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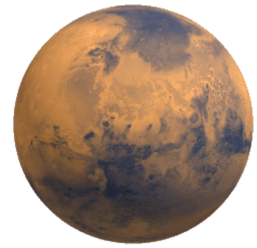

Squeezing Meteorites to Reveal the Martian Mantle

--- Experiments at high temperature and pressure give clues to the composition of the interior of Mars.

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A piece of a Martian lava flow, Antarctic meteorite Yamato-980459, appears to represent the composition of a magma produced by partial melting of the Martian interior. That's the view of researchers Don Musselwhite, Walter Kiefer, and Allan Treiman (Lunar and Planetary Institute, Houston) and Heather Dalton (Arizona State University). Musselwhite and his colleagues determined that this basaltic Martian meteorite represented a primary melt from the mantle. This was an important discovery because magma produced inside a planet contains significant clues to the composition of the region of the interior in which it formed. The lava flows that decorate the surface of planets tell us about the mantle, the rocky region beneath the crust and above the metallic core.

The researchers used apparatus at the Johnson Space Center to determine what minerals are present when samples with the composition of Y-980459 are heated to a range of temperatures and squeezed to a range of pressures like those that planetary scientists expect to exist in the interior of Mars. The results indicate that the magma represented by this special meteorite formed at a depth of about 100 kilometers and a temperature of about 1540 ^{o}C. From the high temperature and high ratio of magnesium to iron in the magma, Musselwhite and his colleagues infer that the amount of melting to produce the Y-980459 parent magma was high, which suggests that the temperature at the boundary between the metallic core and the rocky mantle was higher than previous estimates. This work gives us clues to the composition and dynamics of the Martian interior--all from a rock chipped off a lava flow on Mars and flung to Earth by an impact.

Reference:

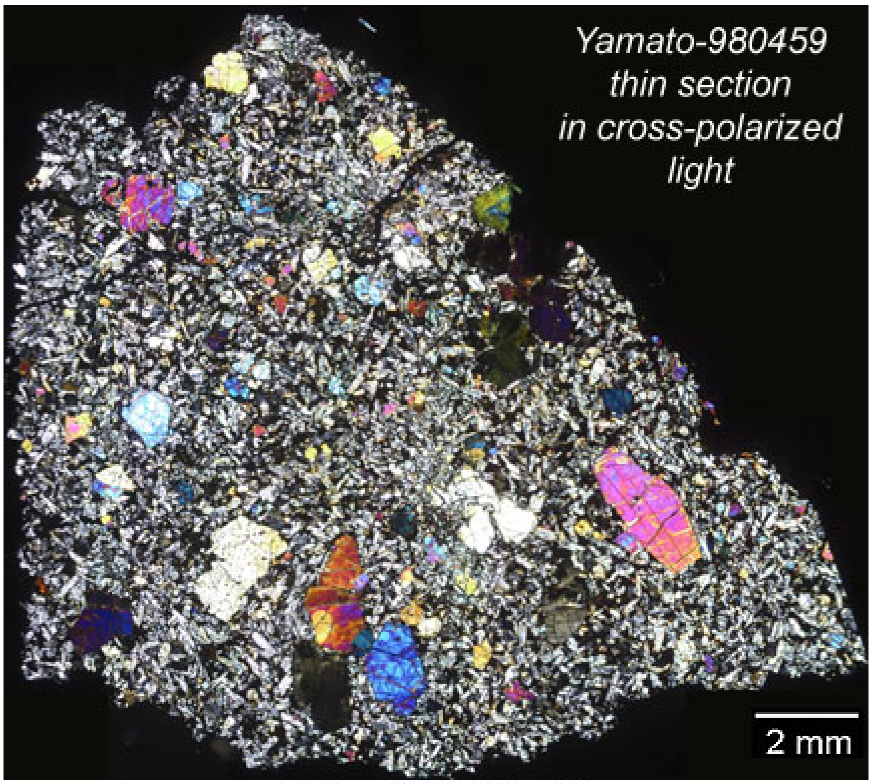
- Musselwhite, D. S., H. A. Dalton, W. S. Kiefer, and A. H. Treiman (2006) Experimental petrology of the basaltic shergottite Yamato-980459: Implications for the thermal structure of the Martian mantle. *Meteoritics and Planetary Science*, v. 41, p.1271-1290.

