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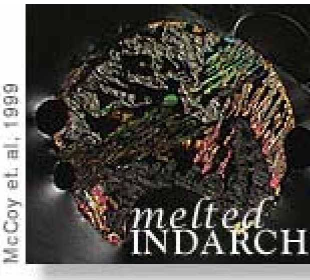

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Difficult Experiments on Weird Rocks

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Enstatite meteorites are a diverse group of strange rocks. They contain little or no oxidized iron, a rare occurrence in the Solar System. Nevertheless, melting experiments on these oxygen-depleted meteorites give clues about magma compositions and core formation in asteroids. Tim McCoy (Smithsonian Institution), Tamara Dickinson (Catholic University), and Gary Lofgren (Johnson Space Center) heated an enstatite chondrite (called Indarch) to a range of temperatures above the temperature of initial melting. They found that the sulfide minerals in the rock melted at 1000º C. This disproved a hypothesis that the calcium sulfide in the rock formed at a very high temperature in the gas-dust cloud from which the planets formed and survived melting in igneous enstatite meteorites. The experiments also indicate that the metallic iron and sulfide minerals begin to form connected networks when only about 20% of the rocky material is melted. This suggests that core formation in the asteroid could have taken place at such low amounts of melting, rather than requiring much higher amounts of melting as some scientists have argued. The experiments also show that igneous enstatite meteorites could have formed from unmelted enstatite chondrites.

Reference:

McCoy, Timothy J., Tamara L.Dickinson, and Gary E. Lofgren, 1999, Partial melting of the Indarch (EH4) meteorite: A textural, chemical, and phase relations view of melting and melt migration, *Meteoritics and Planetary Science,* vol. 34, p. 735-746.

Weird Meteorites

There are several types of meteorites known collectively as the enstatite meteorites. The name derives from the most abundant mineral in them, enstatite, $MgSiO_3$. Enstatite is the magnesium-rich version of a group of minerals called pyroxenes. Pyroxenes in virtually all rocks on Earth, the Moon, and in our meteorite collections contain both magnesium (Mg) and iron (Fe). The strange thing about enstatite meteorites is that they contain almost pure, iron-free enstatite. The iron has been reduced to metallic iron. Stranger still, the highly reducing conditions have caused many elements that normally reside in silicate (rocky) minerals to take up residence in sulfide minerals. The result is that the enstatite meteorites contain a wide assortment of uncommon sulfides. Even the metallic iron has an unusual feature: it contains up to several percent of silicon, the major element in the silicates that make up most rocks. Moving silicon to metallic iron requires a very reducing, oxygen-depleted environment.

The enstatite meteorites include chondrites (many of which have been melted by impacts), aubrites (igneous rocks), stony-iron meteorites, and iron meteorites.

Right: The Norton County (Kansas) aubrite is one of the largest stone meteorites ever collected. It is on display "under glass" in the Meteorite Museum at the Institute of Meteoritics, University of New Mexico. It consists mostly of light-gray to white enstatite crystals up to 8 centimeters long.

Courtesy of: Institute of Meteoritics, Univ. of New Mexico

Below: Sliced, magnified, and photographed in polarized light, a thin section of the Norton County aubrite shows centimeter-sized crystals of enstatite intergrown in a typical igneous texture. The view is 3.5 centimeters across. The small blebs inside the crystals are diopside ($CaMgSiO_6$), which precipitated from the host enstatite crystals. Formation of the blebs requires slow cooling, so the aubrites were not lava flows, which cool rapidly.

Jeff Taylor

Several mysteries surround the enstatite meteorites. Can the aubrites have formed by melting of the enstatite chondrites? There are chemical and mineralogical differences between the two types of rock, and it is difficult to explain these differences from what we know about the melting process.

Aubrites are composed almost entirely of enstatite, with little, if any, feldspar in them. If they formed by melting an enstatite chondrite, the first melts to form would contain lots of feldspar (approximately 50-60%), similar to terrestrial basalts. But where are the enstatite basalts? We have no samples of them. Were they lost by impacts onto the surface of the aubrite asteroid? Did the basaltic magma erupt with such velocity that they were lost into space? Or do basaltic melts not form when enstatite chondrites are melted?

