Hot Idea

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Field photo of EETA79001

An Adulterated Martian Meteorite

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Martian meteorite Elephant Moraine (EET) A79001 is composed of two distinct rock types. Scientists have thought that both formed from magmas, hence are igneous rocks and contain important information about the interior of Mars, the nature of lava flows on its surface, and the timing of igneous events on Mars. All that is now open to question, as a group of investigators at Lockheed Martin Space Operations and the Johnson Space Center led by David Mittlefehldt (Lockheed) has shown that one of the rock types making up EETA79001, designated lithology A, is almost certainly a melted mixture of other rocks. Mittlefehldt and coworkers suggest that formation by impact melting is the most likely explanation for the chemical and mineralogical features seen in the rock. If confirmed by other investigations, this may change the way we view the igneous evolution of Mars.

Reference:

Mittlefehldt, David W., Lindstrom, David J., Lindstrom, Marilyn M., and Martinez, Rene R., 1999, An impact-melt origin for lithology A of martian meteorite Elephant Moraine A79001, *Meteoritics and Planetary Science,* vol. 34, p. 357-367.

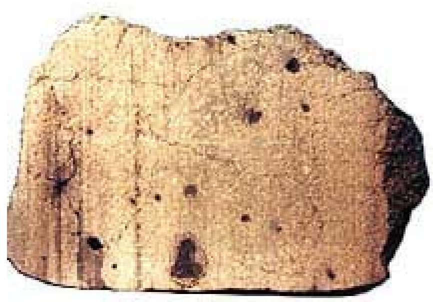
An Important Meteorite

EETA79001 is a very important meteorite because it contains the evidence that settled a raging debate about whether some meteorites come from Mars. Before 1983, planetary scientists knew from isotopic and chemical analyses that several meteorites were related to each other. These were the shergottites, nakhlites, and chassigny, collectively nicknamed the "SNC" meteorites, for the initials of each group. EETA79001 is a shergottite. A striking feature shared by all SNC meteorites was a relatively young age, no more than 1.3 billion years. Some ages were estimated to be as young as 180 million years. While that sounds a tad old to those of us with life spans of only decades, it is quite young by planetary standards. For example, the youngest samples of a lunar lava flow returned to Earth are 3.3 billion years, although some unsampled flows may be as young as 1 to 2 billion years. In contrast, igneous rocks from asteroids are 4.4 to 4.5 billion years old.

The young ages of the SNC meteorites led some scientists to suggest that the SNC had to come from a body that was large enough to remain geologically active until at least 1.3 billion years ago, and perhaps as recently as 180 million years ago. The assumption was that the meteorites were blasted off their planet of origin by a large impact. But which planet or asteroid? Because the rocky planets remain hot in proportion to their size, meteoriticists argued that the SNC meteorites must come from a planet larger than the Moon. Earth was out, since several SNC meteorites were observed to have blazed through the atmosphere, and their oxygen isotopes are distinctly different from those of the Earth and Moon. Venus was not likely because its thick atmosphere would impede escape of impact ejecta. Mars was the best bet.

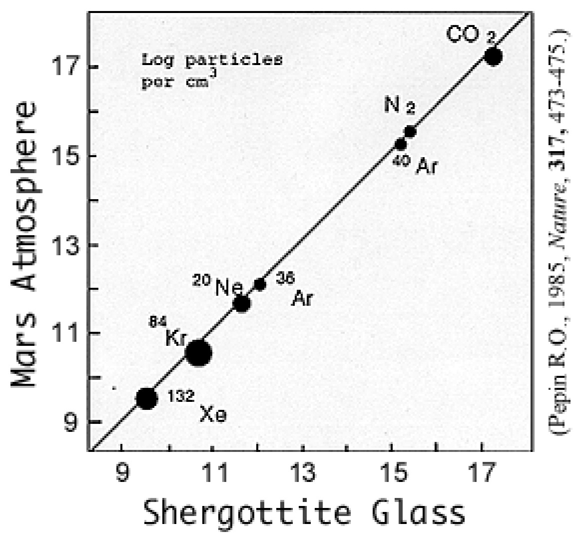
The idea was not embraced enthusiastically, especially by scientists who study the dynamics of the impact process. They argued that there was no way of getting a meteorite off Mars without melting the rock, and there was no evidence for impact melting in the Martian meteorites, although the effects of impact short of melting were evident in many SNC meteorites. In fact, they argued, it was not possible to eject a rock from the Moon without melting it. The discovery of an unmelted meteorite from the Moon in 1981 severely weakened that argument, but the debate raged from the mid-1970s until 1983. That was when Donald Bogard (Johnson Space Center) proved that EETA79001 came from Mars.