A Special Rock from Mars

All meteorites from Mars are special, of course. Some, such as the shergottites, are pieces of more-or-less familiar lava flows. Others are bits of unusual lava flows, such as the nakhlites. One is ancient, ALH 84001, and represents an accumulation of the mineral orthopyroxene deep inside the crust of Mars, but later modified by water and possibly containing evidence for past life on Mars (see the first **PSRD** article: Life on Mars?). But Y-980459 has the added virtue of having the composition of a magma that has not been modified much since it formed by partial melting of the Martian interior a few hundred million years ago. The age of Y-980459 is 472 ± 47 million years based on Rb-Sr and Sm-Nd isotopic measurements.

Samples of a partial melt of a planetary interior are like the Holy Grail. They were at one time in equilibrium with minerals in the interior, so they contain a record of the chemical and mineralogical composition of their place of formation. They are messengers from the interior.

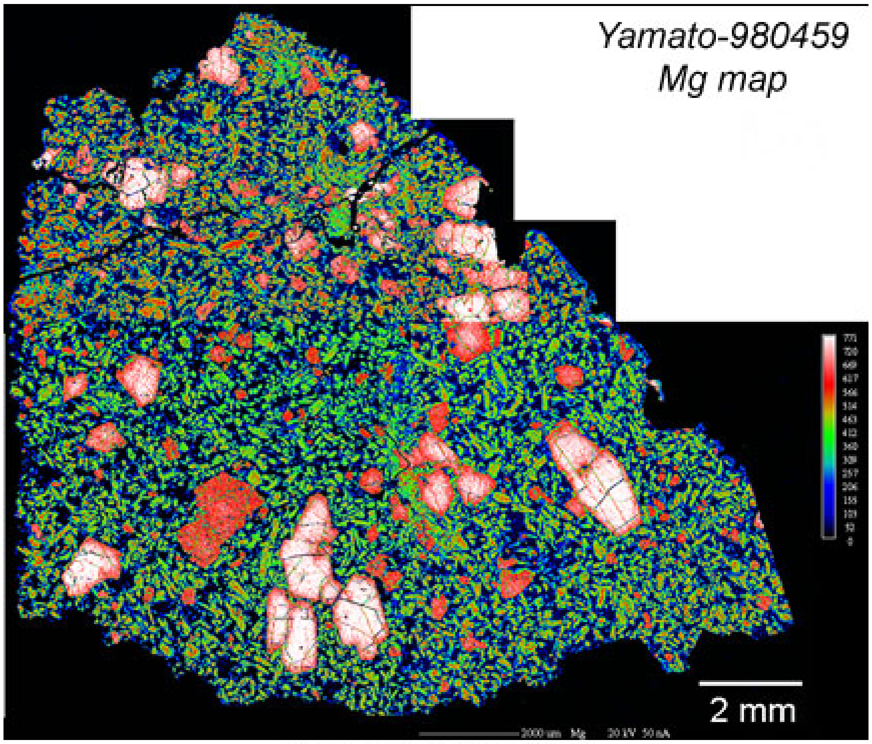
The shapes and sizes of the minerals in Y-980459 and the way the minerals are intergrown indicate that Y-980459 is a piece of a lava flow. It consists of large grains of olivine embedded in a matrix of smaller crystals, including lath-shaped plagioclase feldspar. There is no question that the minerals crystallized in a lava flow.



(Courtesy of Gordon McKay, JSC.)

Two views of a thin slice of Y-980459.

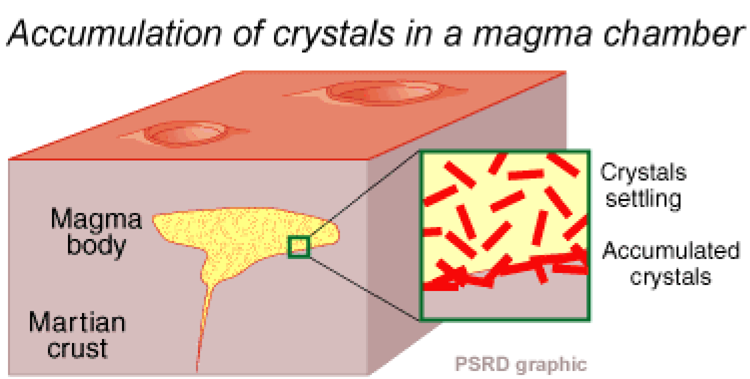
TOP: Photomicrograph of a thin slice of the meteorite as viewed in polarized light in a microscope. The large grains are olivine. They are surrounded by a finer-grained intergrowth of plagioclase feldspar and pyroxene. The straight edges of the olivine suggest that they formed in a magma.



