PLANETARY SCIENCE RESEARCH
PSRD Discoveries

Headline Article

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Two Billion Years of Magmatism in One Place on Mars


Mars (MGS MOC mosaic - NASA / JPL / MSSS)

--- New data from a Martian meteorite extends the time of magmatic activity by 1.8 billion years in a volcanic center that provided us a coherent group of Martian meteorites.

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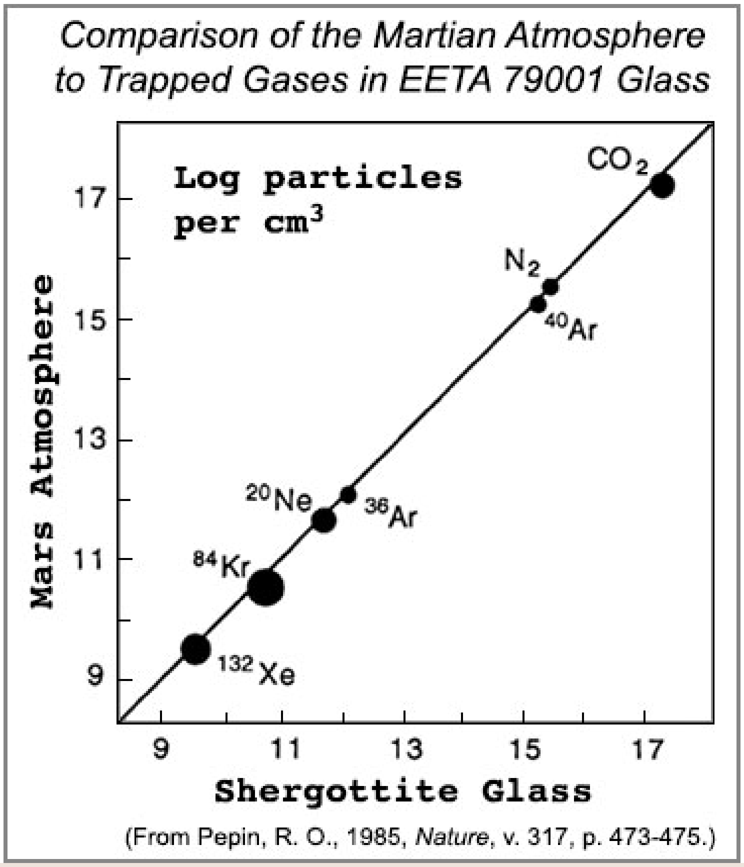
Thomas Lapen and Minako Righter (University of Houston), and colleagues at Aarhus University (Denmark), the Universities of Washington (Seattle), Wisconsin (Madison), California (Berkeley), and Arizona (Tucson), and Purdue University (Indiana) show that a geochemically-related group of Martian meteorites formed over a much longer time span than thought previously. So-called depleted shergottites formed during the time interval 325 to 600 million years ago, but now age dating on a recently discovered Martian meteorite, Northwest Africa (NWA) 7635, extends that interval by 1800 million years to 2400 million years. NWA 7635 and almost all other depleted shergottites were ejected from Mars in the same impact event, as defined by their same cosmic-ray exposure age of ~1 million years, so all resided in one small area on Mars. This long time span of volcanic activity in the same place on the planet indicates that magma production was continuous, consistent with geophysical calculations of magma generation in plumes of hot mantle rising from the core-mantle boundary deep inside Mars.

References:

- Lapen, T. J., Righter, M., Andreasen, R., Irving, A. J., Satkoski, A. M., Beard, B. L., Nishiizumi, K., Jull, A. J. T., and Caffee, M. W. (2017) Two Billion Years of Magmatism Recorded from a Single Mars Meteorite Ejection Site, *Science Advances,* v. 3, no. 2, e1600922, doi: 10.1126/sciadv.1600922. [**Open access article**]
- **PSRDpresents:** Two Billion Years of Magmatism in One Place on Mars --**Short Slide Summary** (with accompanying notes).