EETA79001, in the left photograph below, contains dark splotches of glassy material that almost certainly formed by impact melting. Don Bogard and Pratt Johnson measured the gases trapped inside the EETA79001 splotches and found that they were a perfect match for gases in the atmosphere of Mars as measured by the Viking landers in 1976. Further measurements by Robert Pepin (University of Minnesota) confirmed and expanded Bogard and Johnson's results (see the graph below). The match was so good and the Martian atmosphere so distinct from other planetary atmospheres that the debate ceased instantly. I know of no meteoriticist who does not believe that the SNC meteorites come from Mars. (Another SNC meteorite, Zagami, was also shown by Kurt Marti (University of California, San Diego) and colleagues in 1995 to contain trapped gases like the Martian atmosphere. In 1998 Bogard and Garrison showed that three other SNC meteorites contain Martian atmosphere: Shergotty, Y-793605, and ALH 77005.)



Shergottite EETA79001

Splotches of glassy material contain trapped martian atmosphere.
Rock is 16 cm across.

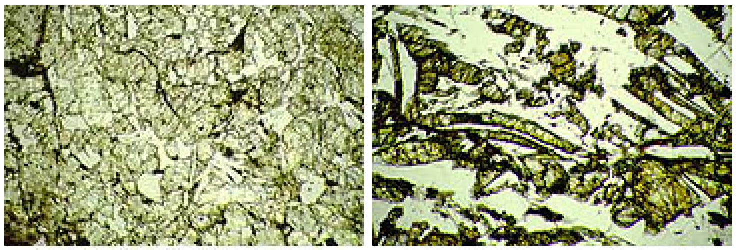


Comparison of Viking-measured Mars atmosphere to trapped gases in EETA79001 Shergottite glass. Figure is from Pepin, R. O., 1985, Evidence of Martian Origins, *Nature,* **317**, p. 473-475.

EETA79001 has some compositional characteristics, such as a high ratio of magnesium oxide to iron oxide, that has led many scientists to use it in studies of the formation and subsequent evolution of Martian magmas. For example, high magnesium to iron is a characteristic of so-called "primary magmas," magmas thought to be unmodified since the time of their formation in the mantle. This characteristic makes them valuable for figuring out the chemical and mineralogical composition of the interior of Mars. Thus, EETA79001 is an important meteorite.

A Complicated Meteorite

There is not much simple about EETA79001. Curators noticed right away when they cut it open at the Curatorial Facility at the Johnson Space Center that the rock contained two distinct lithologies, or rock types. One, named lithology A, makes up about 95% of the rock. Lithology A is a complicated, heterogeneous mixture of large chunks of the minerals olivine, pyroxene, and chromite distributed in a matrix of smaller crystals intergrown in a way that strongly resembles a basaltic lava flow. Lithology B is much more homogeneous, does not contain the chunks of olivine, pyroxene, and chromite, but its constituent mineral grains are also intergrown in a way typical of a lava flow. Lithology B contains larger crystals than the matrix of lithology A, and the minerals in lithology A all contain more magnesium than do those in lithology B. The contact between the two rock types is smeared out over a distance of about 1 centimeter.



EETA79001 Lithology A EETA79001 Lithology B

Each photomicrograph is 2.8 mm across.

The big chunks of minerals in lithology A are similar in chemical composition to the minerals in another Martian meteorite, Allan Hills (ALHA) 77005. This led some scientists to suggest that a rock like ALHA77005 was mixed into a magma like lithology B, producing the magma that made lithology A in EETA79001. However, nobody suggested that the mixing was done by an impact. Instead, they suggested that two magmas mixed or that magma chemically reacted with rock like that found in ALHA77005. Both ideas have problems, however, especially in providing enough heat for the chemical processes to operate. Mittlefehldt and colleagues present further evidence to show that lithology A is a mixture, and then argue that an impact caused the mixing.

Impact Melting and Mixing

Dave Mittlefehldt (who is nicknamed "Duck") has a sharp eye. He is responsible for recognizing that ALH84001, the Martian meteorite suspected by some to contain evidence for fossil life, was actually a Martian meteorite. One might expect a new idea when he trained his sights on EETA79001.

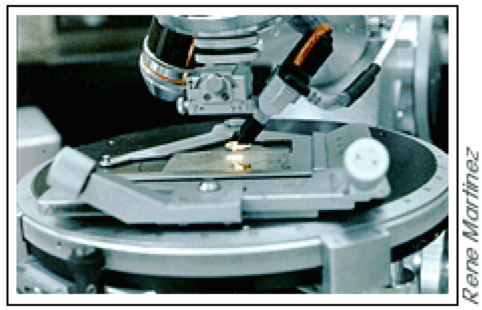
The idea that lithology A in EETA79001 is a mixture is well established, as is the idea that lithologies A and B are quite different. In fact, the chunks of minerals in lithology A cannot have crystallized from a magma with the composition of the matrix of lithology A. That implies some complicated process was at work. To test the mixing idea in more detail, Duck and his colleagues did some elaborate calculations to determine how much of various candidate rocks could be mixed together to make up lithology A. The computations, called "least squares mixing calculations," involve mathematically mixing two rock types together in such a way that the difference between a calculated mixture and the real lithology A is as small as possible.

