Hot Idea

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Scanning electron microscope image of fayalite grain.

From a Cloud of Gas and Dust to an Asteroid with Percolating Hot Water

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Chondrite meteorites contain little objects that formed in the huge cloud of gas and dust from which the Solar System formed. The cloud, commonly known as the solar nebula ,was a complicated place. For decades scientists have studied the materials in chondrites to understand the chemical reactions that took place in the cloud which produced the building blocks of the planets. Some of the constituents in chondrites were affected by chemical reactions after they formed, and there has been a raging debate about where those reactions took place.

One school of thought suggests that most of the alterations took place in the solar nebula, while others argue that most occurred on the asteroids the meteorites came from. Ian Hutcheon at Lawrence Livermore National Laboratory and colleagues there and at the University of Hawai`i tested the nebula versus asteroidal origins for grains of fayalite (Fe_2SiO_4) in a chondrite named Mokoia. How fayalite formed has been a big bone of contention between those favoring nebula origins and those favoring asteroidal origins for the secondary chemical reactions. They determined that the fayalite formed between 7 and 16 million years after calcium-aluminum-rich inclusions, the oldest materials in the Solar System. The fayalite formed at about the same time as carbonate grains in carbonaceous chondrites (which everyone agrees formed in asteroids, not in the nebula) and several types of meteorites that formed by melting in asteroids. Hutcheon and his collaborators conclude that the fayalite formed on an asteroid, not in the nebula.

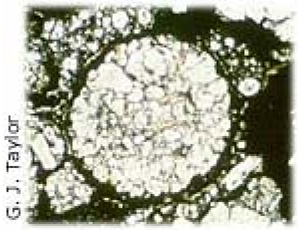
Reference:

Hutcheon, I. D., A. N. Krot, K. Keil, D. L. Phinney, and E. R. D. Scott, 1998, ^{53}Mn-^{53}Cr Dating of Fayalite Formation in the CV3 Chondrite Mokoia: Evidence for Asteroidal Alteration. *Science,* v. 282, p. 1865-1867.

Primordial Solids

Chondrites contain a number of ingredients thought to have formed in the solar nebula. The most prominent and the ones that give chondrites their name are chondrules, millimeter-sized objects that formed by melting aggregates of dust (see PSRD article: Dry Droplets of Fiery Rain). Also present are whitish objects called calcium-aluminum-rich inclusions (CAIs for short), which have the oldest ages of any materials formed in the Solar System, 4.566 billion years, and dark materials that make up the matrices of the rocks. This collection of exotic particles has information about conditions in the solar nebula.

For example, CAIs show that the gas cloud became hot enough in some places to vaporize most of the elements, leaving a residue of minerals enriched in elements, such as calcium and aluminum, that boil at high temperatures. Chondrules were flash melted and then cooled relatively rapidly. Many of the secondary minerals in chondrites require very oxidizing conditions, much more oxidizing than the hydrogen-rich solar nebula was. This has led some scientists to suggest that there were oxidizing episodes in the nebula, perhaps involving evaporation of dust. However, no such oxidizing episodes are needed if the minerals formed in asteroids, thus making the solar nebula a little less complicated to understand. Thus, determining if the secondary minerals formed in the nebula or in asteroids has big implications for our understanding of the earliest history of the Solar System.



The round objects in this photograph of the Tieschitz meteorite are chondrules, small objects that were melted in the solar nebula. The chondrule in the center is 1 mm in diameter.

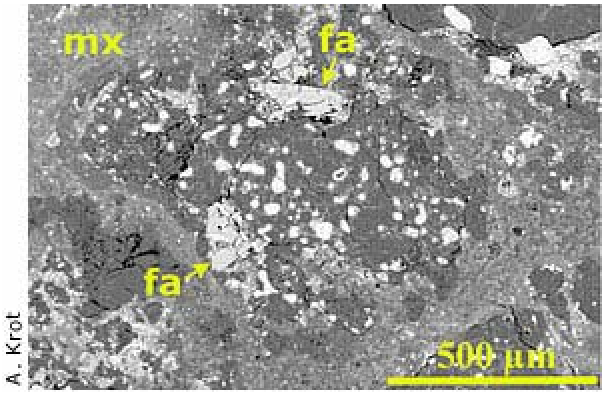
One complication meteorite specialists have to confront is that virtually all chondrites were altered after they accumulated into asteroids. Some were heated from a few hundred to almost a thousand degrees Celsius. Others, especially carbonaceous chondrites, were not heated to as high a temperature, but were heated in the presence of water. Heating with hot water, called hydrothermal alteration, causes all sorts of changes in a rock, and the carbonaceous chondrites show the evidence for it. They contain a baffling array of water-bearing and oxide minerals. Nevertheless, some scientists argue that some of the alteration products formed in the solar nebula, not in the asteroids. The difference is important because the chemical conditions in the nebula and in the asteroids are inferred from the minerals present.

It is not easy to prove how a mineral formed in a rock, especially in wildly complicated rocks like carbonaceous chondrites. Ian Hutcheon and his coworkers thought they might be able to tackle the problem by determining when the alteration products formed compared to the age of the ancient CAIs and younger features in meteorites. If the time of formation of an alteration product in a chondrite was similar to the age of products that had to be formed in an asteroid and at least a few million years after the CAIs, then it would show that the alteration took place in an asteroid. If the age was only about a million years or less after CAIs, then it would be more likely that the reactions took place in the solar nebula.

