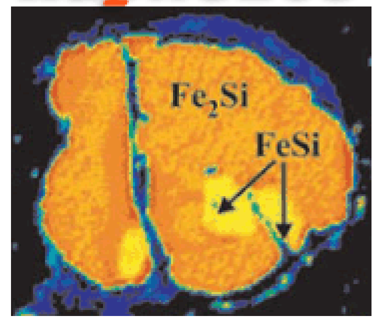
Hot Idea posted July 5, 2004

New Mineral Proves an Old Idea about Space Weathering

--- A newly discovered vapor-deposited iron silicide in a lunar meteorite has been named hapkeite.

hapkeite



(From Anand, *et al.*, *PNAS*, v. 101, p.6848.)

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Discovered in a lunar meteorite, a new mineral named hapkeite honors the scientist, Bruce Hapke (Emeritis Professor at University of Pittsburgh), who nearly 30 years ago predicted the importance of vaporization as one of the processes in space weathering. The new iron silicide mineral (Fe_2Si) was announced by the research team of Mahesh Anand (formerly at the University of Tennessee, Knoxville and now at the Natural History Museum, London), Larry Taylor (University of Tennessee, Knoxville), Mikhail Nazarov (Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow), Jinfu Shu, Ho-kwang Mao, and Russell Hemley (Carnegie Institution of Washington). This mineral likely formed by impact vaporization of the lunar soil and subsequent condensation of the iron and silicon into tiny metal grains. The researchers conclude that Fe-Si phases are more common in the lunar soil than previously thought. It is nanophase-sized Fe^0, these Fe-Si phases, and other space weathering products that profoundly affect the optical properties of the lunar soil at visible and near infrared wavelengths and must be taken into account when interpreting remote sensing data of the Moon.

Reference:

Anand, M., Taylor, L. A., Nazarov, M. A., Shu, J., Mao H.-K., and Hemley, R. J. (2004) Space weathering on airless planetary bodies: clues from the lunar mineral hapkeite. *Proceedings of the National Academy of Sciences,* v. 101, no. 18, p. 6847-6851.

Lunar Surface


NASA AS11-44-6667

The countless craters and basins we see on the Moon attest to a long history of meteorite bombardment. It's a bombardment rate that reached a maximum about 3.85 billion years ago--based on the ages of highland breccia samples returned by the Apollo astronauts. Since then, a lesser but continuous barrage of micrometeorites and charged particles from the Sun and stars has been generating a powdery surface, also called regolith (or soil, though no biologic component is implied in the name.) With nothing to stop or slow down the incoming space debris, due to a near-complete lack of any atmosphere on the Moon, even the tiniest grains (mostly 10s to 150 micrometers) hit the Moon's surface at full cosmic velocity, 20 or more kilometers per second [that is, about 70,000-150,000 km/hr]. The pulverized powdery regolith is just what you'd expect from impact debris. It has rock and mineral fragments, impact glasses, and particles called agglutinates that are mineral and rock fragments stuck together by impact glass. And, the high-energy micrometeorite impacts cause flash-melting, vaporization, and redeposition of some of the surface materials. The phenomenon responsible for the physical and chemical makeup of the Moon's surface is utterly unique to airless planetary bodies--space weathering.

Most of the lunar regolith is smaller than fine sand and about 20% is smaller than 0.02 millimeters, which helps to preserve the astronaut's bootprints. Dragging a rake through the regolith allowed the astronauts to collect rock fragments.

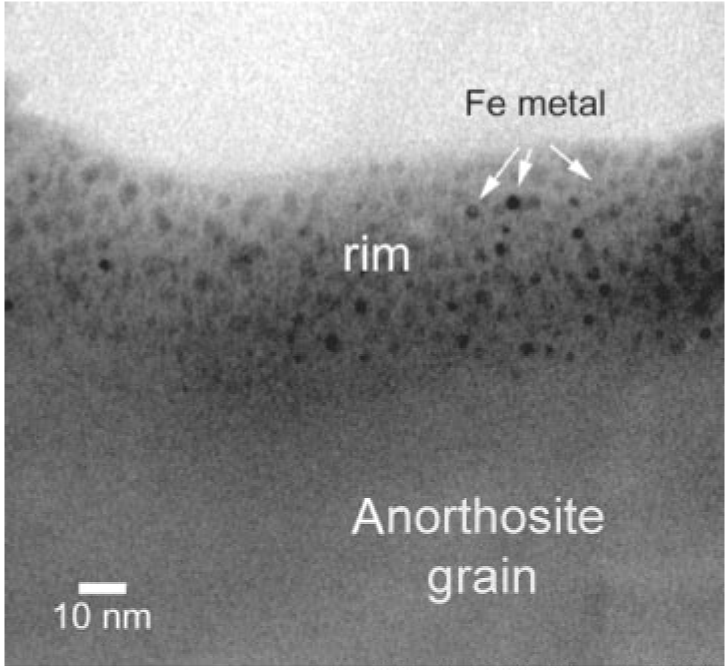
NASA-Apollo 16 photograph.

Space Weathering

Space weathering is generally defined as the processes (such as meteorite, micrometeorite, and cosmic dust bombardment, solar wind ion implantation, and sputtering, but also including deep vacuum and temperatures approaching absolute zero [-273 ^{o}C]) that change the physical structure, optical properties, and chemical and mineralogical properties of the surface of an airless planetary body from their original conditions. It applies to the Moon, Mercury, and asteroids, as well as other small bodies such as Phobos and Deimos. The concept blossomed in the early 1970s when cosmochemists studying rock and regolith samples returned by the Apollo astronauts compared what they were finding with what was already known of the Moon's surface through telescopic spectral studies. There were some surprise results in the laboratories! Apollo regolith samples were darker and spectrally redder than freshly crushed lunar rocks of similar composition.

