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Headline Article

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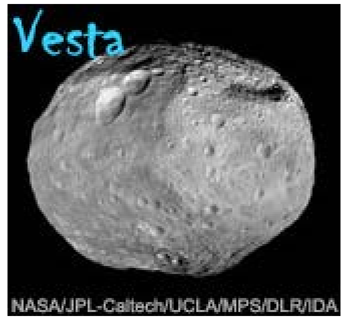

Water in Asteroid 4 Vesta

--- The big, melted asteroid 4 Vesta provides clues to the source of water to Earth and Mars.

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Eucrite meteorites come from asteroid 4 Vesta, which was recently studied from orbit by NASA's Dawn mission. Adam Sarafian (Woods Hole Oceanographic Institute) and colleagues at Woods Hole, the University of Bristol, England, and the University of New Mexico measured the hydrogen concentration and deuterium/hydrogen (**D/H**) ratio in crystals of the mineral apatite (calcium phosphate) in eucrites. They found that the D/H ratio is in the same range as in **carbonaceous chondrites**, most samples of the Earth's mantle, and in samples of basaltic meteorites from Mars. Combined with measurements of the isotopic compositions of nitrogen and carbon, the data suggest that these **volatile** elements were added to Earth early in its history, probably during its formation. Other studies conclude that water with D/H like that in carbonaceous chondrites, Earth, Mars, and Vesta were likely inherited from interstellar ice that predates formation of the solar system.

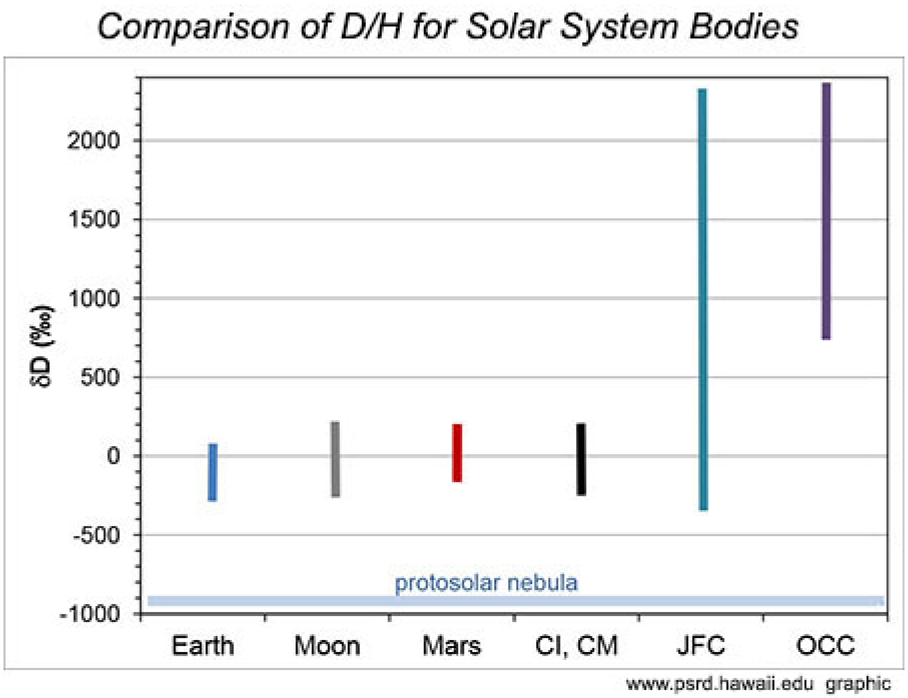
Reference:

- Sarafian, A. R., Nielsen, S. G., Marschall, H. R., McCubbin, F. M., Monteleone, B. D. (2014) Early Accretion of Water in the Inner Solar System from a Carbonaceous Chondrite–like Source, *Science*, v. 346, p. 623-626, doi: 10.1126/science.1256717. [**abstract**]
- **PSRDpresents: Water in Asteroid 4 Vesta** -- Short Slide Summary (with accompanying notes).

The Importance of Water

Besides being an essential ingredient for life, whether as making up the broth in a primordial soup in which life might have arisen or the main fluid we consume when trying to beat back a cold or the flu, water is a useful tracer of processes operating before, during, and after the formation of the solar system. This applies to both its abundance in a planetary body and the ratio of deuterium to hydrogen (D/H). The ratio is particularly helpful in understanding the source of water to the inner solar system bodies (planets, the Moon, and asteroids).