Using Isotopes That No Longer Exist

One of the strangest-sounding specialties in meteoritics is the use of radioactive isotopes that no longer exist. Some isotopes have half lives that are so short that they decayed completely away billions of years ago. Examples are aluminum-26 (half life of 0.73 million years), manganese-53 (3.7 million years), and iodine-129 (15.7 million years). Hutcheon and colleagues used manganese-53, which decays to chromium-53.

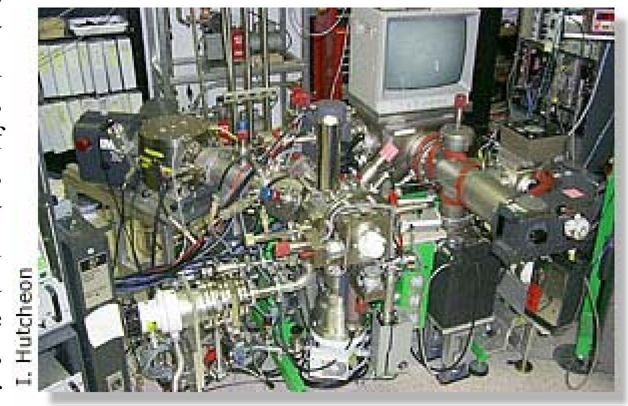
The ideal mineral for dating by this technique would contain lots of manganese and no chromium, so the excess in chromium-53 (most chromium is chromium-52) would be easy to measure. Hutcheon's coworkers at the University of Hawai'i found a suitable, though not perfect mineral: grains of iron-rich olivine called fayalite. Their samples of fayalite contained about half a percent manganese and no measurable chromium. (Their instrument, called an electron microprobe, could detect chromium concentrations down to 0.03%.)



An irregularly shaped chondrule occurs in the center of this scanning electron microscope image (on the left) of the Mokoia chondrite. The chondrule is surrounded by fine-grained matrix material (mx) and contains several grains of fayalite (fa). The bright grains inside the chondrule are magnetite (iron oxide) and iron sulfide. The fayalite grains contain some manganese, but no chromium, making them ideal for dating by the manganese-chromium technique.

The grains of fayalite were found in microscope mounts of the Mokoia carbonaceous chondrite, so the determination of the amounts of chromium-53 had to be done by an instrument that can measure the abundance of an isotope in a thin, polished slice of a rock.

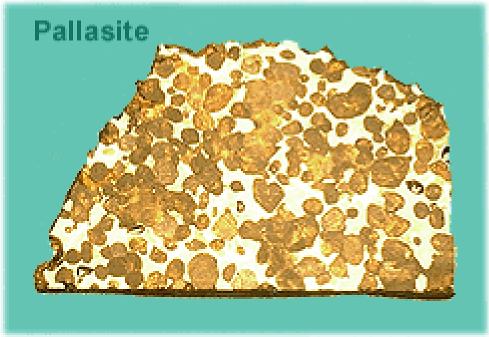
Lawrence Livermore National Laboratory has just the right instrument, an ion microprobe, seen in the photograph on the right. Instruments like these are becoming extremely important in studies of rocks from space and from Earth. Ion microprobe analysis is officially called Secondary Ion Mass Spectrometry, or SIMS for short. In SIMS, a thin beam of ions is accelerated and focused onto a sample, which is usually a polished specimen. The beam, which is only between 1 and 10 micrometers in diameter, sputters material from the upper few layers of atoms. Some of the sputtered atoms are ionized (carry electrical charges), and they are then analyzed in a mass spectrometer . The mass spectrometer separates ions according to the ratio of their mass to charge, allowing scientists to determine the abundances of each isotope.



Hutcheon and his colleague at Livermore, Doug Phinney, used their ion probe to bombard the samples with oxygen ions. These high-energy ions sputtered ions off the surface of the polished thin section of Mokoia. The sputtered ions were then accelerated into a mass spectrometer where the abundance of each isotope could be determined. The size of the oxygen beam is only about 10 micrometers, or 0.01 millimeters. They analyzed several grains of fayalite and several spots on each grain to determine the amount of chromium-53 present.

Time of Fayalite Formation

The data showed conclusively that the fayalite grains in Mokoia formed 7 to 16 million years after CAIs. This is the same time of formation as grains in some carbonaceous chondrites, which all investigators agree formed in an asteroid. Formation in the solar nebula seems to be ruled out by the data.



Even more interesting, meteorites from asteroids that melted substantially also have excesses of chromium-53 that indicate melting 7 to 16 million years after formation of the CAIs. For example, pallasite meteorites formed at the boundary between the molten core and mantle of a melted asteroid. Pallasites (like the 10-cm-wide sample shown on the left) are composed of olivine (yellowish green) and metallic iron (white). Thus, the dating of the fayalite grains in Mokoia by Ian Hutcheon and his collaborators, coupled with research by others, show that meteorite hydrothermal alteration, heating, and melting took place up to 10 million years after the formation of the first solids in the Solar System.

Additional Resources

Hutcheon, I. D., A. N. Krot, K. Keil, D. L. Phinney, and E. R. D. Scott, 1998, ^{53}Mn-^{53}Cr Dating of Fayalite Formation in the CV3 Chondrite Mokoia: Evidence for Asteroidal Alteration. *Science,* v. 282, p. 1865-1867.

Secondary Ion Mass Spectrometry (SIMS) description from Charles Evans & Associates.

On-line tutorial on SIMS theory and instrumentation from Charles Evans & Associates.

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