One of the exotic sulfide minerals in enstatite chondrites and aubrites is oldhamite, calcium sulfide (CaS). This mineral has a very high melting temperature if it is pure, around 2525 ^{o}C. Some scientists, most notably Katharina Lodders (Washington University in St. Louis), have argued that it formed in the solar nebula, the cloud of gas and dust from which the Sun and planets formed. That might be feasible for chondrites, most of which were not melted, but in aubrites the oldhamite must have survived the melting process. Proponents of the nebula idea argue that the aubrites would have melted at about 1500 ^{o}C, well below the oldhamite melting temperature. Opponents argue that oldhamite's high melting temperature is irrelevant in a mixed system with other sulfides.

Experiments are needed to try to solve these problems. Very few experiments had been done because of the high temperatures involved and the extremely reducing conditions required. Tim McCoy and his colleagues took on this challenging task.

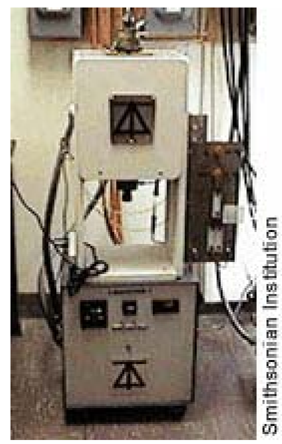
Difficult Experiments

McCoy, Dickinson, and Lofgren obtained a large piece of the Indarch enstatite chondrite from the Field Museum in Chicago. This seemed a logical rock to work with to determine what happens when an enstatite chondrite is melted. They chipped off several grams of Indarch from the interior (to avoid outside oxidation), ground it up, and stored it in a vacuum at 110 ^{o}C to prevent oxidation.

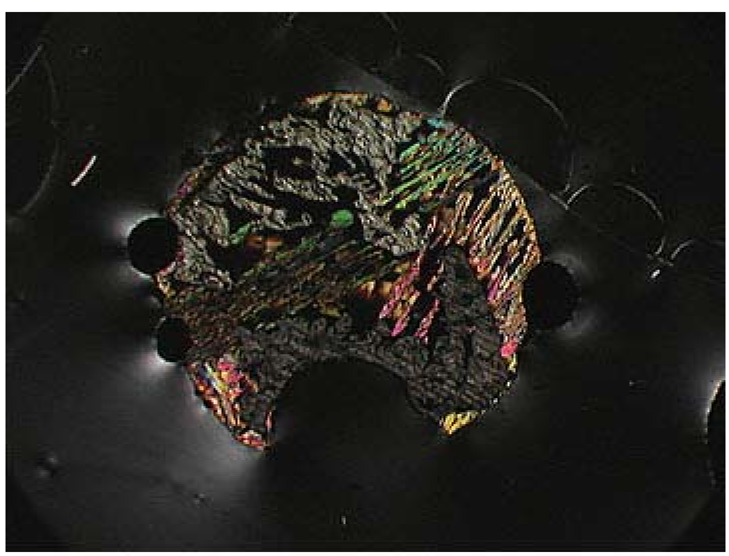
The inherent reduced nature of Indarch was maintained during melting experiments by putting a sample (about 160 milligrams) into a graphite crucible and then sealing it in a silica (SiO_2) tube that had been evacuated. To insure the correct conditions inside the evacuated tube, they also inserted chips of either chromium or vanadium metal. These would react with oxygen to maintain constant-reducing conditions at close to that experienced by enstatite chondrites and aubrites. For each experiment the sealed silica tube was inserted into a cylindrical furnace and heated for 4 to 24 hours at 1000 to 1500 ^oC, and then cooled very rapidly. To complicate matters even further, at these conditions silica can be unstable and react with the surrounding air, so McCoy flowed a mixture of carbon monoxide and carbon dioxide through the furnace. The gas prevented chemical reactions from taking place on the surface of the silica tube.