The D/H ratio is particularly informative. Deuterium is an **isotope** of hydrogen that's also called heavy water. Its nucleus contains a proton and a neutron; hydrogen's nucleus contains only a proton. For reference, the measured D/H in Earth's standard mean ocean water (**SMOW**) is 1.558×10^{-4} and the Earth's mantle is in the range 1.34×10^{-4} to 1.65×10^{-4}. Geochemists commonly use a shorthand way of expressing the D/H ratio in a sample to that in standard mean ocean water, $\delta D = ([D/H]_{sample}/[D/H]_{standard} - 1) \times 1000$. This gives the deviation from mean ocean water in parts per thousand. The diagram below shows the range in D/H in prominent solar system materials.



This diagram shows the ranges in D/H, expressed as δD, in rocks in Earth, the Moon, Mars, in carbonaceous chondrites (CI, CM), and both Jupiter family comets (JFC) and outer solar system Oort cloud comets (OCC). Except for comets, the δD ranges are similar, suggesting that it might be characteristic of the inner solar system. Adam Sarafian and his colleagues tested this idea by analyzing the isotopic composition of hydrogen in igneous rocks (mostly lava flows) from asteroid 4 Vesta.

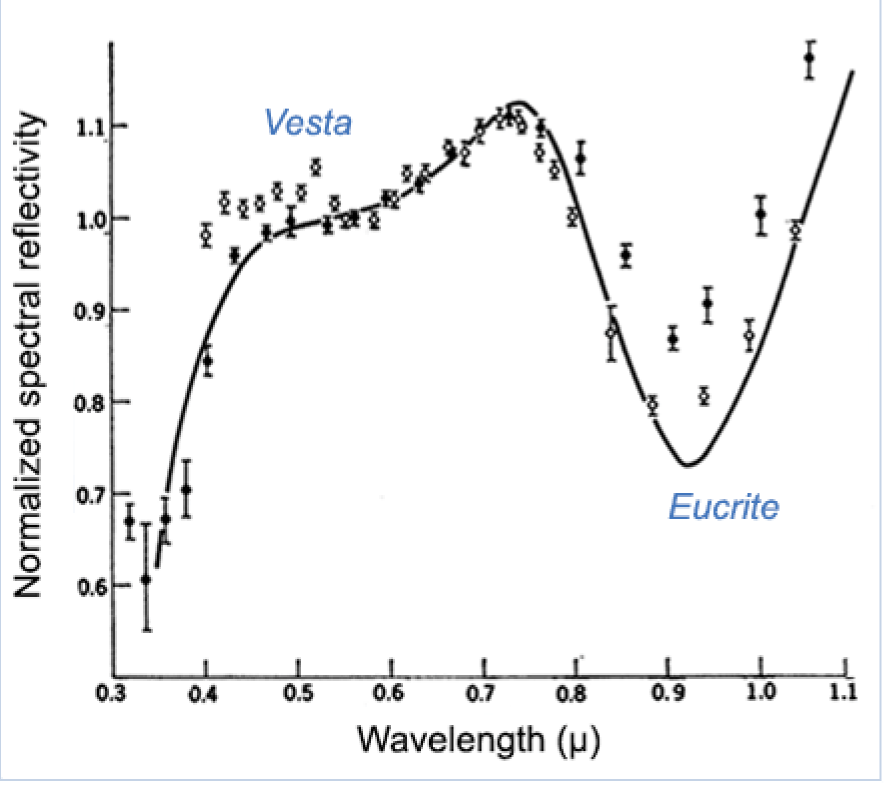
Carbonaceous chondrites cover a larger D/H range than Earth's mantle, but most measurements straddle the terrestrial range (see **PSRD** CosmoSpark report: **Water, Carbonaceous Chondrites, and Earth**). Careful studies of igneous Martian meteorites by Lydia Hallis and colleagues and Tomohiro Usui and colleagues in 2012 show that Mars has D/H in a similar range as carbonaceous chondrites and Earth. In contrast, comets from the Oort cloud in the far reaches of the outer solar system have values of D/H at least two times higher, with δD values of 800 and greater. Jupiter family comets have orbital paths influenced by massive Jupiter. They were thought to have δD similar to the Earth and other inner solar system objects, but results from the Rosetta mission to a Jupiter family comet show that gases escaping from it have δD like outer belt comets. It appears that the inner solar system has a characteristic range in D/H, but icy bodies like comets are different. Do asteroids that melted substantially, such as Vesta, have D/H in this same range? That is the question Adam Sarafian set out to answer. Adding another layer of complexity to the story (as if we needed that), Bob Brown (University of Arizona) and colleagues showed experimentally and theoretically that deuterium can be separated from hydrogen during sublimation of ice as a comet heats during its trip through the inner solar system, thereby casting some doubt about the extent to which measurements of the D/H in water jetting from comets represents the D/H in the interior.

