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A Younger Age for the Oldest Martian Meteorite

--- New isotopic analyses show that famous Martian meteorite ALH 84001 formed 4.09 billion years ago, not 4.50 billion years ago as originally reported.

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The Allan Hills (ALH) 84001 Martian meteorite is famous for containing fiercely-disputed evidence for fossil life. Equally important to many cosmochemists, the meteorite also contains important information about the construction of the Martian crust by magmas derived from the interior, and the subsequent modification of those igneous rocks by large impacts and circulating water. A surprising feature of ALH 84001 has been its extremely ancient age, 4.50 billion years, as determined by samarium-neodymium (Sm-Nd) and rubidium-strontium (Rb-Sr) isotopic dating. If correct, the ancient age implies that the magma in which ALH 84001 formed intruded the primordial crust, perhaps forming in a deep ocean of magma that surrounded Mars during its initial differentiation into metallic core, rocky mantle, and primary crust.

New age determinations by Thomas Lapen (University of Houston) and colleagues there and at the Johnson Space Center, the Lunar and Planetary Institute, the University of Wisconsin, and the University of Brussels, Belgium, indicate that the rock crystallized in a magma 4.091 billion years ago. They used lutetium-hafnium (Lu-Hf) isotopes in determining the new age. This isotopic system has the advantage of not being affected as readily by impact heating and water alteration as are Sm-Nd and Rb-Sr. The new age is consistent with igneous activity throughout Martian history and with a period of heavy bombardment between 4.2 and 4.1 billion years as inferred from the ages of large impact basins on Mars.

Reference:

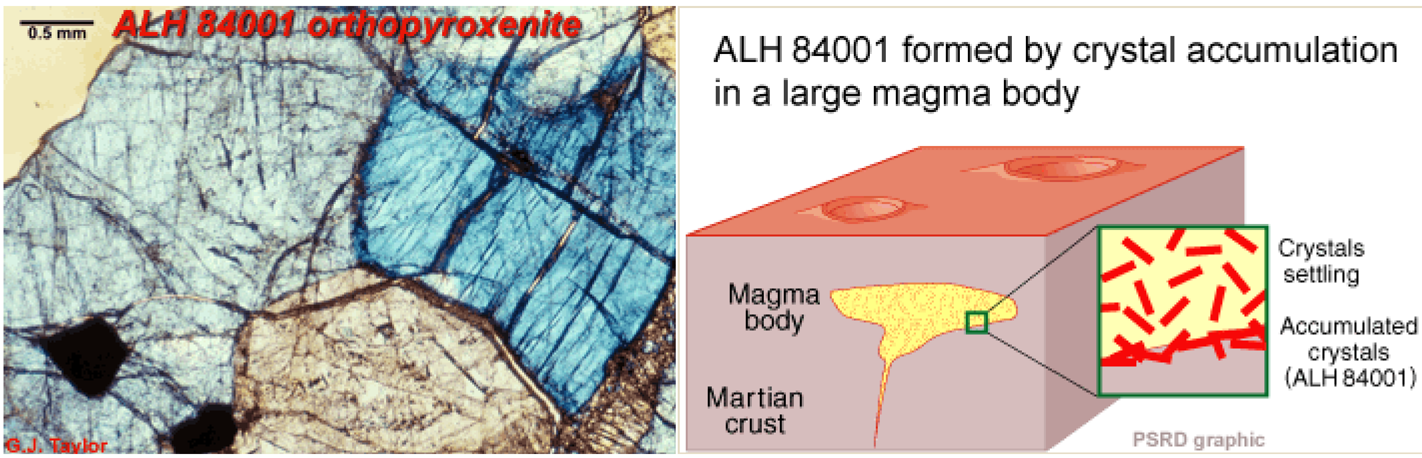
- Lapen, T. J., Righter, M., Brandon, A. D., Debaille, V., Beard, B. L., Shafer, J. T., and Peslier, A. H. (2010) A Younger Age for ALH 84001 and its Geochemical Link to Shergottite Sources in Mars. *Science*, v. 328, p. 347-351.

PSRDpresents: A Younger Age for the Oldest Martian Meteorite --Short Slide Summary (with accompanying notes).