Left: One of the silica tubes used in the experiments, held on its side. The white portion is an aluminum oxide crucible that contains either chromium or vanadium metal. Beneath that (to the left) is a graphite crucible containing a powdered sample of the Indarch enstatite chondrite. After the tube is removed from the furnace and allowed to cool, it must be carefully broken open to allow air in. If air rushes in too fast the sample can be disrupted and lost. Even worse, the tube can shatter and send fragments flying. When the tubes are opened, the experimenter wears a transparent face guard.

Right: Furnace at the Smithsonian Institution; the experiments were done on a similar furnace at the Johnson Space Center. The sealed silica tube is placed in the upper (white box) portion of the furnace. Black tubes running out the top are for the carbon monoxide-carbon dioxide gases used to preserve the silica tubes. The bottom portion contains power supplies and electronics.



Below: Entire experimental sample of Indarch, about 3 millimeters across, from an experiment heated to 1450 ^OC for 16 hours, and then cooled rapidly. Photographed in polarized light. The crystals are enstatite (grayish) and forsterite ($MgSiO_4$ colorful bars) that formed during the rapid cooling. Dark spheres at the edges and some of the dark areas inside the sample are metallic iron and sulfides.



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These were not routine experiments! McCoy and his colleagues did about 40 experiments to get eight successful ones (demonstrating great perseverance), and made detailed observations on each experimental product. It was worth the effort as they opened the door to a better understanding of enstatite meteorites.

Resolving the Calcium Sulfide Debate

Indarch began to melt at 1000 ^{o}C, but like all rocks and other mixed substances, it does not melt all at once. It partially melts, with the amount of melted material (magma) increasing with increasing temperature. For example, at 1100 ^{o}C, only 7% of the original rocky portion of Indarch melted. At 1400 ^{o}C, 20% was melted. It was not until 1500 ^{o}C that all the rocky and metallic minerals had totally melted.

In the partially melted sample, the silicate magma is found between unmelted enstatite crystals. Inside the magma, tiny grains of metallic iron and oldhamite are found, and both were apparently melted during the experiment. It also appears that at a temperature as low as 1100 ^{o}C, all the metallic iron and sulfide minerals melted. This shows that oldhamite formed in the solar nebula cannot survive the melting of an enstatite chondrite. The oldhamite in aubrites (the coarse-grained igneous rocks) must have formed from a sulfide-rich magma.

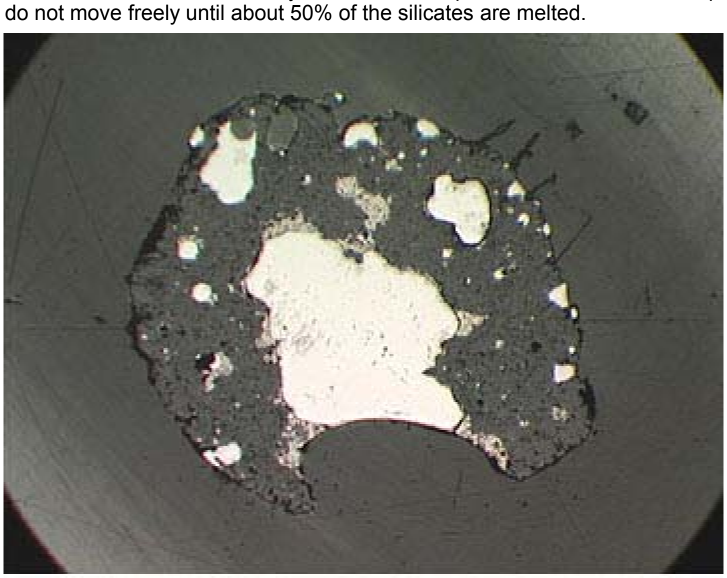
Moving Metals

Planets have dense metallic cores. Some asteroids must, too. Otherwise, we would not have iron meteorites, whose cooling rates are consistent with them residing in the centers of asteroids over a hundred kilometers in diameter. How did the metal sink to the center? Rock is too strong to allow metal to pass through it, so presumably some melting was involved to make the rock weaker. But how much melting?