(Courtesy of Gordon McKay, JSC.)

BOTTOM: Map of the magnesium (Mg) concentration in the minerals in Y-980459, showing the same area as in the photograph on the top. Many of the grains have high Mg concentrations, indicative of olivine.

What Don Musselwhite and other experimentalists want is to know the composition of the magma (also called "melt" by experimental petrologists) produced by partial melting. The problem is that many magmas begin to crystallize and the early-formed minerals accumulate in some portions of the magma (see illustration below). Olivine is usually the first major mineral to crystallize, so often a lava flow will contain large olivine crystals dragged up with the magma from a storage area (magma chamber) beneath the ground. If olivine has accumulated, the chemical composition of the lava does not represent a melt because it has been modified by addition of crystals.



In many cases, one mineral forms first as a magma begins to crystallize. Crystals of this mineral can accumulate inside the magma chamber. If a batch of the magma containing the extra crystals erupted, its total composition (crystals plus liquid magma) would not represent the composition of the original crystal-free magma. Y-980459, however, appears not to have accumulated extra olivine crystals, hence its chemical composition is the same as it was when it formed by partial melting of the Martian mantle.

There is a way to determine if olivine has been accumulated. If olivine crystallized directly from the lava it is found in, it will have the composition (specifically the ratio of magnesium to iron) predicted from experiments to form from a magma of the composition of the lava rock (large olivine crystals plus the finer-grained groundmass surrounding them) in which they occur. Many lava flows contain a olivine crystals with a large range of compositions, which indicate that they accumulated in the magma. Their presence affects the bulk chemical composition and the lava does not represent a pristine liquid derived from the mantle. The composition of Y-980459 has been measured by Japanese researchers E. Koizumi and his coworkers. Musselwhite's calculations indicate that the olivine crystals in Y-980459 would have formed from a melt with the composition of the meteorite. Thus, it is likely that Y-980459 represents an unmodified melt from the Martian mantle. It is a probe of the interior of Mars.

Revealing Mantle Mineralogy

Once planetary scientists know that a rock is a primary melt from the interior of a planet, they want to find out as much as they can about the composition of the mantle rock in which the magma formed and the pressure (hence depth) at which it formed. To do this, Musselwhite and Dalton made a homogeneous glass with a chemical composition equal to that measured by other investigators for Y-980459. Making starting compositions for experiments is part of the art of experimental petrology. In this case, the investigators made a mixture of oxides and carbonates and ground them together in an agate mortar and pestle, with the powdery mixture immersed in acetone to prevent contamination and loss of the finest powder. The mixed powder was then melted in a high-temperature furnace and ground up again to ensure that it was homogeneous. Because multiple experiments were going to be done on the same starting material, it was essential that it be homogeneous.

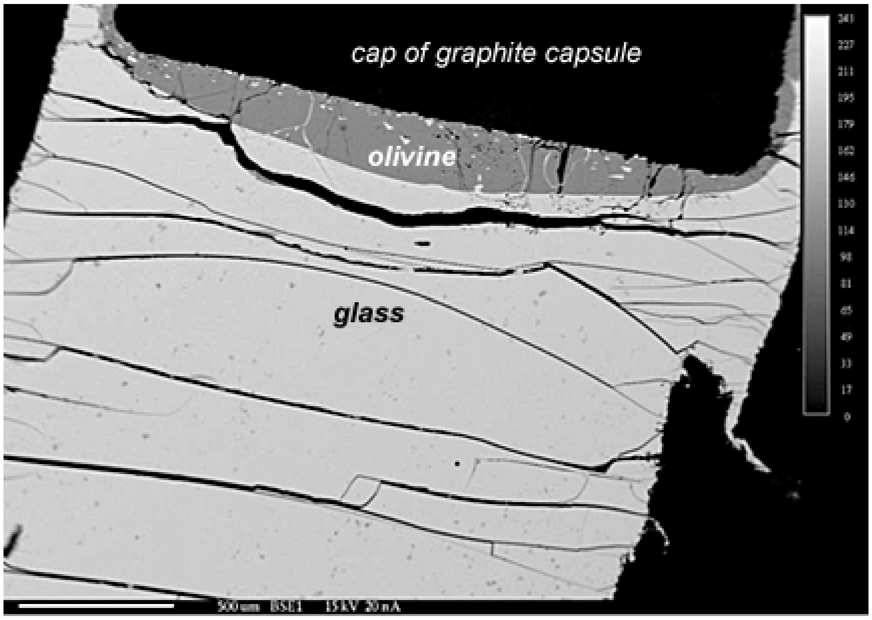
Experiments were done at high temperature and pressure in what **PSRD** calls a Squeeze-O-Matic. Experimental petrologists call this particular piece of gear a "Quickpress non-end-loaded piston cylinder apparatus." The sample was placed inside a graphite capsule that in turn was placed inside a pressure cell made of barium carbonate and magnesium oxide. This was squeezed to a pressure between 7 and 15 kilobars (one bar is the pressure of air at sea level) and heated to temperatures ranging from 1410 to 1615 ^{O}C. After holding the sample at a given pressure and temperature for up to 24 hours, it was quenched to room temperature first, then the pressure was released. Musselwhite and his colleagues took great care to ensure that the measurements of pressure and temperature were accurately calibrated, and include in their paper an extensive Appendix explaining their procedure. Products of the experiments were made into polished pieces and analyzed with an electron microprobe at the Johnson Space Center.

