it assumes a uniform chemical composition for the mantle, but meteorites tell us that the mantle is heterogeneous.

Meteorites: Probing Time and Composition

Samples of planets, the Moon, and asteroids store incredibly detailed information about composition, origin, and timing. Cosmochemists use high-tech analytical instruments to extract that information. A vast array of analytical gear provides data on trace element and **isotope** abundances, complete mineralogy and mineral compositions, ages, and geophysical properties. The only downside to Martian meteorites is that we do not know for sure where they come from on the planet and it appears that they are not representative of all the rocks in the Martian crust. Nevertheless, analysis of Martian meteorites provides a strikingly quantitative look into Martian geochemical history. Because basaltic magma forms by partial melting of the mantle, Martian lava flows are surprisingly reliable probes of the deep interior of the mantle.

A particularly important piece of cosmochemical insight from meteorite studies is that two compositionally-distinct regions in the mantle formed 4.5 billion years ago, and remained unchanged for 4 billion years in spite of widespread volcanism and mantle melting. Then, beginning about 500 million years ago these distinctive regions began to melt sporadically to form the **shergottite** class of Martian meteorites. See **PSRD** article: **The Multifarious Martian Mantle**. (Shergottites formed as lava flows and compose the largest group of Martian meteorites.) The two groups are characterized by several chemical properties, as shown in the table and diagrams below. The parameters include elemental abundances such as the lanthanum/ytterbium ratio (La/Yb) and several isotopic ratios associated with radioactive isotopes such as samarium/neodymium (Sm/Nd), rubidium/strontium (Rb/Sr), and lutetium/hafnium (Lu/Hf). These ratios involve elements that can separate from each other during planetary processing such as partial melting of the mantle to make magma. When combined with radioactive isotope decay, cosmochemists can determine when the separation (called "fractionation") occurred. These elemental and isotopic differences are accompanied by distinct differences in oxidation state.

Taken together, the data clearly indicate at least two distinct reservoirs in the Martian mantle. There are, as is often the case in cosmochemistry, intermediate cases, too. The important point is that the range in inferred mantle compositions of different parts of the Martian mantle shows that the mantle is chemically and mineralogically heterogeneous. When did this heterogeneity arise?

Enriched Reservoir	high La/Yb low Sm/Nd ($-\varepsilon_{Nd}$) high Rb (high $^{87}Sr/^{86}Sr$) oxidized
Depleted Reservoir	low La/Yb high Sm/Nd ($+\varepsilon_{Nd}$) low Rb (low $^{87}Sr/^{86}Sr$) reduced