The Tortured History of an Excellent Igneous Rock

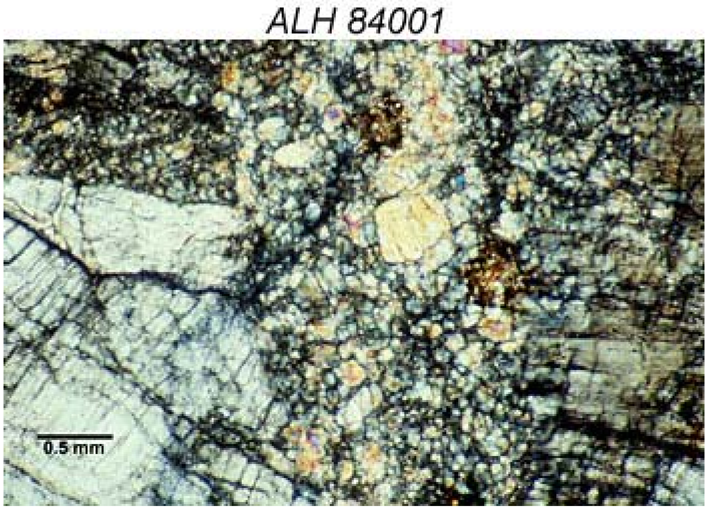
At the risk of revealing my deep-seated biases, I have to say that ALH 84001, whether it ever teemed with microorganisms or not, is one great igneous rock. And igneous rocks are wondrous products that reveal the composition of planetary interiors, the processes that operated in magmas as they migrated to the crust, and how the magmas crystallized far beneath the surface or in lava flows that erupted onto it, shaping the landscape. Igneous rocks are fundamentally important. And thin sections of them look great in a polarizing microscope.

ALH 84001 is a piece from a mass of magma that crystallized inside the Martian crust. As the magma crystallized, one of the first minerals to form was orthopyroxene (iron-magnesium silicate), accompanied by small amounts of chromite (iron-chromium oxide). These early-crystallizing minerals accumulated at the base of the magma chamber, forming a rock consisting of 97% orthopyroxene, 1% chromite, and other minerals that crystallized from magma trapped between the accumulated pyroxene crystals.

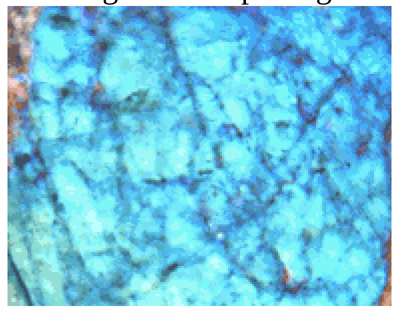


[LEFT] Large crystals of orthopyroxene in ALH 84001 show that this rock formed in a magma chamber deep inside Mars. Dark areas are chromite (an oxide of chromium and iron). The photograph is of a thin slice of the rock as viewed in polarized light. [RIGHT] ALH 84001 formed 4.09 billion years ago, according to new age dating by Tom Lapen and his colleagues. The rock crystallized in a relatively large magma body inside the crust of Mars. Its high abundance of one mineral (orthopyroxene) indicates that this mineral must have accumulated in the magma, probably near the bottom of the magma body, eventually forming the original igneous rock with large crystals of orthopyroxene.

Martian geological processes did not leave the ALH 84001 cumulate to rest in peace. Early bombardment by huge projectiles reworked the crust, heating, melting, and mixing pre-existing rocks into a jumbled, cratered surface. ALH 84001 shows the wounds from the bombardment in the form of shock-damaged mineral grains, some melted and squirted into veins, and areas where the large crystals of orthopyroxene have been crushed (see photograph below). Detailed study of the meteorite, particularly those by Alan Treiman (Lunar and Planetary Institute, Houston), show that the rock was affected by more than one impact, further complicating the interpretation of isotopic data.