Quickpress

(Photo courtesy of Don Musselwhite.)

The Quickpress apparatus used in the experiments on Y-980459. This device generates very high pressures at high temperatures.

Experimental product of Olivine and Glass

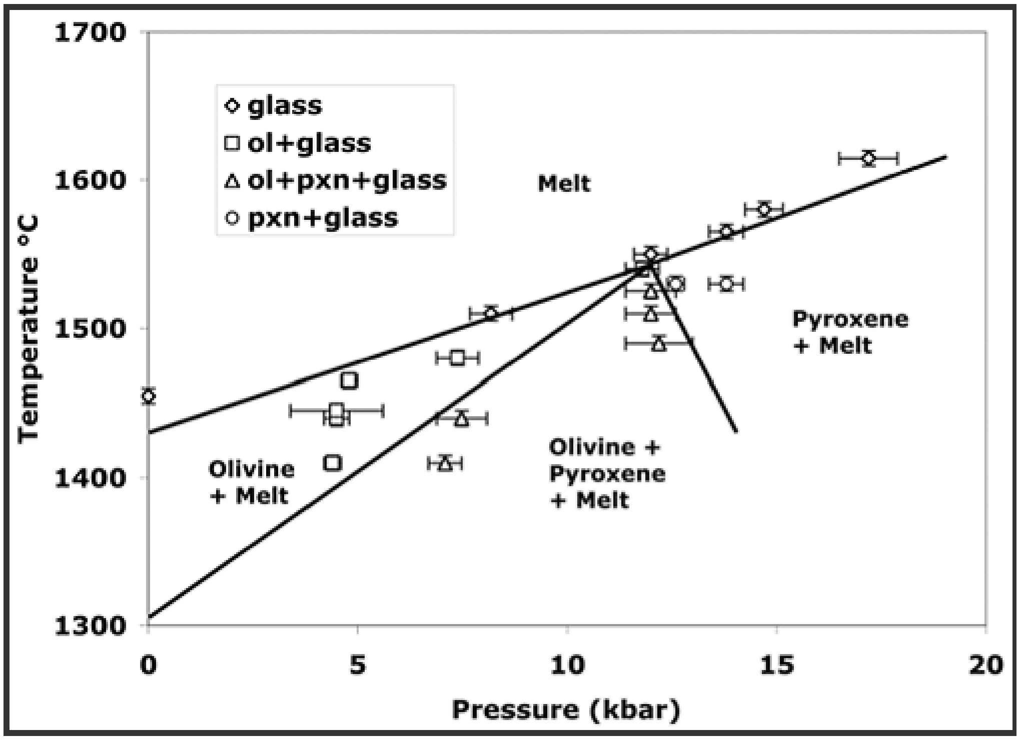


(from Musselwhite, D.S. *et al.*, 2006, *MAPS*, v. 41, p. 1271-1290.)

Electron microscope image of a polished sample of an experimental run product. The dark material at the top is the graphite capsule the sample was placed in. The light gray is glass (which was molten during the high temperature and pressure at which the experiment was run), and the gray area contains olivine crystals. Electron microprobe analysis of the glass and olivine gives their chemical compositions.