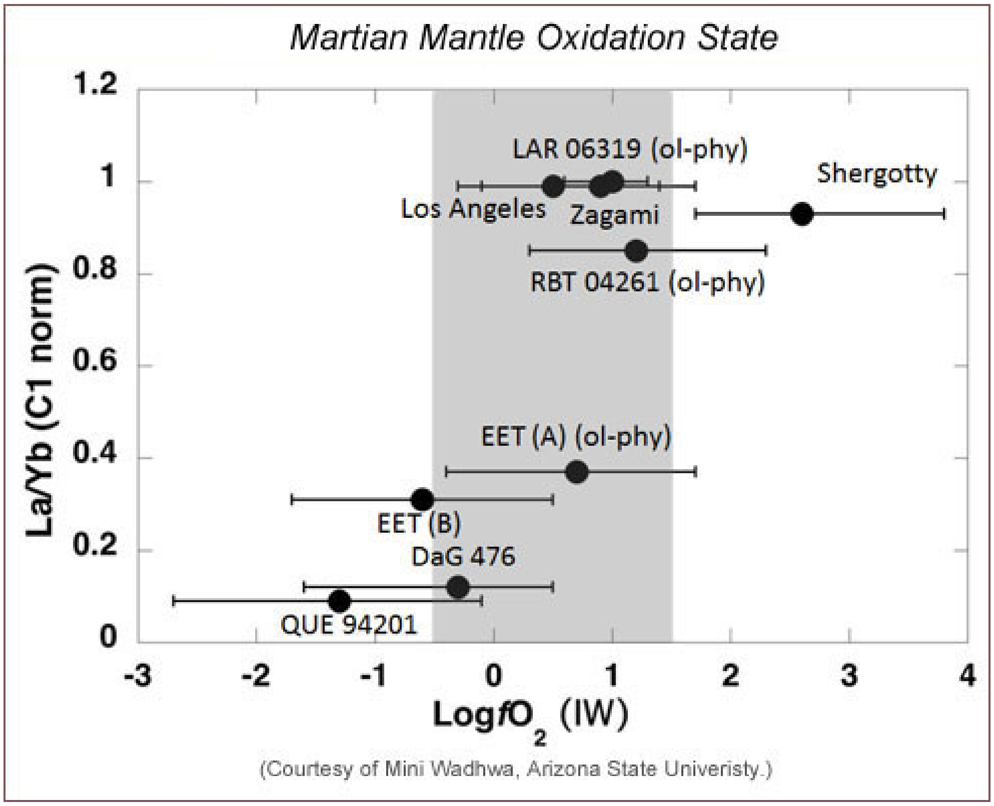
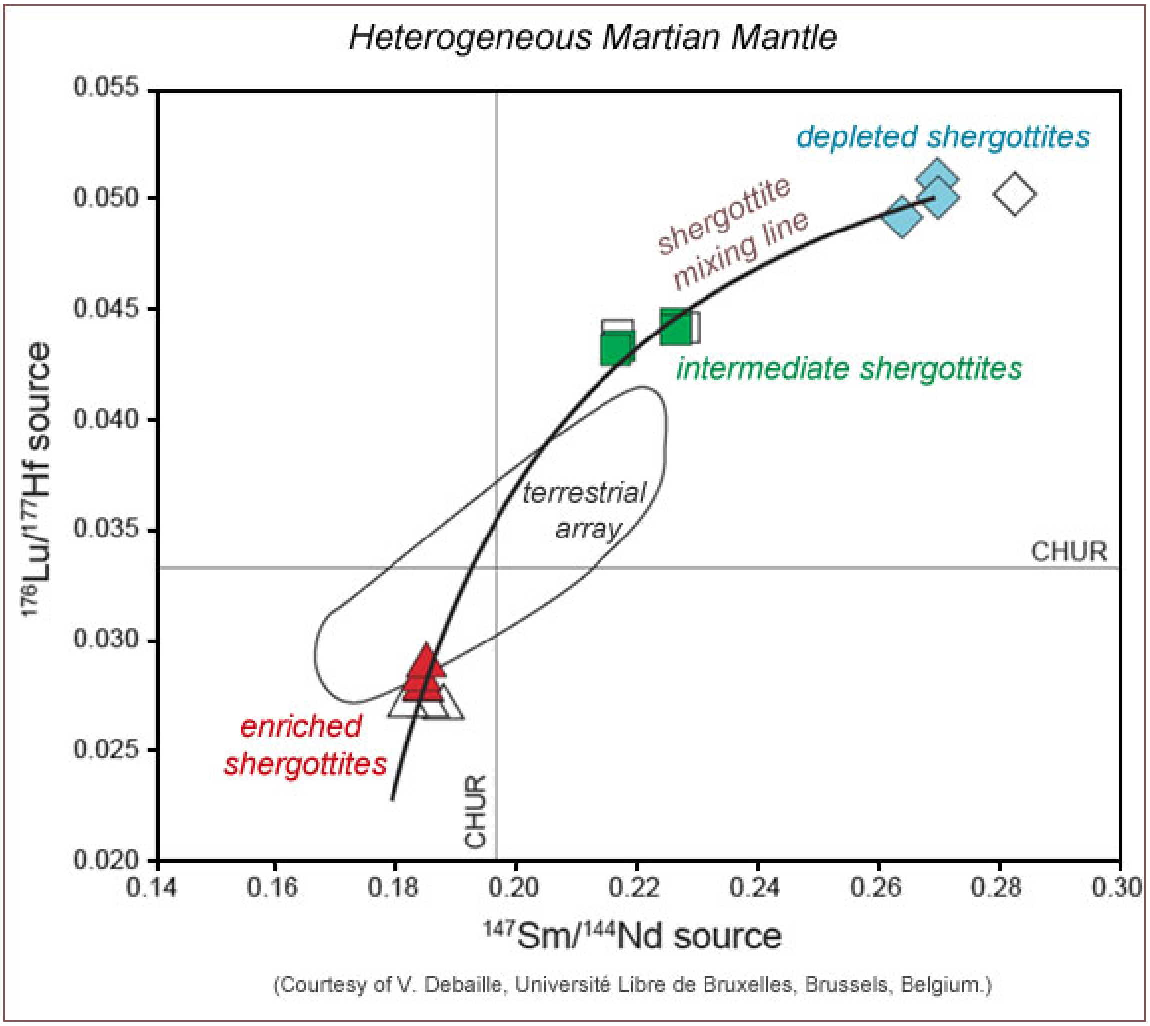
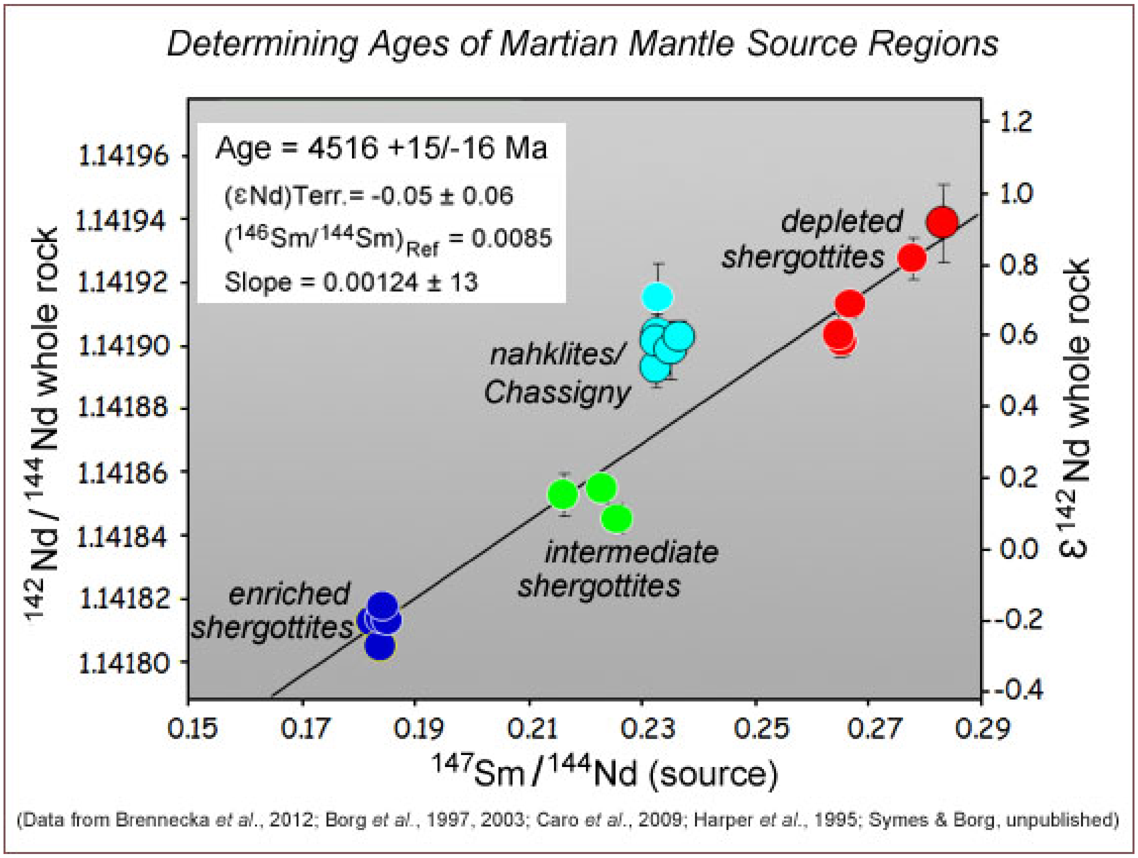