The Shergottites

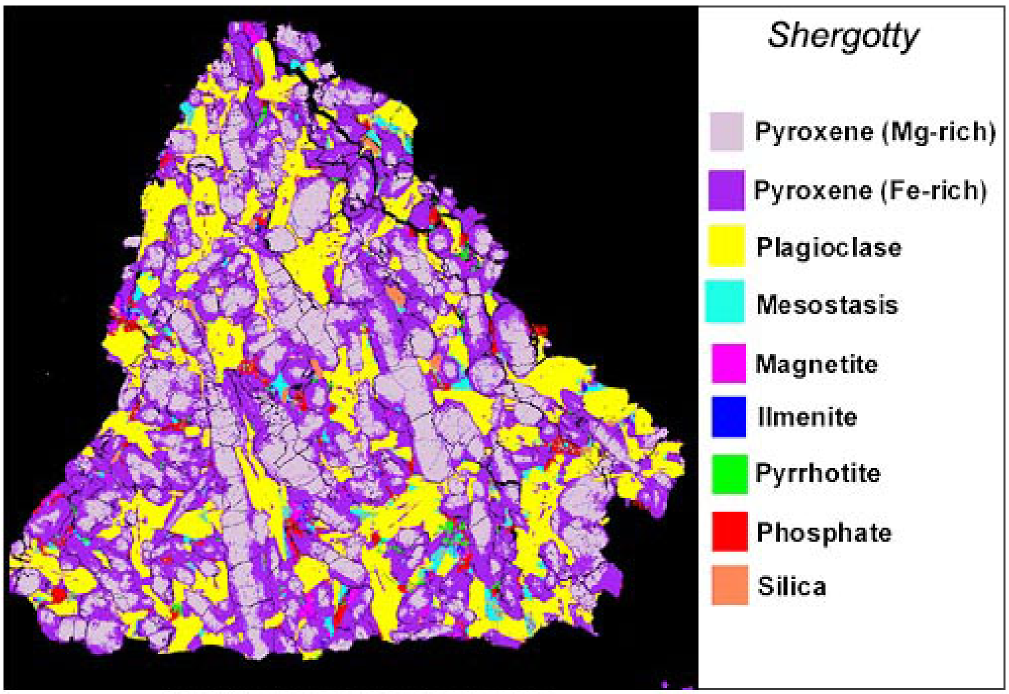
The main group of Martian meteorites are the **shergottites**, named for the first one identified, Shergotty [Data link from the **Meteoritical Database**], which fell in India in 1865. About 90 shergottites have been found, giving us a nice collection of a few places of the Martian surface. The shergottites are **basalts** and related rocks, containing **olivine** (not all samples have this), both low-calcium and high-calcium **pyroxene**, and **plagioclase feldspar**, plus assorted minor phases. During liftoff from Mars by a big impact, shock waves converted most of the feldspar into a non-crystalline form called maskelynite. This unfortunate shock damage has messed up the rocks a bit, but this is a small price to pay for free delivery of samples from another planet. We know they come from Mars because some samples contain trapped gas whose element and **isotopic** abundances match that of the Martian atmosphere as measured by the Viking landers in the mid-1970s.



A debate raged in the late 1970s to early 80s about whether the SNC meteorites (the S stands for shergottite) came from Mars. The big breakthrough in showing that they do come from Mars was the discovery by Don Bogard and Pratt Johnson (Johnson Space Center) in 1983 and Bob Pepin (University of Minnesota) in 1985 that EETA 79001 [Data link from the Meteoritical Database] has trapped gas in it and that the gas matches the Martian atmosphere. This settled the argument. For additional information about EETA 79001, see PSRD article: An Adulterated Martian Meteorite.

As they are prone to do, cosmochemists have subdivided the 90 Martian meteorites into subgroups. The two abundant groups are depleted and enriched shergottites, with an intermediate group. Although all the samples are basaltic, they differ in fundamental geochemical ways from each other. See details in **PSRD** article: **The Multifarious Martian Mantle**. But briefly, the depleted shergottites have a depletion in light **rare earth elements** such as lanthanum, giving them a lower lanthanum/ytterbium ratio (La/Yb) than in the enriched shergottites. These elemental variations are correlated with differences in the isotopic abundances and oxidation state (depleted shergottites are less oxidized than are the enriched shergottites).

Photo of a sawn surface of the Shergotty meteorite. Large whitish grains are pyroxene. The dark surface on this stone is the fusion crust, formed during entry into the Earth's atmosphere.