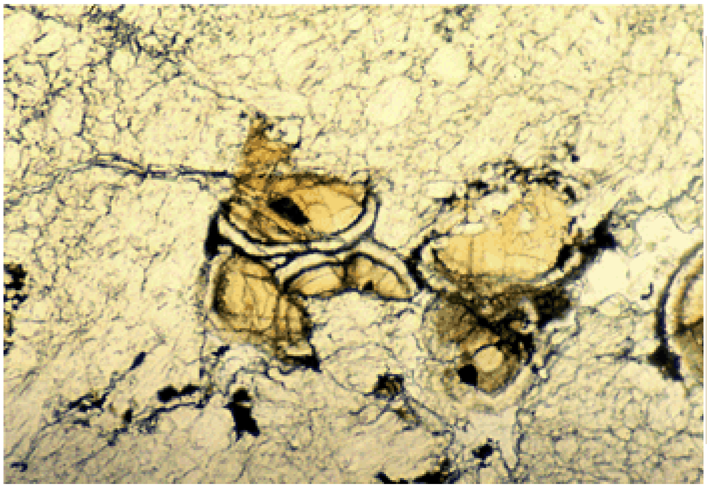
Rotating microscope stage

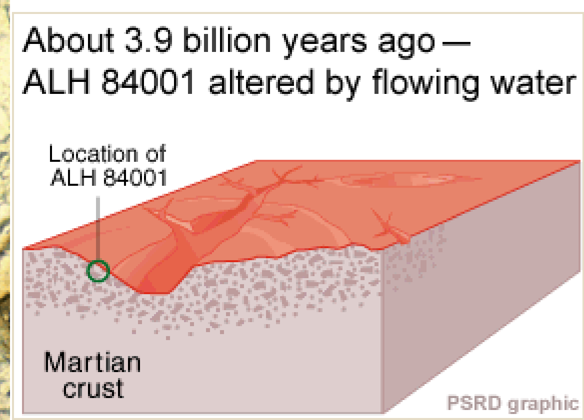


[LEFT] Crushed portion of the ALH 84001 meteorite, as seen in a thin section. Such impact-induced crushing and the accompanying heating likely affected the record of the original igneous crystallization age of the rock. [RIGHT] A shock damaged pyroxene crystal from ALH 84001 in the polarizing light microscope. The uneven way the mineral color changes as a section is rotated in cross-polarized light is indicative of deformation, in this case by shock. Image courtesy of Ed Scott (University of Hawaii).

ALH 84001 also contains deposits of carbonate minerals. These clearly formed from water flowing through the rock, though after it had been affected by one or more impacts. The fractures caused by passage of impact-induced shock waves may have created path ways for water and sites of carbonate deposition. This wet event, although not wet enough to alter the main silicate minerals, may have chemically changed phosphate minerals, the hosts of samarium and neodymium, thereby affecting age measurements. In spite of the complexity of carbonates and how water affected some of the original minerals in the rock, in 1999 Lars Borg and colleagues at the NASA Johnson Space Center managed to painstakingly separate different mineral phases by differential dissolution and then measure the isotopic composition of rubidium and strontium in the rock. The resulting Rb-Sr age is 3.90±0.04 billion years. They also measured the age using lead isotopes, which gave the same value within experimental uncertainty, 4.04±0.10 billion years. Apparently the carbonates precipitated from water that had soaked the rock about 3.9 billion years ago, showing that water could flow through the rock for at least a short time. For more details about carbonate formation and the shock effects on them and the rest of the rock, see **PSRD** articles: Carbonates in ALH 84001: Part of the Story of Water on Mars and Shocked Carbonates may Spell N-O L-I-F-E in Martian Meteorite ALH84001.

ALH 84001 Carbonate Globules





(Allan Treiman, Lunar and Planetary Institute)

[LEFT] Carbonate assemblages in ALH 84001. Carbonates are orange, clear, and dark, (in the center) and are surrounded by orthopyroxene (lighter colored). Small dark grains are chromite. The carbonates were deposited from water that soaked the rock for short periods of time. They have been the focus of the argument about the evidence for fossil life in ALH 84001. Field of view is about 0.5 millimeters across. [RIGHT] Sometime around 3.9 billion years ago ALH 84001 had been excavated from its deep original position in the Martian crust and was part of the upper crust, probably in rubbly crater ejecta. Mars was wetter then than it is now, and water flowed through its crust and across its surface, including through the deposit containing the shock-damaged rock that would become ALH 84001.