Diagram of data for a variety of Martian shergottite meteorites showing how oxidation state, expressed as the oxygen fugacity (related to the partial pressure of oxygen available to react), varies with the ratio of lanthanum to ytterbium. The La/Yb elemental ratio is divided by the ratio in primitive carbonaceous chondrites (that's what the "C1 norm" means). The oxygen fugacity is in relation to the value when both metallic iron and iron oxide (FeO) are both present in equilibrium with each other and oxygen. Note the two distinct groups, one more reduced (lower fO_2) with lower La/Yb than the other. The points show the fO_2 of the mantle source regions, determined from the abundance of europium (which is very sensitive to oxidation conditions). The gray area shows the range in fO_2 of the shergottite lava flows, which may have been affected by crystallization or loss of volatiles, so only indirectly record oxidation conditions in the mantle.



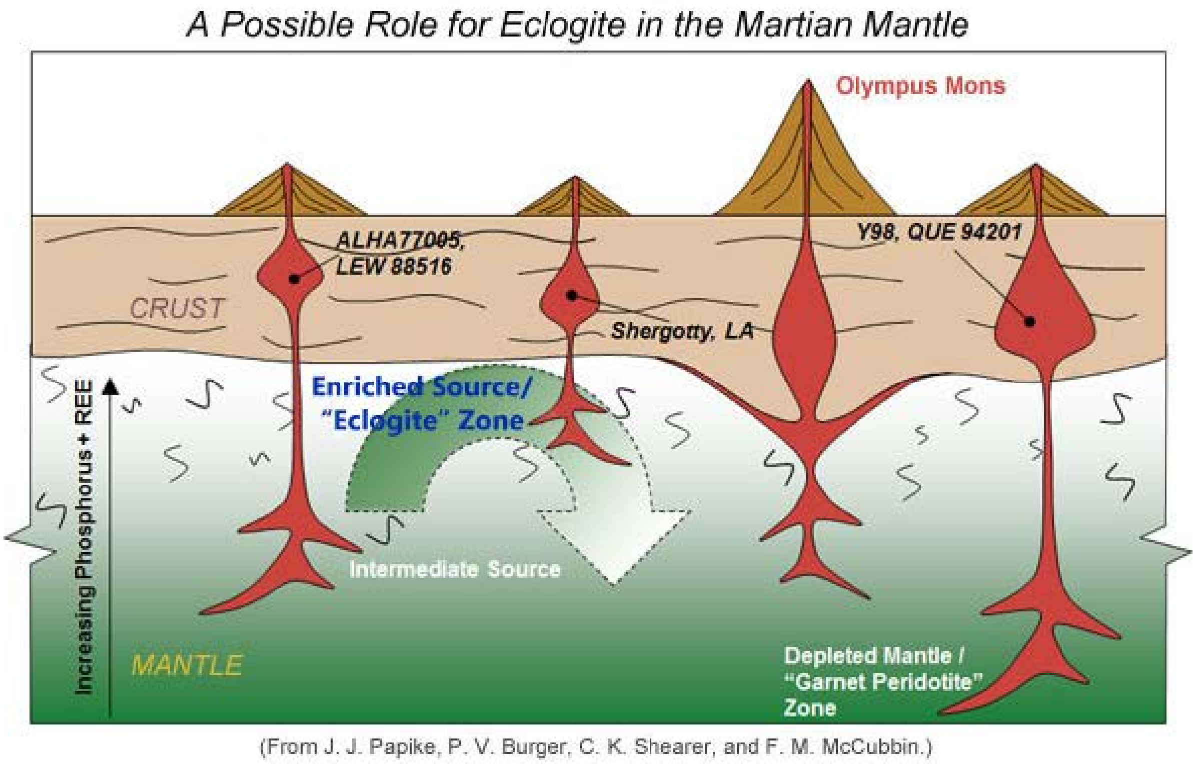
Plot showing variations in isotopic compositions of the regions of the mantle (called "source regions") in which different shergottite Martian meteorites formed. CHUR stands for chondritic uniform reservoir, a kind of baseline of the average chemical composition of chondrites that cosmochemists like to make comparisons to. The range for Martian meteorites is much larger than the spread of terrestrial rocks (see field outlined in black), indicating that the Martian mantle is quite heterogeneous.