The answer depends on how the metal moves. It might form an interconnected network that would allow the metal to flow to the center of an asteroid. However, on the basis of theoretical considerations and one published experiment, I proposed several years ago that metal does not form a continuous network. Instead, it forms globules and stays in the silicate matrix until there is enough silicate melting for the globules to fall. I estimated that half the rocky material would have to be melted before the globules sank. David Stevenson (California Institute of Technology) reached the same conclusion when addressing core formation in the Earth. Subsequent experiments by several groups of investigators indicate that metallic melts inside rock, as predicted, generally form globules.

If this is correct, the experiments done by McCoy and his colleagues should not show metallic melt moving around until the melting reached 50%. In fact, the metal moved around readily when only about 20% of the surrounding rock had melted. Instead of being disseminated in small grains throughout the experimental sample, as was the case initially and when there was only a few percent of melting, charges heated to 1400 ^{o}C (20% melting) consisted of large globules of metal-sulfide mixtures.

Below: Experimental sample (about 3.5 millimeters across) shown in reflected light. Large white areas are metallic with small sulfides included inside. Off white areas are mixtures of sulfide minerals. Gray areas are silicates (typical rocky stuff). This sample was heated to 1400 ^{o}C, causing about 20% of the silicates to melt. Because the metal and sulfides were distributed in small grains before melting, metallic and sulfide melts must have moved readily inside the sample. This is at odds with predictions that metallic melts do not move freely until about 50% of the silicates are melted.



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Why do these experiments show metal moving so easily while others did not? A possible explanation is that the metal-sulfide combination in the Indarch experiments contains so much sulfur that it behaves differently. This is also predicted by theory, and borne out by a few of the experiments done by others. The more sulfur in the metallic melt, the greater the tendency to flow rather than form little balls that go nowhere. This suggests that a core may have formed easily in the asteroid in which the aubrites formed.

Clues to Finding the Missing Basalts

The initial magma produced by partial melting of Indarch is like basalt, as expected. However, it also contains quite a bit of sulfide minerals. McCoy and colleagues suggest that we should search meteorite collections for basalts rich in sulfide minerals, rather than looking for rocks composed of roughly equal amounts of feldspar and enstatite. The experiments could not answer the question of whether the basalts were lost because they erupted at velocities exceeding the escape velocity of the aubrite asteroid, or were lost by being chipped away by thousands of impacts.

Making Aubrites from Enstatite Chondrites

One problem in relating aubrites to enstatite chondrites like Indarch is that sulfide minerals in them have different chemical compositions. For example, in aubrites iron sulfide crystals contain more titanium than does iron sulfide in enstatite chondrites. The experiments show that this is a natural consequence of redistribution of elements when a chondrite is melted. Another problem is the presence in aubrites of much more forsterite (Mg_2SiO_4) than in enstatite chondrites. During the experiments, the composition of the magma changed significantly with progressive amount of melting, and reached a point where abundant forsterite crystallized. This suggests that aubrites could form by melting in an asteroid whose initial composition resembled an enstatite chondrite like Indarch.

The experiments done by McCoy, Dickinson, and Lofgren are as informative as they are difficult, but they cannot give us all the answers. What caused the melting of the aubrite asteroid? Was it the decay of very potent radioactive elements? Heating by the Sun being intensely active early in the history of the Solar System? Why did the asteroids that give us enstatite chondrites not melt while the one that gave us aubrites did? How close together in the asteroid belt are these asteroids? The answers to these questions await better information about the nature of asteroids. This undoubtedly requires close inspection with spacecraft, possible including returning samples.

Additional Resources

Lodders, K., 1996, Oldhamite in enstatite achondrites (aubrites). *NIPR Symposium on Antarctic Meteorites,* , vol. 9, p. 127-142.

McCoy, Timothy J., Tamara L.Dickinson, and Gary E. Lofgren, 1999, Partial melting of the Indarch (EH4) meteorite: A textural, chemical, and phase relations view of melting and melt migration, *Meteoritics and Planetary Science,* vol. 34, p. 735-746.

Meteorite Museum and Collection at the Institite of Meteoritics, University of New Mexico.

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