Messed-Up Ages

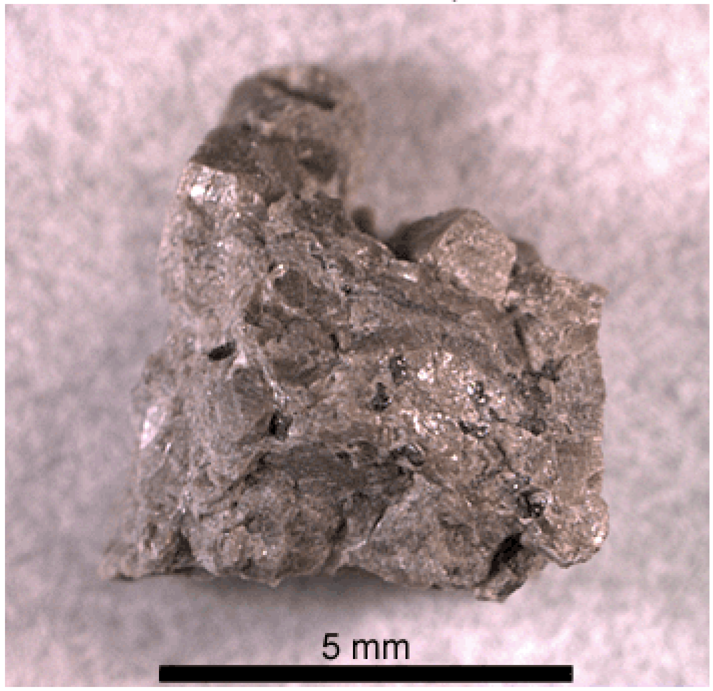
One result of smashing impacts and flowing water is to mess up the distribution of Rb and Sr, Sm and Nd, thereby compromising our ability to determine a reliable age for the original crystallization of ALH 84001. Until now, the only age measurements were reported by Larry Nyquist and his colleagues at NASA Johnson Space Center, in an abstract in the Lunar and Planetary Science Conference. They reported a good isochron for the Sm-147/Nd-143 system, giving an age of 4.50±0.13 billion years, and a slightly older age of 4.56 billion years by the Rb-Sr system. This is the age that has been cited for the rock since the abstract was published in 1995. Most of us have accepted it, especially because the isotope experts were not arguing about it as they often do about ages, but most cosmochemists also felt vaguely uneasy about it. Nyquist and his colleagues had even raised a warning in their 1995 report, noting that data for the short-lived Sm-146/Nd-142 system hinted at a younger age: radioactive Sm-146 (half-life of 103 million years) had substantially decayed away before the rock formed.

Tom Lapen and his colleagues draw attention to the particular sensitivity of Sm-Nd and Rb-Sr to shock heating and to alteration by water. For example, they point out that 58% of the Sm and 78% of the Nd reside inside phosphate minerals, which are subject to alteration by water. A bit of alteration results in redistribution of the parent and daughter isotopes, giving incorrect age results. We need a system that is less subject to alteration by water, shock, and heat. The lutetium-hafnium system fills this tall order.

Seeing through the Damp Rubble

In contrast to most of the Sm and Nd being housed in alteration-prone phosphate minerals, 97% of the Lu and 96% of the Hf reside in orthopyroxene. The remaining 4% of the Hf is in chromite, and an insignificant 3% of the Lu is in phosphate minerals. Orthopyroxene and chromite are not prone to resetting by either shock or reactions with water, so Lapen and his colleagues figured the analyses had a good chance of giving the true igneous age of the rock. In addition, they selected samples that had well-preserved igneous textures, not much granulation of the samples, and no visible carbonates or other alteration.