Painstaking isotopic measurements of the products of radioactive decay show that the diverse shergottite source regions formed 4.5 billion years ago. The ancient age derives from measurements of neodymium (Nd) and samarium (Sm) isotopes. Cosmochemists find that the ratio of ^{142}Nd to ^{144}Nd increases as the ratio of Sm to Nd increases, indicating that ^{142}Nd was present in the Martian mantle when it formed. This is a big deal because ^{146}Sm decays to ^{142}Nd with a relatively short half-life, 103 million years. This makes it a sensitive indicator of events that happened long ago when Mars was young. The data in the diagram below show that the shergottites fall on a line that indicates an age of 4.5 billion years. The **nakhlites** (another group of Martian meteorites) fall off the line, indicating that they come from a distinctive region of the mantle. The nakhlites also differ in other isotopic systems such as tungsten, reinforcing the idea that they come from a different place in the mantle than do the shergottites.



This complicated diagram tells a simple story. All data are isotopic compositions in whole-rock analyses of shergottites (blue, green, and red circles) and nakhlites (turquoise circles). The horizontal axis is really just the elemental ratio of Sm to Nd. The y-axis is the abundance of ^{142}Nd, which is the decay product of short-lived (103 million year half-life) ^{146}Sm, normalized to the amount of Nd in the rock. The linear correlation among the shergottites (everything but the turquoise circles) indicates that the ^{142}Nd was a decay product of Sm. The data fall on a line that define an age of 4516 million years (about 4.516 billion years), indicating that these source regions in the Martian mantle formed very early in the planet's history. The distinct differences in Sm/Nd, coupled with the other differences such as oxidation state and La/Yb, demonstrate that there are at least two source regions that produce shergottites, with another intermediate between them.

Ideas for how the shergottites were produced center on partial melting of mantle source regions that have the characteristics revealed by meteorite studies (see table and diagrams above). The consensus seems to be that these compositionally-distinct volumes of mantle rocks were probably produced when the magma ocean crystallized and then overturned in a convective spasm, although other magmatic events might have modified those sources. Melting beginning a few hundred million years ago produced the shergottites from the enriched, intermediate, and depleted sources. J. J. Papike (University of New Mexico) and colleagues added the twist that the enriched sources might correspond to eclogite, a dense, garnet-bearing rock of basaltic composition that contains garnet (a dense mineral) as the main aluminum-bearing mineral. This dense rock might sink readily to mix with enriched rocks to form the intermediate sources. The details of the primary manufacture of the sources and their subsequent melting are not yet crystal clear.



Dense, garnet-bearing eclogite (a high-pressure rock with the composition of basalt) plays a role in producing mixed shergottite source regions in the Martian mantle in this picture of shergottite genesis by Jim Papike and colleagues. The enriched source might represent early basaltic magmas that were buried at the bottom of the growing crust, forming eclogite. (Meteorite names are shown in black.)

Discussion at the conference made it clear that we do not know everything yet. The details of the primary manufacture of the diverse shergottite sources and their subsequent melting are obscure. In fact, we do not know for sure how many sources there are in the mantle. Differences between the shergottites and nakhlites, and between all Martian meteorites and the rocks sampled by surface rovers, indicate that there are almost certainly more mantle sources than just the two main ones represented by the shergottites. The mantle might be even more heterogeneous than the meteorites indicate.