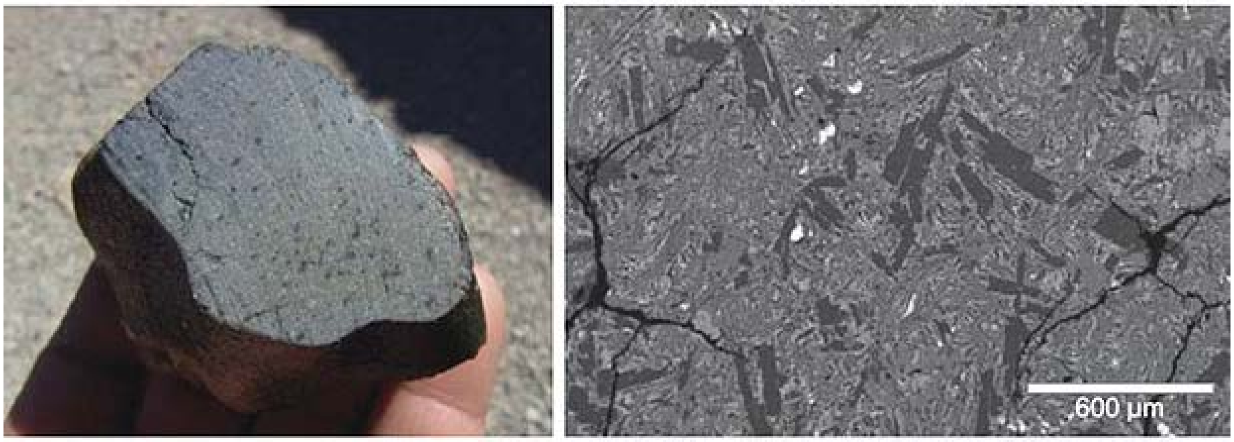
(Tara-Hicks-Johnson, University of Hawaii.)

Mineral map of a polished thin section of the Shergotty meteorite. The map was made by an electron microprobe by moving the electron beam in small steps and classifying the elemental abundances into different mineral groups using image analysis techniques. Both the high-Mg and high-Fe pyroxenes are present in two forms not distinguished, low-calcium and high-calcium. Shock during ejection from Mars converted all the plagioclase (yellow) into a non-crystalline, glassy form. Photo courtesy of Tara Hicks Johnson (then at the University of Hawai'i).

Newest Shergottite

Tom Lapen and colleagues studied Northwest Africa (NWA) 7635 [Data link from the **Meteoritical Database**] and found that it is a depleted shergottite. In fact, it extends the compositional range of depleted shergottites. It differs from other depleted shergottites by having only high-calcium pyroxene, rather than both high- and low-calcium pyroxenes. Nevertheless, its overall chemical composition makes it easy to classify as a depleted shergottite.