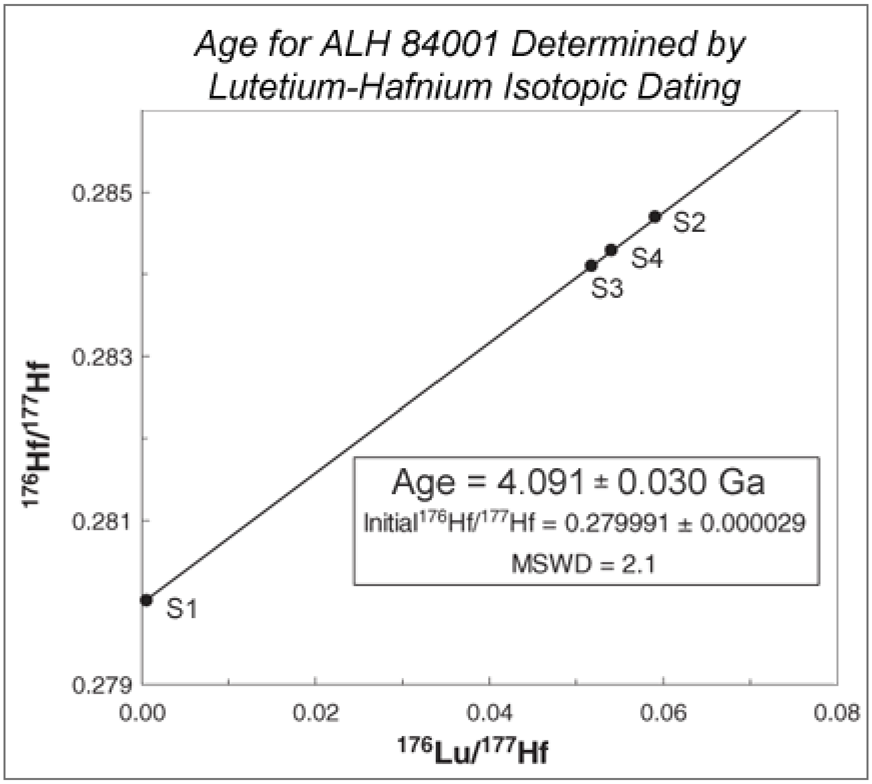
ALH 84001 Sample



(Courtesy of Thomas Lapen, University of Houston.)

One of the igneous-textured fragments used by Tom Lapen and his colleagues to determine the crystallization age of ALH 84001. Samples like this are less likely to have their isotopic systems disturbed by shock.

Lapen and coworkers separated the fragments into four samples: S1, 100% chromite; S2, pure orthopyroxene; S3, an unseparated bulk rock sample; and S4, the bulk sample after separating chromite. They also did some other chemical separations for new measurements of Sm and Nd isotopes, but we will concentrate on the Lu-Hf data here. Lapen separated Lu and Hf from the other elements and from each other by a series of chemical processes using ultra-pure chemicals, and the resulting solutions were measured for their isotopic compositions using a inductively-coupled plasma mass spectrometer at the University of Wisconsin. The results are shown in the isochron diagram below. The four Lu-Hf data points define a precise line on the diagram and indicate an age of 4.091±0.03 billion years (uncertainty is at the 95% confidence level). This probably represents the time when the ALH 84001 cumulate orthopyroxenite crystallized from a magma inside the Martian crust. The age is substantially younger than the previous age measurements (4.50 billion years).