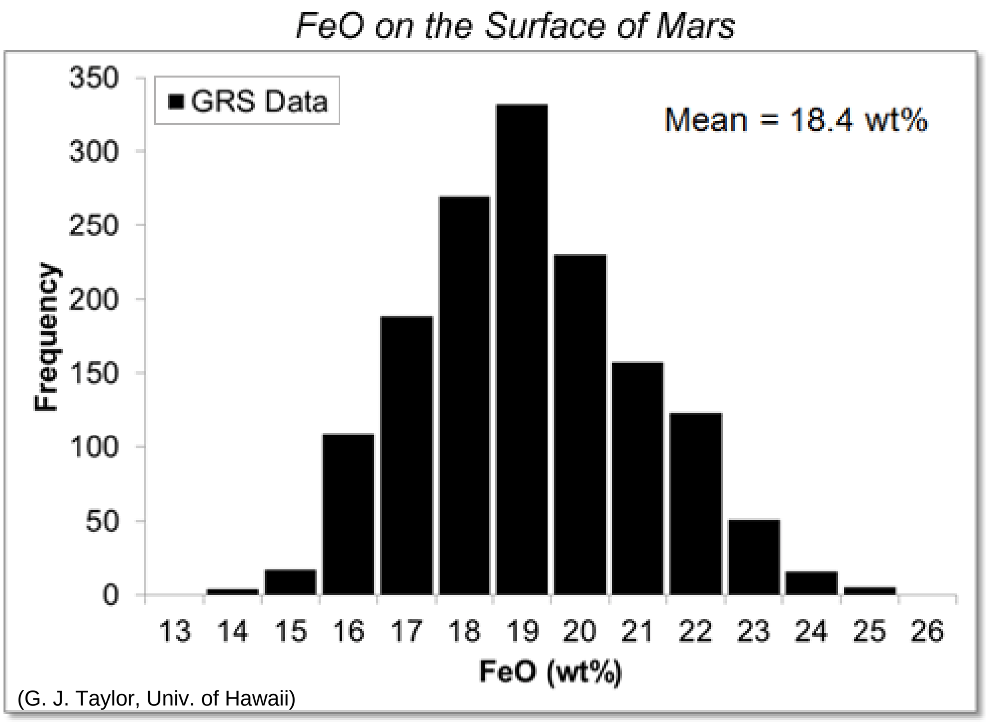
Estimating the Composition of Mars

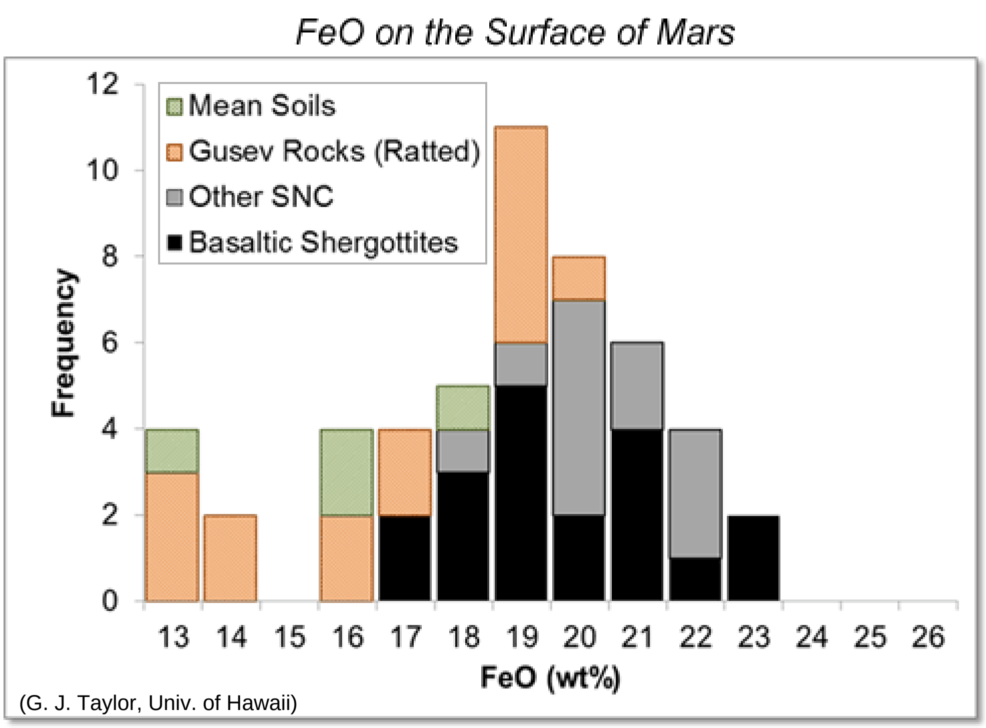
To fully unravel the history of the Martian mantle we need to know the composition of the entire silicate (rocky) portion of Mars. To determine the bulk composition, we need to figure out the history of mantle melting and production of the crust. This seems to be a hopelessly circular task. Fortunately, we know how elements behave in the solar nebula before planets began to form and how they behave inside planets, giving cosmochemists clever ways to see through the extensive chemical processing that took place when planets differentiated and continued to produce crustal rocks. At least we hope we know all that.

G. J. Taylor (University of Hawai‘i) summarized the standard model for the bulk composition of Mars, which was developed in the 1980s and 1990s by Heinrich Wänke and Gerlind Dreibus (Max Planck Institute, Mainz, Germany), and incorporated the vast amount of data returned from orbital and landed missions and analyses of numerous Martian meteorites. Like practically all estimates of planetary compositions, it assumes that refractory elements were present in chondritic proportions when the planets formed. Studies of chondritic meteorites and refractory inclusions in them tend to confirm this assumption.

A significant difference between the Wänke-Dreibus Mars composition and the bulk composition of Earth is that Mars contains significantly more FeO than does the bulk Earth. Based on only a handful of Martian meteorites, Wänke and

Dreibus estimated that Mars contains about 18 wt% FeO compared to only 8 wt% in Earth. Global data from the Gamma-Ray Spectrometer (GRS) onboard the Mars Odyssey spacecraft, new meteorite data, and analyses of rocks and soils at landing sites on Mars indicate that this enrichment in FeO is almost certainly correct (see diagrams below). The GRS data, for example show that every 5x5 degree grid point (about 500-km across) is richer in FeO than terrestrial basalts. Iron in Mars appears to be more oxidized than in Earth. (This does not mean that Mars does not have an iron-rich metallic core, just that a greater percentage of its iron is in oxide rather than metallic form.)