Martian Meteorite NWA 7635

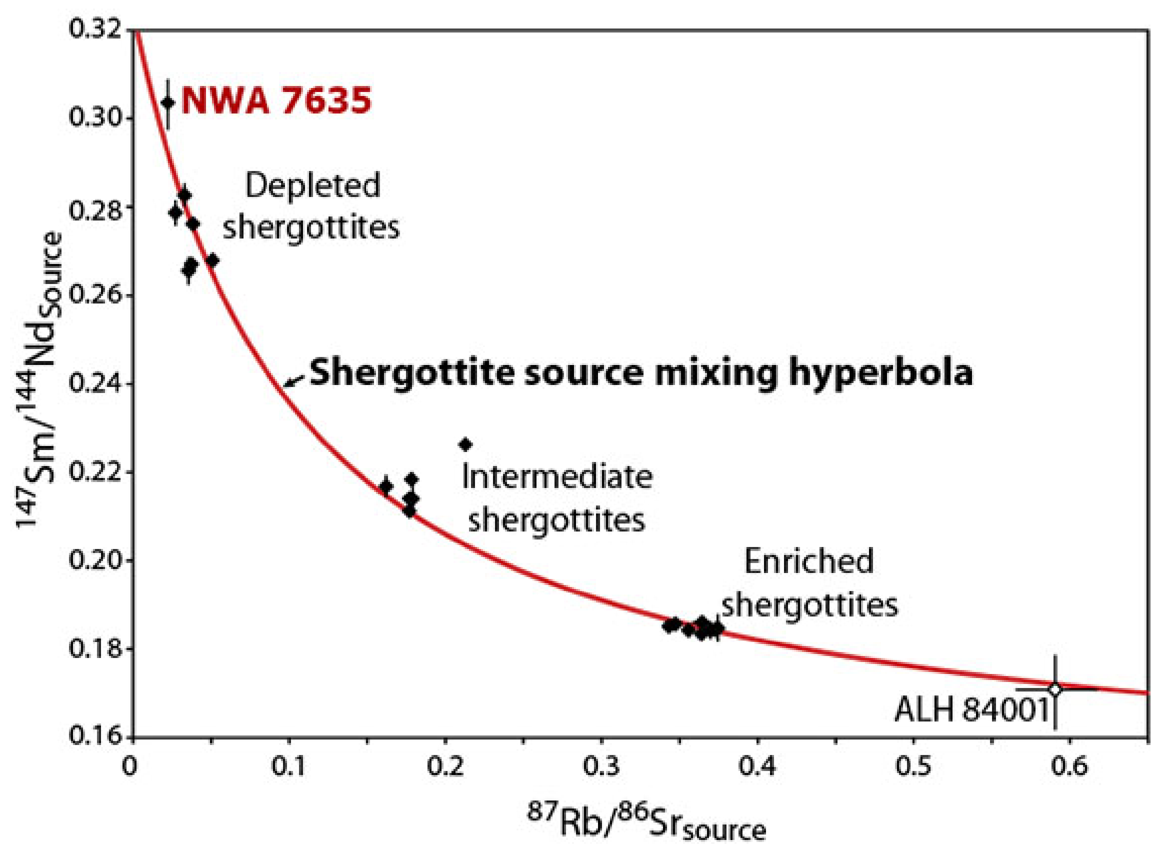


(From Lapen, T. J., *et al.*, 2017, *Science Advances*, v. 3(2), e1600922, doi: 10.1126/sciadv.1600922.)

[LEFT] Hand specimen of NWA 7635 (photo by Mohammed Hmani), showing fine-grained gray rock and black, shiny fusion crust. **[RIGHT]** Backscattered electron image of a thin section of NWA 7635 (image by Scott Kuehner). The large dark grains are plagioclase (converted to maskelynite), which are set in a groundmass of medium-gray pyroxene and olivine. Bright grains are magnetite (Fe_3O_4) and iron sulfide.

More telling than similar chemical composition and mineralogy is that isotopic compositions indicate that NWA 7635 shares close kinship with other depleted shergottites. The investigators used samarium-neodymium (Sm-Nd) and rubidium-strontium (Rb-Sr) isotopes to determine the isotopic compositions of the regions in the Martian interior where the shergottite magmas were produced by partial melting. The data show that NWA 7635 is related to other depleted shergottites, as shown in the diagram below. Note also that the data points in the diagram all fall along the same curve, which indicates mixing between enriched and depleted sources in the Martian mantle.