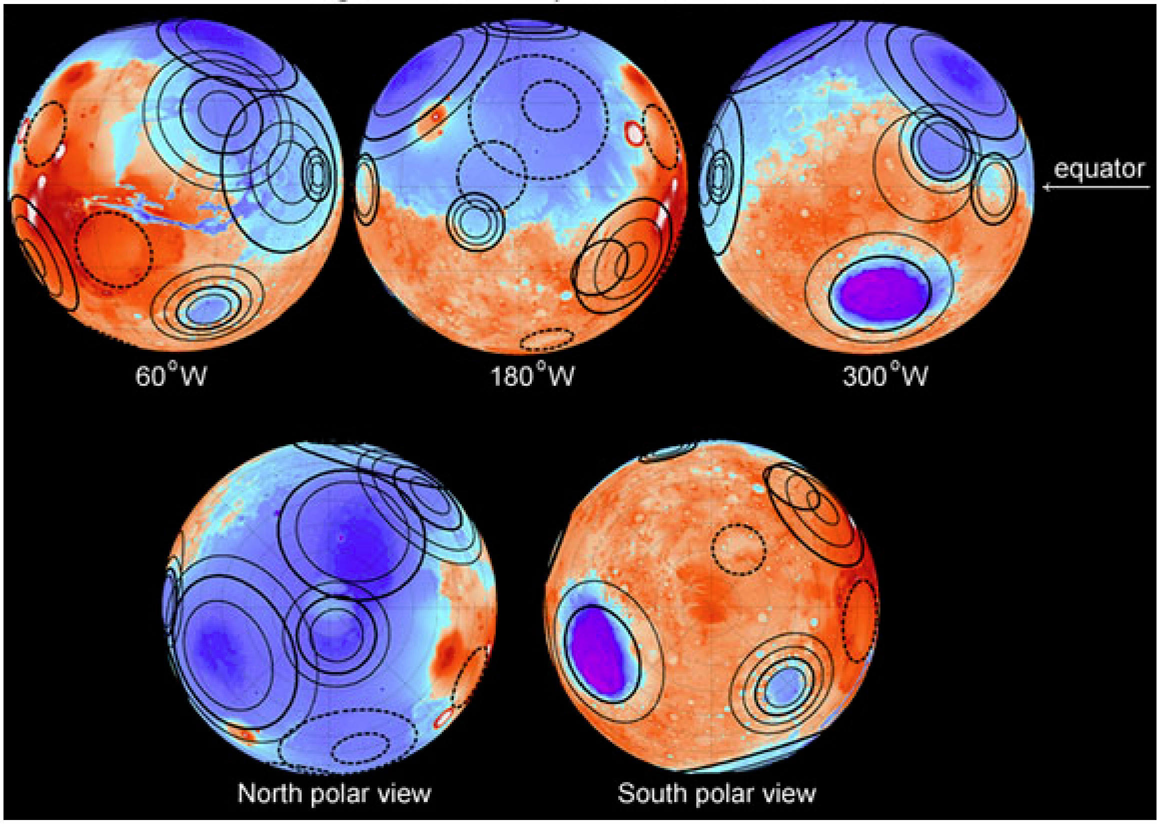
(From Lapen, *et al.*, 2010, *Science*, v. 328, p. 347-351.)

Four different mineral and rock samples from ALH 84001 fall on a precise isochron line. Lutetium-176 is the radioactive parent isotope (half-life of 37.8 billion years). It decays to Hafnium-176. Both are divided by Hafnium-177, a stable isotope of Hf. The slope of the line defines the age (the steeper the slope, the older the age) and the intercept on the y-axis provides important information about the history of the region of the Martian interior where the ALH 84001 magma formed.

Martian Bombardment

Herb Frey (NASA Goddard Space Flight Center) has developed two imaginative techniques to identify old, degraded impact basins on Mars. Both use the detailed topographic data obtained by the Mars Observer Laser Altimeter. One approach uses ghostly outlines of ancient, eroded basins, which Frey calls "Quasi-Circular Depressions," or QCDs for short. The other identifies even more ghostly (but real) circular features, which he identifies on maps of inferred crustal thickness. On these maps the circular depressions are shown by thin crust surrounded by narrow rims of thicker crust. Frey calls these structures "Circular Thin Areas," or CTAs. (Crustal thickness is determined from the combination of topography, variations in the gravitation field around the planet, and geophysical calculations.) The locations of QCDs and CTAs, hence of impact basins, larger than 1000 kilometers across are shown in the maps below.