FeO concentrations on the surface of Mars as determined from Gamma-Ray spectrometry from orbit (top) and from meteorites and landed spacecraft (bottom). Note that all entries are much greater than the typical composition of mid-ocean ridge basalts on Earth (about 10 wt%) and the FeO concentration in the bulk silicate Earth (about 8 wt%). On the bottom histogram, the Gusev rock data are only for rocks that were analyzed after grinding with the Rock Abrasion Tool (RAT) on the Mars Exploration Rovers Spirit and Opportunity. The soil data shown are averages for landing sites.

The high FeO on the surface corresponds to high FeO in the interior as iron does not strongly concentrate in either magma or solids. Using the ratio of manganese to iron in Martian meteorites, Wänke and Dreibus concluded that the Martian interior contains 18 wt% FeO. Jeff Taylor's analysis using the same approach but with many more Martian meteorite analyses indicates the same value. However, other approaches based on terrestrial analyses and experiments indicate that the Martian interior might average about 15 wt%. Geophysical data are consistent with an iron content in that range, which is still about double that of Earth.

Related to the FeO abundance is the ratio of magnesium to iron, expressed by the useful ratio Mg/(Mg+Fe). This is almost always expressed in mole percent (reflecting the abundances of atoms, not their weights). The ratio reflects the amount of either partial melting that took place to produce magma or the amount of crystallization that occurred before the magma crystallized in or on the crust. It is useful because magnesium's geochemical behavior is biased in favor of solid magnesium-iron silicates such as olivine and pyroxene rather than magma, while iron's geochemical behavior is agnostic. This leads to big, informative fractionations of iron from magnesium. The Wänke-Dreibus Mars composition indicates an Mg/(Mg+Fe) value of 75 mol%; if FeO is lower, around 15 wt%, then the Mg/(Mg+Fe) value would be closer to 80 mol%, still much smaller than in Earth, about 89 mol%. This has important implications for melting inside Mars because rocks with lower Mg/(Mg+Fe) melt at lower temperatures than those with higher values, other factors being equal.

Abundances of **volatile** elements are greater in Mars than in Earth. Both Martian meteorites and global gamma-ray data indicate a potassium to thorium ratio of 6000, compared to about 2900 in the bulk rocky Earth. Highly volatile elements such as thallium and cadmium also seem to be somewhat enriched in Mars compared to Earth, but the concentrations of these low-abundance elements are quite uncertain in both planets. One of the most interesting volatile compounds is H_2O. It affects melting temperatures and its transport to the surface might cause aqueous alteration, flowing rivers, lakes, oceans, and environments in which life could form. The water contents in Martian meteorites, reported at the conference by Francis McCubbin and colleagues at the University of New Mexico, indicate that interior H_2O is about the same as in Earth. However, discussion at the conference made it clear that we do not know Earth's bulk water content very well. The terrestrial mantle has regions that are much wetter than others, particularly in subduction zones were one tectonic plate slides beneath another.

A particularly interesting point brought up in McCubbin's presentation (actually given by co-author Steve Elardo) is that the distinctive sources for the Martian meteorites do not appear to differ significantly in H_2O content. See **PSRD** article: **How Much Water Is Inside Mars?** McCubbin and coworkers argue that the overlap in H_2O concentrations combined with the enormous range in ε_{Nd} of the diverse mantle source regions indicates that water was already present in Mars when it differentiated 4.5 billion years ago.

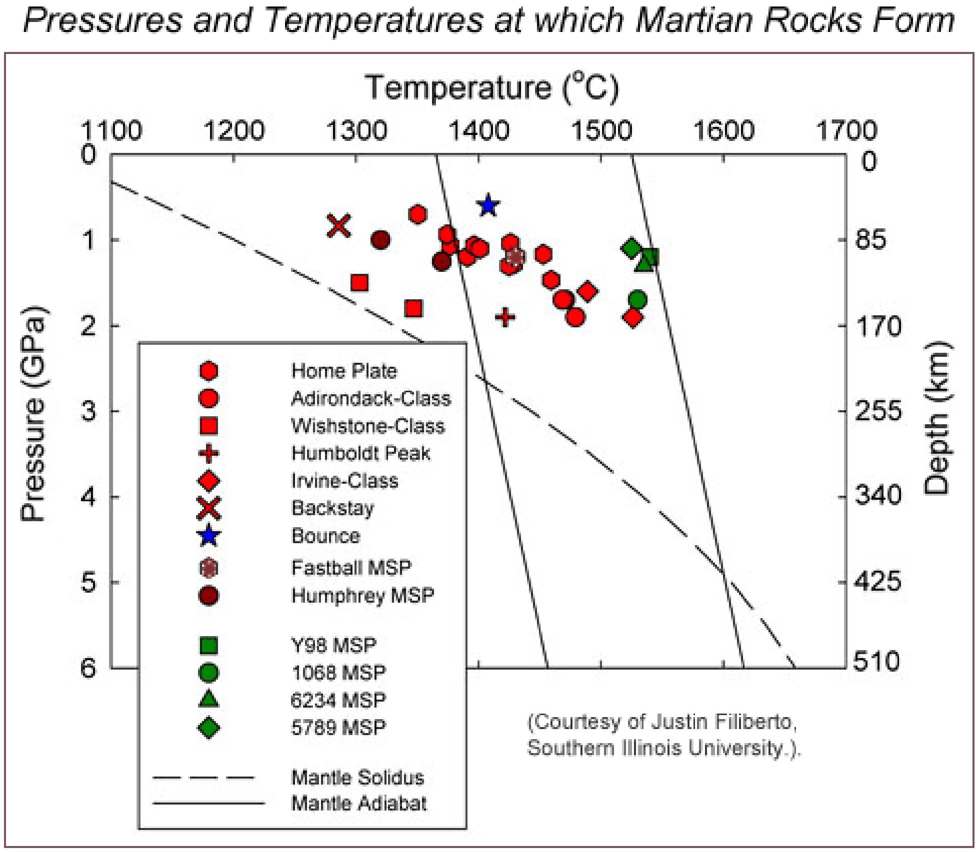
A fundamental uncertainty that was raised often at the meeting is that the Martian meteorites are not representative of the full range or rock types in and on Mars, and that even they represent several distinct reservoirs in the mantle. How many other reservoirs are there? Could their compositions be so drastically different that it would require large revisions to what we think we know about the bulk composition of Mars? What is the overall volatile content of the mantle, especially of elements that are pertinent to life and affect how magma forms: carbon, hydrogen, oxygen, and sulfur?