Isotope Systematics and Source Composition of Shergottites



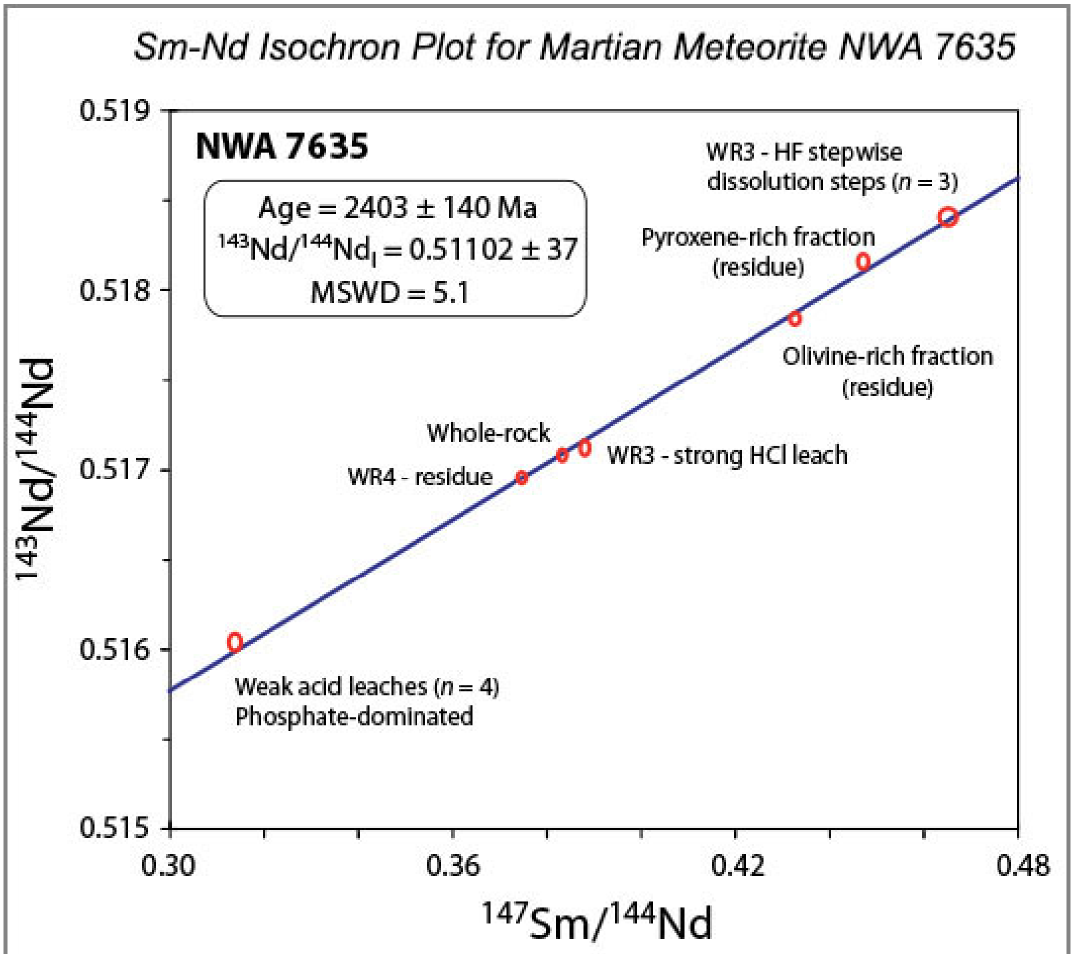
(From Lapen, T. J., *et al.*, 2017, *Science Advances*, v. 3(2), e1600922, doi: 10.1126/sciadv.1600922.)

Isotopic compositions measured in an igneous rock can be used to determine the isotopic composition of the mantle source regions that produced the magma from which the rock formed. All the shergottite data points fall along the same curve, which derives from mixing of enriched (high Rb/Sr, low Sm/Nd) and depleted (low Rb/Sr, high Sm/Nd) sources. (Mixtures are usually along straight lines, but when dealing with ratios, mixtures fall along a hyperbola.) Note that NWA 7635 plots with the other depleted shergottites. (ALH 84001 [Data link from the Meteoritical Database] was not used to constrain the mixing line, but it happens to lie on it.)

The Newest Shergottite is the Oldest Shergottite

The depleted shergottites have ages in the range 325–600 million years. Because they are clearly pieces of lava flows and/or shallow **intrusions**, this age range indicates that magmatic activity, including eruptions, occurred during this interval. Tom Lapen and colleagues measured the crystallization age (which means the time the lava flow giving rise to NWA 7635 solidified), using the precise and unperturbable Sm-Nd method. To do this, they first crushed a 1-gram sample by hand in an aluminum mortar and pestle (no samarium or neodymium in it), then separated the Sm and Nd in different minerals using sequential dissolution by weak to strong acids. The solutions were separated in ion exchange columns to obtain small volumes of liquid containing only a few tens of nanograms of Sm or Nd. Finally, they measured the abundances of the isotopes of both elements using a mass spectrometer, which has the impressive full name of a Nu Instruments NuPlasma II MC-ICP-MS. (MC means multicollector, which allows simultaneous counting of the flux of more than one isotopic mass at a time. ICP means inductively-coupled plasma, which uses an ionization process involving heating an atomized sample by electromagnetic induction. See a description in this **PSRD** article: **ICP-MS and Planetary Geosciences**. MS means mass spectrometry, in which an ion beam is accelerated through a magnetic field to create separate paths for ions of different masses.) Such instruments look, sound, and are impressive!