Large Ancient Impact Basins on Mars

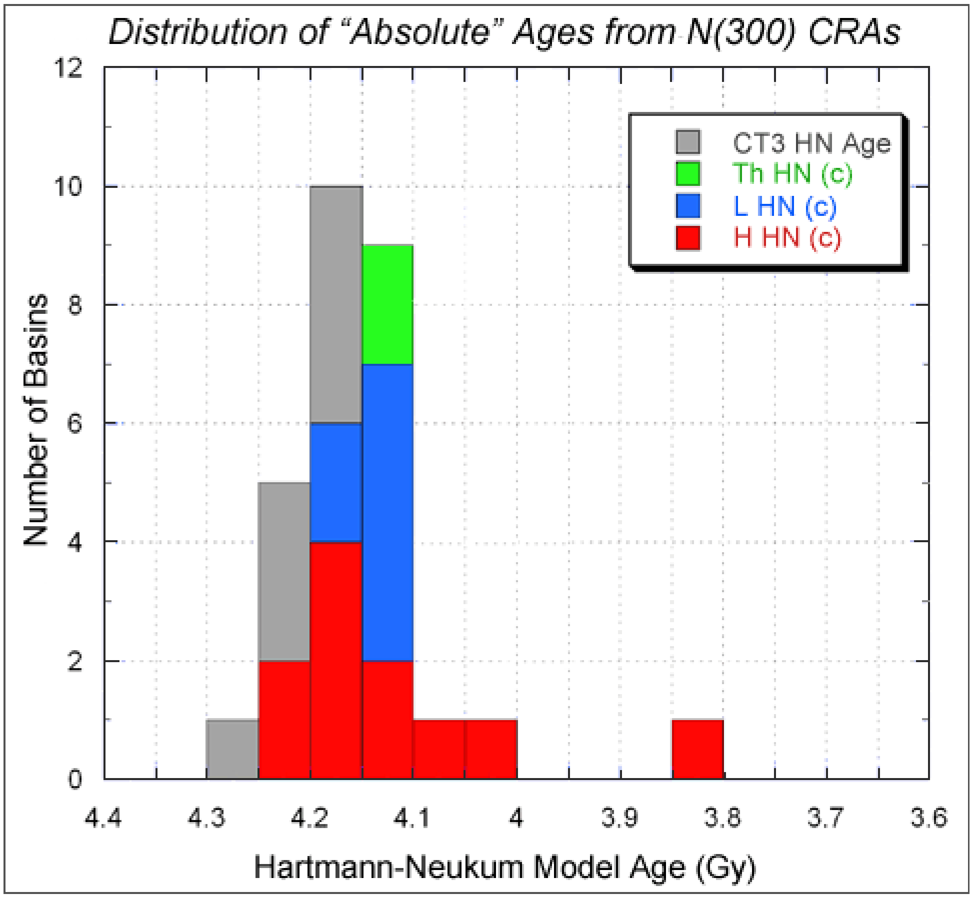


(From Frey, H. (2008) *Geophys. Res. Lett.*, v. 35, L13203, doi:10.1029/2008GL033515.)

Impact basins larger than 1000 kilometers diameter are shown on a series of Mars topographic maps. On the maps, reddish and white colors are high in elevation, blues and purples are low. Solid circles indicate QCDs; dashed circles indicate CTAs. The three maps on top are views of the equator at 60^{o} west longitude (left), 180^{o} west (center), and 300^{o} west (right). The maps on the bottom are views looking down on the north pole (left) and the south pole (right).

Herb Frey estimated the ages of each of the 20 basins larger than 1000 kilometers by counting the number of craters (QCDs and CTAs) larger than 300 kilometers inside each of the basins. This gives a solid measure of their relative ages. Converting these relative ages into absolute ages is much trickier. The method, uncertainties, and issues are discussed in detail in a review paper by Bill Hartmann and Gerhard Neukum. For younger surfaces, such as the lunar maria, the number of craters on them is directly proportional to the age, and lunar samples have allowed a good calibration of the number of craters as a function of time for the past 3.5 billion years or so. The problem arises when the rate of impact was higher, before about 3.9 billon years. Not only is the flux of impactors higher, but smaller craters are eroded faster than larger ones. This led Bill Hartmann, back in 1966, to devise a measure called the "crater retention age," or CRA, which takes into account the extent of retention versus crater size. Herb Frey used this approach and the correlation of CRA with age given by Hartmann and Neukum. (He actually used the average of the Hartmann's and Neukim's estimates because they do not agree with each other!)

Considering these complexities, determining absolute ages by counting craters might seem to be a pretty flaky business. In fact, alert readers might think, considering how hard it has been to determine a precise igneous age for ALH 84001 in state-of-the-art laboratories on Earth, that dating distant planetary surfaces is hopeless. Fortunately, it is not. The relative ages are well established, and the uncertainty in the age of a specific impact basin is on the order of 0.1-0.2 billion years. This uncertainty is larger than the uncertainty of 0.03 in the Lu-Hf age of ALH 84001, but possibly smaller than the uncertainty in the age derived from Sm-Nd dating. Recognizing the uncertainties, the 20 impact basins identified by Herb Frey have a range of ages from about 3.85 to 4.25 billion years, with a sharp peak in the range 4.1-4.2 billion years (see diagram below).