Probing the Mantle with the Right Rocks and the Right Experiments

As noted above, planetary basalts are dependable probes of the composition of the interior. The hitch is that the record of mantle composition is made less readable by everything that happened to magma as it migrated from its mantle birthplace to the surface (partial crystallization at depth, reactions with older crustal rocks) and how the crystallized basalt was affected by surface processes such as reactions with surface water. This leads cosmochemists to search for primary magmas—rocks whose bulk chemical compositions represent a partial melt of the mantle. It is much like searching for the Holy Grail. Once found, experiments and geochemical modeling can be used to infer key compositional parameters about the mantle and about the pressure (hence depth) and temperature at which a magma formed.

Geochemists identify primary magmas by searching for igneous rocks (almost always lava flows) that have high Mg/(Mg+Fe), both in a bulk chemical analysis and in analyses of the interiors of olivine crystals. The high Mg/(Mg+Fe) indicates that little fractional crystallization has taken place. In addition, elements that readily go into olivine (usually among the first minerals to crystallize), such as nickel and chromium, are higher than in evolved magmas that have experienced fractional crystallization. Primary melts are ideal for using experiments at high temperature and pressure to find the conditions under which two or more minerals coexist with a melt (magma). The pressure and temperature when this happens in the experiments provide a good estimate for the pressure and temperature in the interior, hence for the depth of origin. In addition, the compositions of the minerals provide data on the chemical composition of the interior, such as the highly useful Mg/(Mg+Fe). See **PSRD** article: **Squeezing Meteorites to Reveal the Martian Mantle**.

Four meteorites have been deemed primary or close to it. Based on experiments using mixtures of powders with the compositions of the meteorites, these primary magmas appear to have separated from their mantle source regions at pressures corresponding to depths between 90 and 150 kilometers (see diagram below). This is in the upper mantle, a perfectly reasonable place for them to form by partial melting. Quite a few rocks were analyzed by instruments onboard Spirit and Opportunity rovers, but only two (named Fastball and Humphrey) have been used for multi-saturation experiments. They seem to have separated from their mantle source regions at depths of 80 to 100 kilometers.



Experimental and calculated pressures (hence depths, right axis) and temperatures at which Martian rocks formed. Meteorites (green symbols) and surface rocks are included. Inferred depths correspond to the upper mantle of Mars. The dashed line shows how the initial melting temperature of the Wänke-Dreibus Mars composition varies with pressure (depth); it is based on experiments. Because of higher FeO and alkali elements in Mars, a similar curve for Earth would be 30 to 50 degrees Celsius hotter. Solid lines are examples of how the temperature of a parcel of rock varies inside Mars if it is moved from lower to higher pressure without losing heat; the temperature difference arises from the work done to compress or expand the parcel. Taken together, the data and calculations indicate Martian basaltic magmas separated from their mantle source regions at depths between 80 and 150 kilometers.

Justin Filiberto (Southern Illinois University) and Rajdeep Dasgupta (Rice University) reported on geochemical calculations based on element partitioning experiments. The calculations indicate formation at depths of 50 to 160 km. Filiberto and Dasgupta also estimated that the basalts began to melt (presumably in rising plumes of hot mantle) at depths ranging from 230 to 425 kilometers and that the Martian mantle, even as far back as the **Noachian** period (more than 3.5 billion years ago), was up to 200 degrees Celsius cooler than the mantle of the early Earth. This is consistent with the smaller body cooling faster, but raises questions about how the mantle source regions for the young shergottites (all less than 500 million years old) could become hot enough to melt.

The broad story of melting in the Martian mantle has been outlined, but the details have not been filled in. The concentrations of alkali elements (potassium and sodium in particular) affect the melting temperature, but we do not know their abundances, how they vary throughout the mantle, and how much resides in the crust. This greatly affects mantle melting temperatures and how they could have varied with time because of transfer of alkalis to the surface. In fact, we do not know the rate at which the heat-producing elements potassium, uranium, and thorium were extracted from the mantle and deposited in the growing crust, further clouding our view of mantle evolution. The conference featured interesting discussions of heat transfer from core to mantle and even back again, and the history of convection in the metallic core. A major uncertainty in mantle magma production is the role of impacts early in Martian history, as discussed by James Roberts (Applied Physics Laboratory of Johns Hopkins University). Herb Frey (Goddard Space Flight Center) has identified 20 impact basins larger than 1000 kilometers, and five impact basins larger than 2500 kilometers, all of which formed early in Martian history when most of the crust was produced. (See the section on the basins in PSRD article: **A Younger Age for the Oldest Martian Meteorite**.)