A central purpose of the experiments was to determine the pressure and temperature at which the Y-980459 magma formed. But how do we figure that out? The experiments show what minerals are present at different compositions, what their compositions are, and what the composition of the co-existing melt is. At some pressure the experimental product might be olivine and melt (which is preserved as glass in the experimental samples). At another pressure and temperature pyroxene might be present with glass. This means that if the Y-980459 magma formed at those conditions the left over solid rock would contain just one mineral, olivine or pyroxene. This is unlikely. For a typical mantle rock inside a planet, it takes about 50% melting to leave just one mineral behind. Hot magmas are so mobile (low viscosity) that they readily move up in the planet when the amount of melting is as low as a few percent, and quite rapidly at 20%. Thus, experimental petrologists look for the pressure and temperature at which a melt co-exists with two or more minerals. For Y-980459 that pressure is 12 kilobars (plus or minus 0.5 kilobars), equivalent to a depth of about 100 kilometers inside Mars.

A quick reminder: When most substances melt they do not go from solid to liquid at a single temperature. Pure materials like ice do melt at a single temperature, but complex ones like rocks melt over a range of temperatures and the chemical composition of the molten material and the minerals present change as the amount of melting increases.



(from Musselwhite, D.S. *et al.*, 2006, *MAPS*, v. 41, p. 1271-1290.)

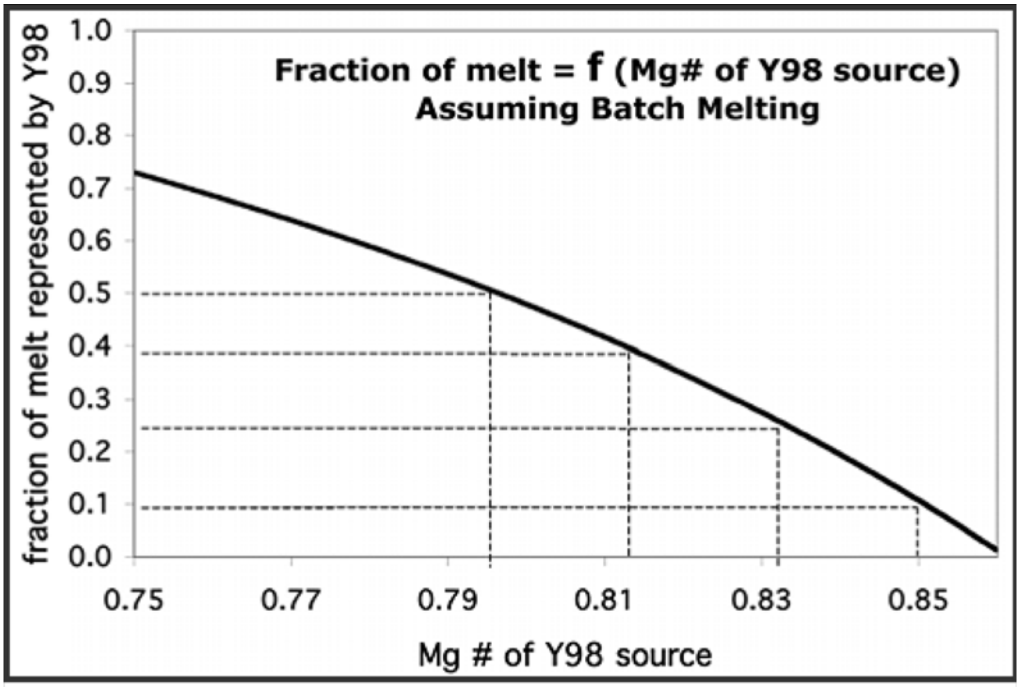
The plot, above, shows results of the experiments done by Don Musselwhite and his colleagues. Above the uppermost diagonal line, a magma with the composition of Y-980459 would be completely molten; this line is called the "liquidus," which means that everything is molten above it. In the lefthand field labeled "olivine + melt" it would consist of olivine and molten silicate; this corresponds to conditions as the magma was nearing eruption at low pressure. At high pressure the magma consists of pyroxene and melt. There is a region in between where melt is accompanied by olivine and pyroxene. The liquidus at this point is the likely formation pressure and temperature of the Y-980459 magma, 12 kilobars (equivalent to a depth of 100 kilometers on Mars).