(Revised from Frey, H. (2008) *Geophys. Res. Lett.*, v. 35, L13203, doi:10.1029/2008GL033515.)

Histogram showing the distribution of ages of 28 Martian impact basins larger than 1000 kilometers across, determined by Herb Frey from crater counting. These are from his 2008 paper with updates in 2010. (Red = highland basins. Blue = lowland basins. Green = Tharsis basins. Gray = recently-identified basins using a revised map of crustal thickness created by Greg Neumann and colleagues at Goddard Space Flight Center.) Note the distinct peak in the 4.1 to 4.2 billion year range. The igneous age of ALH 84001, 4.09 billion years, is close to the lower boundary of this range, and the age of carbonate deposition is lower, between 3.9 and 4.0 billion years. Note the startling lack of large impact basins before 4.25 billion years. Rocks formed that early in Martian history might exist as boulders in basin ejecta, if their ages were not reset by the spike in impacts between 4.1 and 4.2 billion years. (Uncertainties in the relation of crater counts to absolute age might shift the distribution to younger or older ages, but will not change the shape of the distribution--Mars experienced a peak in bombardment rate after a post-accretion lull.)

Searching for the Oldest Mars Rocks

Isotopic dating and crater counting indicate that ALH 84001 formed as an igneous intrusion during a period of intense bombardment of the Martian surface. After cooling in an intrusion 4.09 billion years ago, it was excavated by a large impact, exposed to flowing water (probably beneath the surface), and smashed by another impact event as shown by effects on the carbonate assemblages. This is an impressive bit of forensic geology. Are all these geologic events consistent with the record of basin formation revealed by Herb Frey's work? The formation age of 4.09 billion years is near the tail end of intense cratering on Mars, according to the crater count calibration. Perhaps the entire distribution in basin ages should be shifted to the right by 0.2 billion years (about the uncertainty in basin ages), to make a distinct peak at 3.9 to 4.0 billion years. If so, then ALH 84001 formed as the late heavy bombardment was beginning, but managed to survive. Or, perhaps formation of a huge impact basin triggered the melting that led to formation of ALH 84001. Testing the possibilities requires more samples from the ancient surface of Mars.

A downside of the new, younger age of ALH 84001 is that we no longer think we have a rock that formed in the primary Martian crust. Can we find 4.5 billion year old pieces of primary crust? Perhaps the fierce bombardment around 4.1-4.2 billion years reset all the ages. It certainly resurfaced the ancient Martian crust, but that does not mean it erased all record of earlier events. The Moon has been similarly bombarded, but igneous rocks returned from the lunar highlands record a range of ages from 4.4 to 3.9 billion years, revealing a long and compositionally-diverse magmatic history. As in ALH 84001, the record in lunar samples is not always particularly crisp. For example, the oldest lunar samples, the anorthosites, almost certainly make up the primary crust of the Moon, but their isotopic systems have been disturbed by impacts after their formation. See **PSRD** article: The Oldest Moon Rocks for details.

Dating and understanding the formation of the primary crust of Mars will require obtaining direct samples of the crust. Finding the right samples, or the places to search for them, will require remote sensing data to pick appropriate sites and detailed geologic field work of the sites. It is not clear that such intensive work can be done effectively by rovers, so studying the ancient crust might have to wait until people roam the surface of Mars for extended periods of time.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** A Younger Age for the Oldest Martian Meteorite --Short Slide Summary (with accompanying notes).

- ALH 84001 sample photos and microscope images from NASA Johnson Space Center.

- Borg, L. E., J. N. Connelly, L. E. Nyquist, C.-Y. Shih, H. Wiesmann, and Y. Reese (1999), The Age of the Carbonates in Martian Meteorite ALH84001, *Science,* v. 268, p. 90-94. [NASA ADS entry]
- Corrigan, C. M. (2004) Carbonates in ALH 84001: Part of the Story of Water on Mars, *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/July04/carbonatesALH84001.html.
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