Rocks from Asteroid 4 Vesta

The Dawn mission spent a little over a year orbiting Vesta, collecting remote sensing data. This valuable dataset confirmed that we have rocks from the little planet and helped put them into a geologic context. The rocks make up the Howardite- Eucrite-Diogenite (**HED**) group of meteorites (see **PSRD** article: **Getting to Know Vesta**. Having a global remote sensing dataset to provide a broad geologic perspective and samples that allow us to measure practically everything imaginable in exquisite detail is a powerful combination. The H abundance and D/H ratio can only be measured in labs on Earth, so the meteorites are the stars of the Sarafian show.

How can we be sure that the HED meteorites actually come from Vesta? The best evidence is that the meteorites and the asteroid look alike, at least spectrally. This was first noticed by Thomas McCord (University of Hawai‘i) and colleagues in 1970. The reflectance spectrum of the asteroid was strikingly similar to the spectra of eucrite meteorites, which are pieces of basaltic rock that formed in lava flows. The link between Vesta and the HED meteorites was made stronger by Rick Binzel and Shui Xu in 1993. They showed that a group of asteroids with spectral properties like Vesta had orbits that ranged from the asteroid belt where Vesta is to orbits that crossed Earth's orbit. This string of Vesta pearls provide us with the HED meteorites.

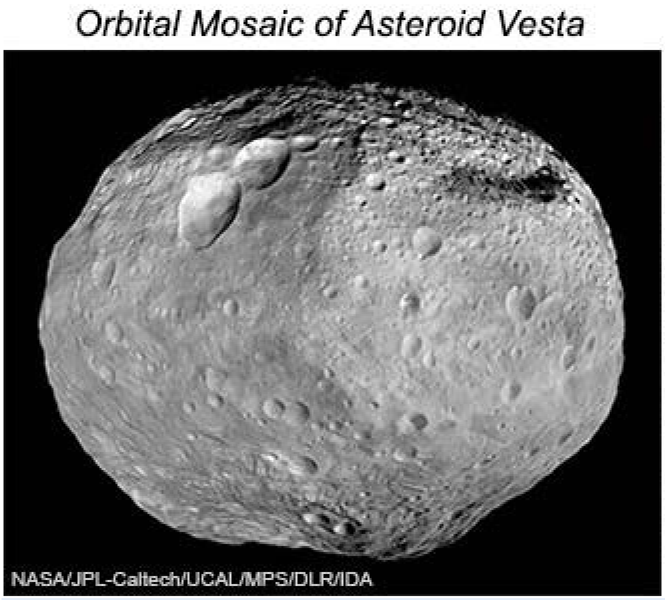
Reflectance Spectrum of Asteroid Vesta Compared to Laboratory Spectrum of Eucrite Meteorite