This approach to determining the depth of origin and mineralogy of the mantle was applied to basalt lava flows from the lunar maria, too. Investigators (mostly in the 1970s and 1980s) sought primary magmas like Musselwhite and his colleagues did for Martian meteorites. Experiments at high pressure and temperature showed that the pressure at which a melt co-existed with two or more solids varied, corresponding to depths of 100 to 400 kilometers.

Amount of Melting and Composition of the Mantle

The experiments suggest that when the Y-980459 magma formed the leftover solid minerals were olivine and low-calcium pyroxene. Neither contains much aluminum or calcium, so the amount of melting must have been high enough to completely dissolve minerals that contain those elements (plagioclase feldspar, oxides, or garnet). This implies that the amount of melting was at least 15-20%. The experiments tell us what the olivine composition was when the magma separated. It contained 86 mole percent forsterite (Mg_2SiO_4) and 14 mole percent fayalite (Fe_2SiO_4). This composition can be abbreviated as the Mg#, simply the ratio of magnesium to magnesium plus iron [Mg/(Mg+Fe)], in this case 0.86. This means that the leftover olivine in the mantle after the Y-980459 magma had migrated away had an Mg# of 0.86.

Knowing the composition of the residual minerals is useful, but we really want to know the composition of the mantle before it melted. That gets us a step closer to figuring out the composition of the entire Martian mantle. Unfortunately, this cannot be determined uniquely from knowing the composition of the residual minerals because different amounts of melting give different calculated Mg#. Musselwhite and his colleagues calculated the Mg# of the initial, pre-melting Y-980459 mantle source rock as a function of the amount of melting. To do this, they used well-established geochemical equations that describe the partial melting process. As shown in the diagram below, the amount of melting could range from an infinitesimal amount (corresponding to Mg# of 0.86) to over 70% (Mg# of 0.75 in the original mantle rock).



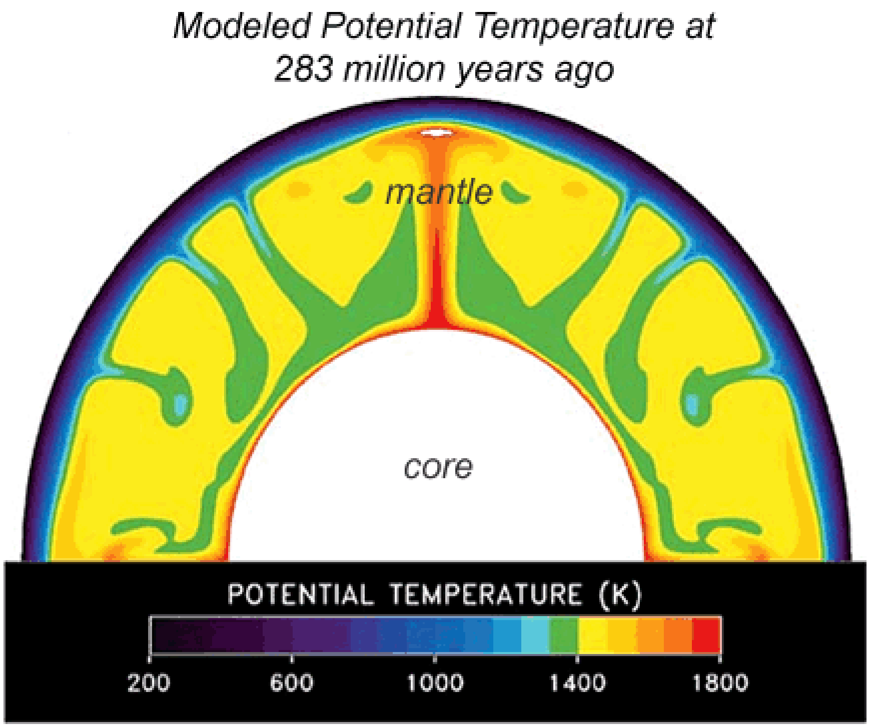
(from Musselwhite, D.S. *et al.*, 2006, *MAPS*, v. 41, p. 1271-1290.)

This graph shows calculations of the Mg# of the mantle for different amounts of partial melting to produce Y-980459. The common view is that the average Martian mantle has a Mg# of about 0.75. If so, then formation of Y-980459 required over 70% melting, an unreasonably large value in a single event. In fact, if the amount of melting was much over 40% all the pyroxene would have been melted, leaving only olivine in the residual solid. Musselwhite and his colleagues suggest that the source in the mantle had already experienced one or more melting events before the one that produced the magma in which Y-980459 crystallized.