Duck assumed that one of the rock types in the mixture was identical to lithology B, and then tested four others as candidates for the other component: (1) The light regions of ALHA77005 (recall that the mineral fragments in lithology A resemble the minerals in ALHA77005). (2) The dark parts of ALHA77005. The fact that ALHA77005 has light and dark portions shows how complicated that rock is, and how tricky this kind of work is. (3) ALH84001, the rock with the suspected fossils. (4) The meteorite Chassigny, which contains lots of olivine, a prominent mineral among the large mineral fragments in lithology A.

The best match for the actual composition of lithology A was for a mixture of 56% ALHA77005 (light portion) and 44% lithology B. This is consistent with the match in the compositions of the minerals in ALHA77005 and the large fragments in lithology A.

The chemical comparison was between ALHA77005 and the entire lithology A, meaning the finer-grained matrix plus the large mineral chunks. Duck and his colleagues wanted to determine the composition of the lithology A matrix alone to see if that also was a mixture. However, the mineral fragments are distributed so thoroughly throughout the matrix that it is difficult to chip out a sample of pure matrix. This is where Dave Lindstrom's micro-coring device came in handy. This device can extract tiny disks from rock slices only 60 micrometers thick. Each sample weighs only about 35 micrograms. Such small samples are very difficult to measure by standard techniques, but the team has also developed the capability of determining the compositions of such tiny samples by a technique called micro-instrumental neutron activation analysis. Armed with these techniques, Duck and his colleagues extracted 13 micro-cores from lithology A for analysis.

Micro-coring device attached to a standard petrographic microscope.



The results of the chemical analyses indicate that the matrix of lithology A is a mixture of about 75% rock like lithology B and 25% rock like ALHA77005. This means that the lithology A magma dissolved some of the rock that resembles ALHA77005. Although this can happen by other processes, Duck and colleagues believe that impact melts are more likely to do such dissolving. In addition, their microanalysis shows that gold is present in the matrix of lithology A. This is consistent with impact melting as impacting meteorites contain high concentrations of gold and other elements that concentrate in metallic iron. Upon impact and vaporization of the impactor, some of the gold ends up in the melt produced by the impact.

Two other suggestions have been made to explain the mixed character of lithology A. One idea depicts the formation of the mixed magma by a process called assimilation, in which a magma (like lithology B) comes in contact with a solid rock with the characteristics of ALHA77005. The magma heats up the colder rock, then begins to dissolve it. However, this takes much more energy than is available, and very little dissolving can be done. In contrast, impact melts are extremely hot, usually heated well above their melting temperatures. The other idea suggests that two magmas mixed, one like lithology B and the other like ALHA77005. There is substantial evidence that magmas on Earth can mix, so the idea is reasonable. However, it is difficult to envision a magma of the composition of ALHA77005, which formed by accumulation of minerals. In spite of the problems with these two alternatives, the impact hypothesis is not yet proven, and more work, and perhaps discovery of additional samples of rock like lithology A, will be needed before the case is closed.

Implications

If EETA79001 lithology A is an impact melt, we need to change some of our ideas about the history of Mars. One is our view of the ages of many of the Martian meteorites. EETA79001 has an age of 173 million years (determined by the rubidium-strontium technique). This is similar to the ages of lithology B, ALHA77005, Shergotty, and Zagami, all Martian meteorites. This relatively young age has been taken to be the age when they formed from magmas on Mars, and extends the time of active volcanism to quite recently. If EETA79001 is an impact melt , the age data gives the time when the ages of older rocks were reset because of the heating. In this case, perhaps none of those meteorites are as young as 173 million years. Thus, volcanism on Mars may have stopped much earlier. Some data indicate that the igneous ages of EETA79001 and the other meteorites listed above could be as old as 1.3 billion years.

An important quest in geology is to find "primary magmas." These are magmas made by melting inside a planet and then not modified by any other processes until they crystallized rapidly on the surface. A rock formed in this way would contain an enormous amount of information about the composition of the interior of Mars. EETA79001 lithology A has some chemical characteristics of a primary magma, and so has been used in numerous experiments and theoretical calculations to infer the nature of the Martian mantle and the evolution of its crust. If lithology A is an impact melt, it cannot be used to unravel the chemical evolution of Mars, and numerous thorough, elegant studies are thrown into doubt. This is why much more work is needed on EETA79001. It is essential to be sure about how it formed before we use it to figure out the nature of the Martian mantle and the crust formed from it.

Additional Resources

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