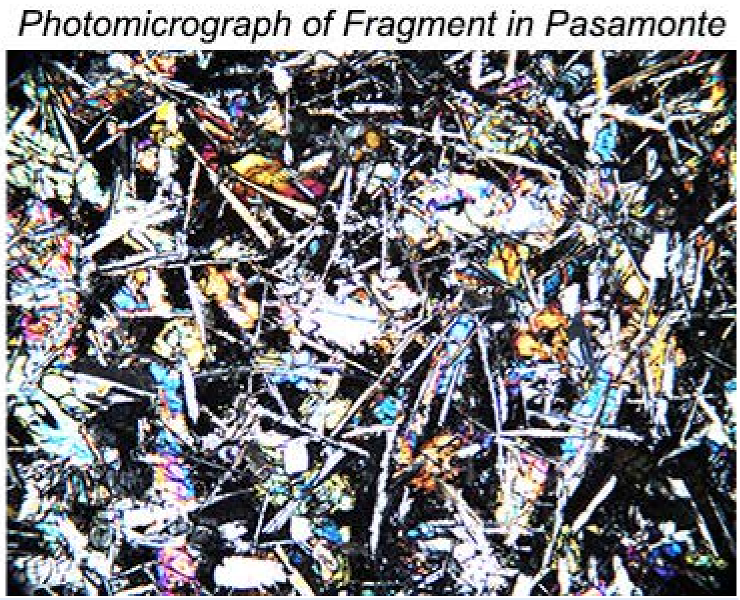


(From McCord *et al.*, 1970, *Science*, v. 168, p. 1445-1447, doi:10.1126/science.168.3938.1445.)

Spectrum of infrared light reflected from Vesta (dots with error bars) obtained at Cerro Tololo, Chile and Mount Wilson compared to a laboratory spectrum (solid line) of a eucrite meteorite, Nuevo Laredo [Data Link from the Meteoritical Bulletin], as shown in the original 1970 paper by Tom McCord and colleagues. The match is impressive and is even more impressive now after many more observations of Vesta by the Hubble Space Telescope and the Dawn Mission, and improved laboratory spectra of HED meteorites.

The link between Vesta and HED meteorites appears to be secure, so studies of the meteorites reveal the geochemical and geological history of the second-largest asteroid. The eucrites in particular are useful because they are clearly igneous rocks that formed very early in the history of the solar system, more than 4.55 billion years ago; in fact, only 8–20 million years after the solar system began to form. The geochemical properties of these extraordinarily ancient igneous rocks, therefore, represent the time those properties were established. In the case of water in the eucrites, their ancient ages indicate that the water was probably added to Vesta as it formed, giving us important information of when the water—with the inner solar system δD values—was added to this region of the solar system.





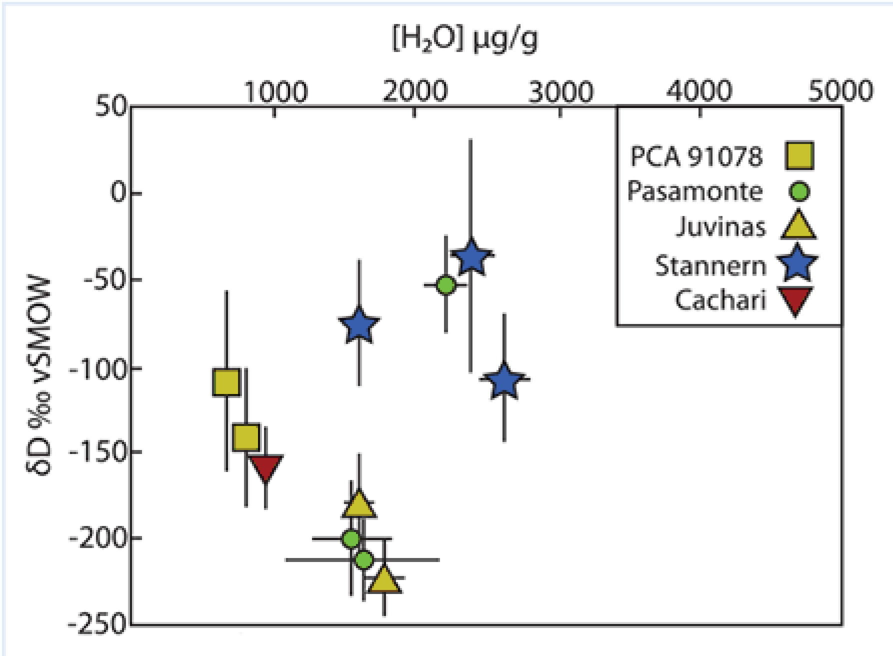
[Left] Photomosaic of Vesta taken by the Dawn mission, showing its cratered landscape. The view shows the south polar region near the bottom of the image, which is decorated with a mountain twice as high as Mount Everest. The mean diameter of Vesta is 525 kilometers. [Right] View taken in polarized light of a thin slice of an igneous rock fragment in the eucrite Pasamonte [Data Link from the Meteoritical Bulletin]. Gray mineral is plagioclase feldspar, more colorful mineral is pyroxene, the characteristic minerals in basalts. The view is 4 millimeters across.