The result of all this work is a diagram of $^{147}Sm/^{144}Nd$ vs $^{143}Nd/^{144}Nd$. Seven dissolution products plot along the same well-defined line (see plot below). The slope of the line defines the age using the well-established decay law. The data show that NWA 7635 crystallized 2403 ± 140 million years ago, which is 1800 million years (1.8 billion years) before the oldest depleted shergottite analyzed previously. Lapen and coworkers take this as solid proof that magmatic activity produced the depleted shergottites over a two-billion year period. An important question is whether all the magmatic activity occurred in the same place on Mars. **Cosmic ray exposure ages** of the depleted shergottites suggest that they do come from the same place on Mars.

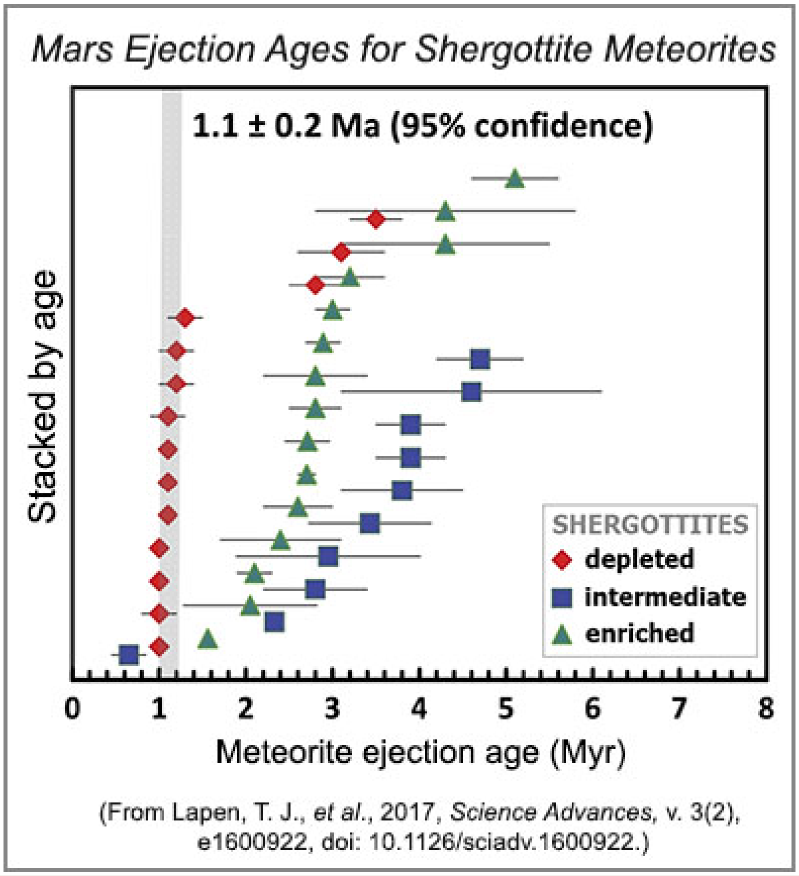


(From Lapen, T. J., *et al.*, 2017, *Science Advances*, v. 3(2), e1600922, doi: 10.1126/sciadv.1600922.)

Seven chemical separates from NWA 7635 fall along a line, indicating an age of 2403 ± 140 million years. The uncertainty derives from the small amount of scatter around the line. Thus, formation of the depleted shergottites began at least 2400 million years (2.4 billion years) ago and lasted at least until 325 million years ago (the age of the youngest depleted shergottite dated so far).

Same Place on Mars

Besides their crystallization ages, Martian meteorites have another important age: their cosmic ray exposure age. This allows cosmochemists to determine when a given meteorite was liberated from Mars by a large impact. Team members made the measurements using accelerator mass spectrometer systems at Purdue University and the University of Arizona. They determined the abundances of radioactive isotopes that are produced only by exposure to cosmic rays (mostly high-energy protons), namely ^{10}Be, ^{26}Al, and ^{14}C, and found an exposure age of 1.0 ± 0.1 million years. Thus, NWA 7536 was blasted off Mars a million years ago. Ten other depleted shergottites also have ejection ages close to a million years, averaging 1.1 ± 0.2 million years. This tight cluster differs from the ejection ages of other shergottites (see diagram below).



Measurements of isotopes produced by cosmic rays allow cosmochemists to determine the time of ejection from Mars. This diagram shows ejection ages of different types of shergottites. Note that 11 depleted shergottites (red diamonds) were ejected about a million years ago. The crystallization (eruption) ages of this set of lava flow samples, including NWA 7536, ranges from 325–2400 million years, indicating an extensive period of eruptions in one small region of Mars, possibly a single volcano.