The Restless Mantle

Planetary interiors are not stagnant piles of hot rock. Small density differences (usually driven by small differences in temperature) cause buoyant regions to rise, denser ones to sink. Rising parcels inside planets begin to melt when they get to lower pressures, causing magma production and crustal construction. Geophysicists have modeled convection inside Earth and Mars. Discussion at the conference made it clear that we have a lot to learn.

One unresolved issue is the extent to which Martian magma production involved decompression melting throughout Martian history. (Melting temperature increases with pressure, so moving a hot mass of mantle to lower pressure can cause it to begin melting.) A significant amount of crust might have formed as the direct result of crystallization of a magma ocean. It seems likely that convection plays a role in magma generation, but we do not know how the style and vigor of convection has changed with time.

A big discussion topic was how a convecting Martian mantle preserved the distinctive source regions identified through studies of Martian meteorites. As discussed above, these regions formed 4.5 billion years ago, yet did not mix. Geophysicists pointed out that convection in Earth and Mars appears to be quite different, with subduction of plates recycling crustal materials back into the mantle on Earth. However, even on Earth, ancient mantle reservoirs exist inside Earth, as shown by isotopic data from lavas from Baffin Island in the Canadian arctic and in West Greenland, as reported in 2010 by Matt Jackson (Boston University) and others. These source regions formed about 4.5 billion years ago, yet were preserved in spite of energetic convection inside Earth.

Answering the Questions

The lively discussions and differences of opinions at the Mars Mantle Conference demonstrated that we have a lot learn about the mantle. Continued research with Martian meteorites and mission data will certainly help, as will additional experiments designed to reveal the mineralogy of the interior and elucidate how elements partition between magma and minerals, and metal and silicates, at high pressure. Fortunately, new data are coming.

SOURCES OF NEW DATA

More meteorites.

Martian meteorites continued to be found by national Antarctic programs and private collecting expeditions, especially to the hot deserts of northwest Africa. Many are similar to those we already have, but at the conference Carl Agee (University of New Mexico) described a newly discovered Martian meteorite that has unique properties, including an intriguing age of about 2 billion years, thus filling a gap between the nakhlites (1.3 billion years) and ALH 84001 (4.1 billion years). It appears to be a volcanic breccia and contains a whopping 0.6 wt% H_2O. This interesting rock, which is only beginning to be studied, shows the value of searching for additional Martian meteorites—we will not only get the same old, same old.

[RIGHT] Field photograph of the MIL 03346 Martian meteorite collected by the Antarctic Search for Meteorites Program (ANSMET) on an ice field in the Miller Range, Antarctica in 2003. (ANSMET) Click for more information.

Mars Science Laboratory (MSL) Curiosity.

The Curiosity rover has begun its two-year drive inside Gale crater. Initial results suggest that the spectacular layered deposits have a significant component derived from basaltic rocks. Even if proven to be sedimentary rocks, it is likely that new information about the range of mantle-derived igneous rocks will be discovered. [RIGHT] The Curiosity rover began its two-year mission on August 5, 2012, roaming toward a geologically interesting and visually stunning layered sequence at the base of Mount Sharp. (NASA/JPL-Caltech/MSSS) Click for more information.

InSight.

The recently-funded NASA Discovery mission called InSight will deploy a burrowing heat flow probe and a seismometer. The heat flow measurement will provide important information about the thermal history and radioactive element inventory in Mars. The seismometer will provide a solid measurement of the density structure of the mantle and the radius of the metallic core. [RIGHT] The InSight mission (slated for a 2016 launch) is a geophysical probe that will analyze heat flow on Mars and determine the structure of the mantle beneath the landing site, as depicted in this artist's rendition. (JPL/NASA artwork) Click for more information.

Mars Sample Return.

Plans are underway for a robotic sample-return mission to Mars. No doubt it will focus on assessing the planet's habitability and looking for signs of life, but the samples will contain important information about igneous rock compositions, hence about the mantle of Mars. The important advantages of having samples in terrestrial laboratories is that they can be studied in much more detail than even the impressive instruments on the MER and MSL rovers can manage, and they can be carefully curated for future studies when new analytical techniques are developed. [RIGHT] Artist's rendition of a future mission showing a container with samples blasting off Mars as the first step of their journey to laboratories on Earth. (NASA/JPL artwork) Click for more information.

Cosmochemists and geophysicists are continuing their efforts to unlock the secrets of the Martian interior, using existing data and available meteorites, doing experiments to understand processes at high pressure and temperature, using their planetary science savvy, and waiting for the next round of missions. Mars awaits.

Additional Resources

Links open in a new window.

- Jackson, M. G., Carlson, R. W., Kurz, M. D., Kempton, P. D., Francis, D., and Blusztajn, J. (2010) Evidence for the survival of the oldest terrestrial mantle reservoir. *Nature*, v. 466, p. 853-856, doi:10.1038/nature09287 [**abstract**]
- *The Mantle of Mars: Insights from Theory, Geophysics, High-Pressure Studies, and Meteorites,* Meeting from September 10-12, 2012. [**Meeting website**]