Water in Eucrites

Apatite is a calcium phosphate mineral that, auspiciously for hydrogen isotope aficionados, contains hydrogen and is usually present in planetary basalts. It has the formula $Ca_5(PO_4)_3$ (OH,F,Cl), in which Ca, PO_4, and OH-F-Cl have specific sites inside an apatite crystal. In terms of numbers of atoms, the site containing the hydroxyl ion (OH), fluorine (F), and chlorine (Cl) totals one compared to 5 calciums and 3 phosphates. The hydroxyl site can consist of only one of those ions, but often contains them all. Unfortunately, their relative abundances vary so much as apatite crystallizes in a magma that it is impossible to determine how much hydrogen was present in the magma from the amount of OH in the apatite. Fortunately, for extraterrestrial samples just having some OH proves the presence of water and the D/H ratio accurately portrays that of the magma.

In a pair of studies Adam Sarafian and colleagues used a combination of electron microprobe and secondary ion mass spectrometry to determine the major element concentrations and the F, Cl, OH, and all-important hydrogen and hydrogen isotopic composition (D/H) in apatite in five basalts (eucrite meteorites) from Vesta. The analyses show that the apatite in these asteroidal basalts contain OH, hence so did the lava flows in which they solidified, thus verifying Sarafian's previous analyses of apatite in eucrites based on electron microprobe only. Vesta, which analyses of eucrites and data from the Dawn mission show, is depleted in volatile elements such as potassium, contains water and probably formed with it before it melted and differentiated into core, mantle, and basaltic crust. More importantly, and also unambiguously, Vesta has D/H (expressed as δD in the graph below) in the range of the Earth, Mars, and carbonaceous chondrites.

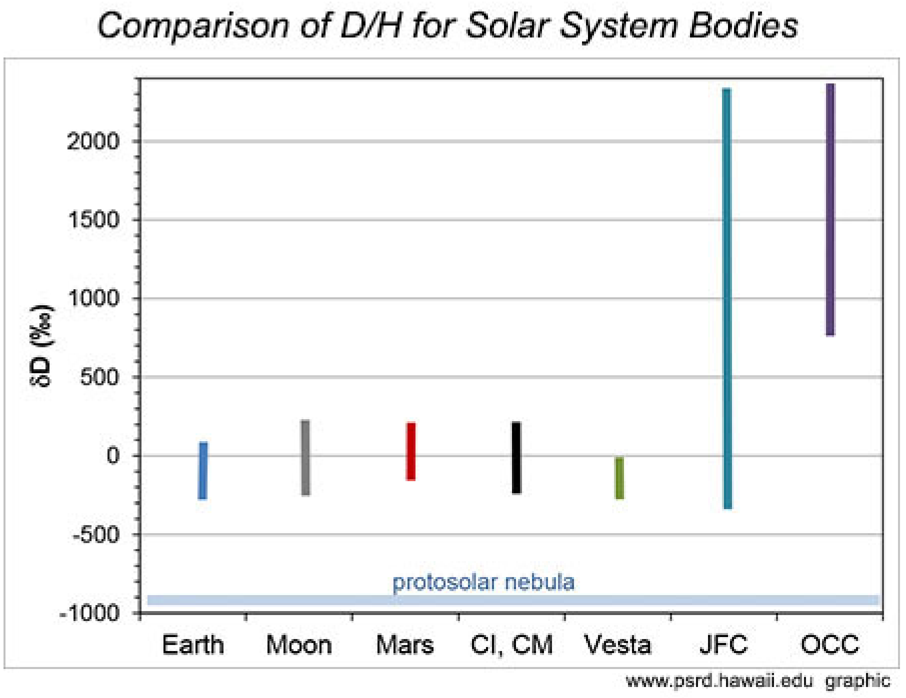
Hydrogen Isotopic Composition vs.
H_2O Concentration of Eucrite Apatites



(From Sarafian *et al.* 2014, *Science*, v. 346, p. 623-626, doi:10.1126/science.1256717.)