The similarity in chemical and isotopic compositions, mantle sources, and ejection ages leads Lapen and coworkers to conclude that most of the depleted shergottites, including NWA 7635, come from the same volcanic site on Mars. This site, perhaps a single volcanic construct, was volcanically active from at least 2400 to 325 million years ago, possibly longer. This long time span implies that the ejection process sampled a layered sequence of lava flows and shallow intrusions that would otherwise require a deep-drilling sample return mission. Geological mapping of Martian volcanoes shows clear evidence for long-lived volcanic activity associated with a single volcano (see **PSRD** article: **Timeline of Martian Volcanism**). This is consistent with a volcanic system fed by a long-lasting mantle plume. Geophysicists have modeled mantle plumes using fluid dynamics, and find that these features could last up to billions of years.

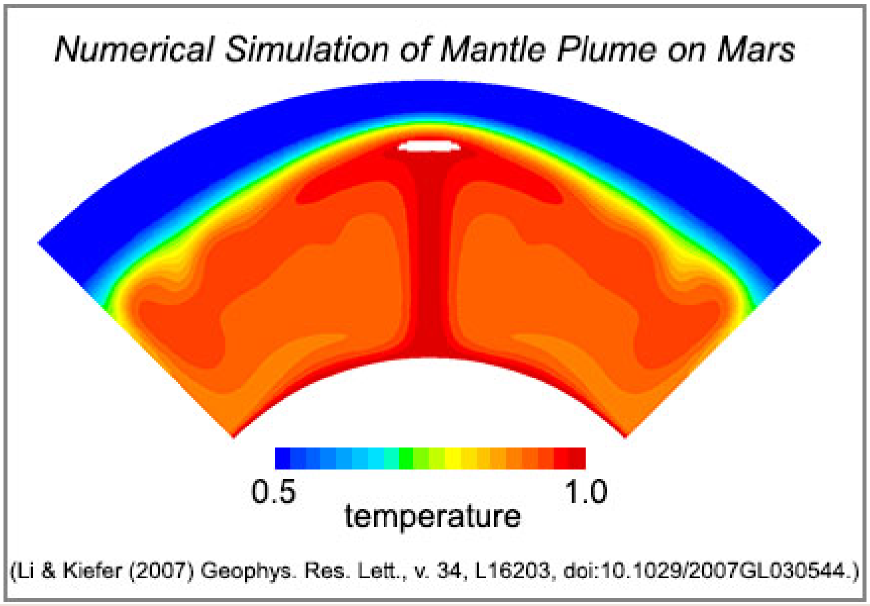


Illustration of the model results of fluid dynamic and thermal calculation of a plume inside Mars that begins at the boundary between the core and mantle, from work by Qingsong Li and Walter Kiefer (Lunar and Planetary Institute, Houston). Temperature scale represents relative values. The hot plume (red) is about 120°C hotter than the surrounding mantle, so is buoyant, causing the plume to rise as a solid mass that melts when the pressure becomes low enough, at about 100 kilometers below the surface.

The work by Lapen and coauthors provides evidence for long-lived plumes in the Martian interior, which emphasizes the importance of this type of convection in Mars. Earth has plumes, too, but also larger-scale convection and plate tectonics, in contrast to Mars where we have no evidence for plate tectonics. It appears that Mars and Earth evolved differently, perhaps because Mars is much smaller. Whatever the reasons, studies of Martian meteorites are giving us new insight to Martian volcanism and the dynamics of its mantle.

Additional Resources

Links open in a new window.

- **PSRDpresents:** Two Billion Years of Magmatism in One Place on Mars -- **Short Slide Summary** (with accompanying notes).

- Bogard, D. D. and Johnson, P. (1983) Martian Gases in an Antarctic Meteorite? *Science*, v. 221, p. 651-654.
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- Taylor, G. J. (July 1999) An Adulterated Martian Meteorite, *Planetary Science Research Discoveries,* **http://www.psrd.hawaii.edu/July99/EETA79001.html**.
- Taylor, G. J. (June 2004) The Multifarious Martian Mantle, *Planetary Science Research Discoveries,* **http://www.psrd.hawaii.edu/June04/martianMantle.html**.

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