Percentages of melting higher than 50% are not reasonable, except in the early stages of a planet?s life when it could have been mostly molten. This means that either the Martian mantle has a higher Mg# than we think (say 0.80 instead of 0.75), or that multiple episodes of melt extraction occurred. Either is reasonable and we have no unique way of determining which is correct. It is possible that there was an initial large melting event, say the Martian magma ocean (see **PSRD** article: A Primordial and Complicated Ocean of Magma on Mars), resulting in formation of a region with relatively high Mg#. Subsequent melting could have formed the Y-980459 magma, possibly after an intermediate melting event or events that produced other, unsampled magmas.

Thermal State of the Interior

Results of these experiments and calculations have implications for the temperature inside Mars as a function of time. Co-author Walter Kiefer used a complex geophysical computer model to estimate temperature inside Mars, from the core-mantle boundary to the base of the lithosphere (the upper, relatively cool, rigid part of the planet that extends from the surface to a depth of about 200 kilometers). In this case he updated the approach he took previously, taking into account the high temperature reached to melt the mantle that gave rise to Y-980459, and including some other tricks of the geophysics trade. The fact is that these calculations are both informative and uncertain. The uncertainty stems from the large number of variables that must be accounted for, including temperature, viscosity of the solid mantle, the volume of magma produced over time and over specific time periods, the percentage of melting, how many melting episodes, to name a few.



(from Kiefer, W.S., 2003, *MAPS*, v. 39, p. 1815-1832.)

This shows the temperature inside Mars at about 280 million years ago (the middle of the range in ages of the shergottie Martian basalts), using Walter Kiefer's previous calculations. The central hot feature (red) is a plume of hot mantle rock that flowed upwards from the core-mantle boundary. When shallow enough, it began to melt, indicated by the white region. The updated calculations are similar, but tying them to the high melting temperature needed to make Y-980459 raises the temperature at the core-mantle boundary. ("Potential temperature" means the physical temperature minus the effects that pressure has on temperature caused by the work done to squeeze solid rock.)

The new calculations suggest that the temperature at the boundary between the mantle and the core is hotter than calculated previously. This might be caused by the core containing less sulfur than thought, a higher viscosity than used in the calculations, or by a high concentration of radioactive elements (potassium, thorium, and uranium) at the base of the mantle. These elements are important because they release heat when they decay, raising the local temperature. The last hypothesis may be most likely and is consistent with geophysical models of what could have happened in a Martian magma ocean. This is itself a very complicated process, but it seems likely that it would have overturned, depositing dense rock at its base. Some of the dense minerals, such as garnet, would have concentrated thorium and uranium. See **PSRD** article: A Primordial and Complicated Ocean of Magma on Mars for details.

Just the Beginning . . .

Identifying a primary melt from the mantle of Mars is a another step on the road to unraveling the detailed composition of the Martian interior. The shergottite Martian meteorites have already told a complicated story of the mantle (see **PSRD** article: The Multifarious Martian Mantle). Nevertheless, we need more samples that represent magma compositions, and preferably magmas that represent formation over a range of time back to more than four billion years ago. To find them we need more samples. The search for Antarctic meteorites and meteorite finds in desert regions on Earth are helping fill in gaps, but they are biased towards younger samples. Returning samples from volcanic areas and the ancient Martian surface would help enormously. There might even be mantle rocks excavated when huge basins such as Hellas (2500 kilometers in diameter) formed. The sample returns could be supplemented by installation of a geophysical network that could use Mars quakes to probe the interior. The chemical composition of Mars is an important piece of the puzzle of planet formation, and Martian samples help us put those pieces together.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Kiefer, W. S. (2003) Melting in the Martian mantle: Shergottite formation and implications for present-day mantle convection on Mars.*Meteoritics and Planetary Science,* v. 38, p. 1815-1832.
- Musselwhite, D. S., H. A. Dalton, W. S. Kiefer, and A. H. Treiman (2006) Experimental petrology of the basaltic shergottite Yamato-980459: Implications for the thermal structure of the Martian mantle. *Meteoritics and Planetary Science,* v. 41, p.1271-1290.
- Taylor, G.J. (1996) Life on Mars? *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Oct96/LifeonMars.html
- Taylor, G.J. (2004) The Multifarious Martian Mantle. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/June04/martianMantle.html
- Taylor, G.J. (2006) A Primordial and Complicated Ocean of Magma on Mars. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Mar06/mars_magmaOcean.html

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