Hydrogen isotopic composition versus H_2O concentration in apatite in five different basalt samples (eucrite meteorites) from Vesta. Note the large range in δD, suggesting variation in D/H inside Vesta, but the variation is within the range observed in other inner solar system objects. The lack of correlation between δD and water content suggests that the eucrite lavas did not lose enough water when they erupted on Vesta to separate D from H by loss of H_2 or D_2, which would have led to an increase in D/H and δD. (*Here's a fun, though admittedly nerdy, geochemical note, buried in a figure caption.* The H_2O is really OH in the apatite, as explained above, but geochemists and cosmochemists frequently express oxides in a variety of ways. For example, iron oxide in an analysis of a rock sample might be expressed as FeO or Fe_2O_3, even if Fe is present as Fe^{2+} or Fe^{3+} or a mixture of both. So, expressing the concentration of H in apatite as OH or H_2O is acceptable and we can figure out the value of one from the other. H_2O has the advantage that the problem cosmochemists are trying to solve is how much water or H_2O ice inner solar system planetesimals might have had. On the other hand, OH has crystallographic significance in apatite. Either way is fine as long as it is specified, but the choice can lead to interesting and even entertaining arguments. PSRD is agnostic about the issue, but enjoys the arguments.)

The similarity between Vesta and other inner solar system bodies—Earth, Mars, the Moon, carbonaceous chondrites—is striking, at least compared to outer solar system comets and one Jupiter-family comet. Mars does have materials in its atmosphere that are impressively elevated in δD, in the comet range and even higher, but those samples reflect loss of H in preference to D from the atmosphere. The value for the inside of Mars (most likely reflecting the composition of ancient Mars) is given by igneous rocks that were not affected by the loss of H from the atmosphere. These values are in the same range, as shown in the diagram below (same diagram as shown previously, but with Vesta added). The bottom line is that water in Vesta is like that in other inner solar system objects.



This diagram shows the ranges in D/H, expressed as δD, in rocks in Earth, the Moon, Mars, in carbonaceous chondrites (CI, CM), Vesta, and both Jupiter family comets (JFC) and outer solar system Oort cloud comets (OCC). Vesta is in the range of the inner planets and carbonaceous chondrites.

Adam Sarafian and his colleagues were not satisfied with using the isotopes of just hydrogen in assessing the differences between Vesta and all those other inner solar system objects from which we have samples. They also checked out published data for the concentrations of nitrogen and carbon isotopes. These data are also consistent with a common origin for all the volatile elements to the inner solar system. They conclude that the inner solar system was permeated with a common source of water and other volatile elements. Considering the ancient age of basalts on Vesta, this common material was strewn about the inner solar very early in its history, before Vesta differentiated and lavas flowed onto its surface, which was only 8–20 million after the solar system began to form. How did this water with a specific D/H become common in the inner solar system as planets began to form? Sarafian and coworkers suggest that their observations could help decide between two ideas. One portrays the fledgling solar system as being almost disturbingly dynamic: the outer planets migrated inwards and outwards, gravitationally flinging planetesitmals inwards and outwards. This flinging episode caused by giant planet roaming is physically plausible. On the other hand, maybe the water in the inner solar system was always there: the protosolar nebula always had a gradation in δD and the δD in the inner solar system had this characteristic value. Which is right? The answer is not simple, but cosmochemists and astrophysicists will continue to focus their brain waves on the problem.

Additional Resources

Links open in a new window.

- **PSRDpresents:** Water in Asteroid 4 Vesta--**Short Slide Summary** (with accompanying notes).

- Alexander, C. M. O'D., Bowden, R., Fogel, M. L., Howard, K. T., Herd, C. D. K., and Nittler, L. R. (2012) The Provenances of Asteroids, and Their Contributions to the Volatile Inventories of the

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- **NASA's Dawn Mission**
- Sarafian, A. R., Nielsen, S. G., Marschall, H. R., McCubbin, F. M., Monteleone, B. D. (2014) Early Accretion of Water in the Inner Solar System from a Carbonaceous Chondrite–like Source, *Science,* v. 346, p. 623-626, doi:10.1126/science.1256717. [**abstract**]
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- Usui, T., Alexander, C. M. O'D., Wang, J., Simon, J. I., and Jones, H. H. (2012) Origin of Water and Mantle-crust Interactions on Mars Inferred from Hydrogen Isotopes and Volatile Element Abundances of Olivine-hosted Melt Inclusions of Primitive Shergottites, *Earth adn Planetary Science Letters,* v. 357, p. 119-129, doi:10.1016/j.epsl.2012.09.008. [**abstract**]

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