Bruce Hapke (Emeritis Professor at University of Pittsburgh) and colleagues worked on the question of why the lunar soil becomes darker and spectrally redder with time. In 1975, they proposed that metallic iron would be among the elements and compounds vaporized during space weathering and subsequently condensed in glassy coatings on the surfaces of surrounding soil grains. These iron droplets would be minute, only nanometers in size (billionths of a meter), but they would dramatically alter how light interacts with the surface materials and, hence, how it would be sensed remotely. At the time of the predictions, however, no one could find any trace of vapor condensates on the lunar soil particles.

Finally, technology caught up with human inspiration. In 1993, Lindsay Keller and David McKay (Johnson Space Center) using transmission electron microscopy (TEM) found nanophase-sized metallic iron beads in silica-rich glassy rims on individual mineral grains in Apollo lunar samples. In the same year, Carlé Pieters (Brown University) and colleagues determined that the greatest spectral changes due to space weathering were in the smallest grains of the lunar regolith and concluded that they were caused by changes on the surfaces of grains rather than within the grains. The general consensus reached in the past few years is that no single space-weathering phenomenon entirely explains the darkening and spectral-reddening characteristics of mature lunar regolith. Rather, processes work in concert (grain fragmentation or damage due to impact, agglutinate formation, solar-wind sputtering or impact vaporization and condensation of nanophase-sized iron) to alter the optical properties of the lunar regolith, with vapor-phase deposition of nanophase-sized iron playing the most significant role.

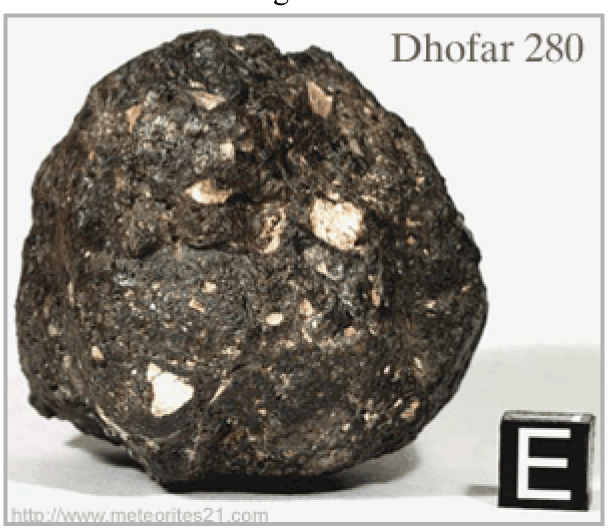


(From Keller *et al.*, 1999; Pieters *et al.*, 2000.)

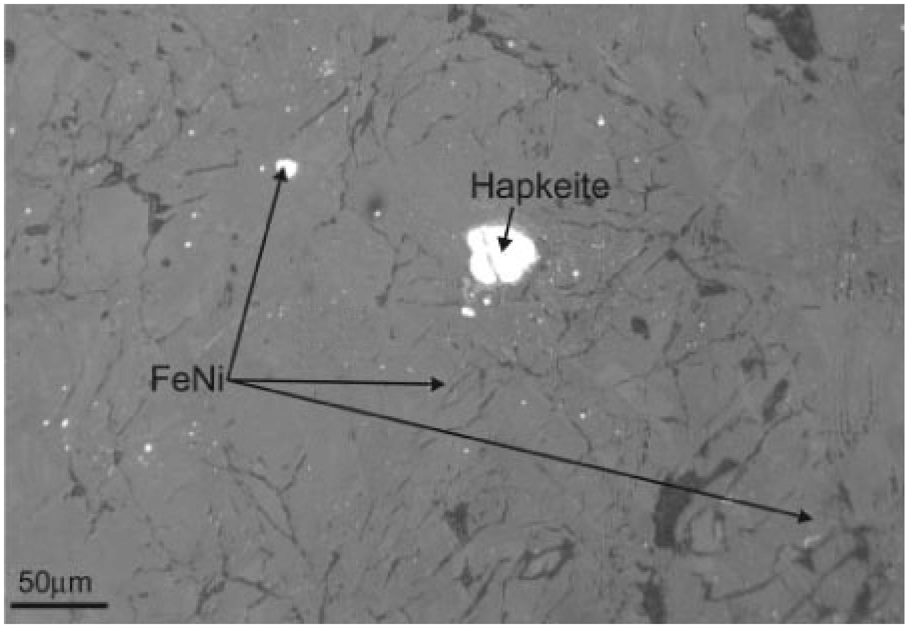
Vapor-deposited Fe metal particles (Fe^0) in a SiO_2-rich glassy rim of anorthosite grain from a mature lunar soil. Virtually all grains of a mature mare soil (long exposed to space weathering) have such rims.

The Newest Evidence of Vapor-deposited Iron

Metallic iron particles not associated with grain coatings have now been identified within a lunar meteorite. The host rock of the newly discovered mineral is lunar meteorite, Dhofar 280 (pictured below), collected in 2001 in the Dhofar region of Oman. It is classified as an anorthositic fragmental breccia.



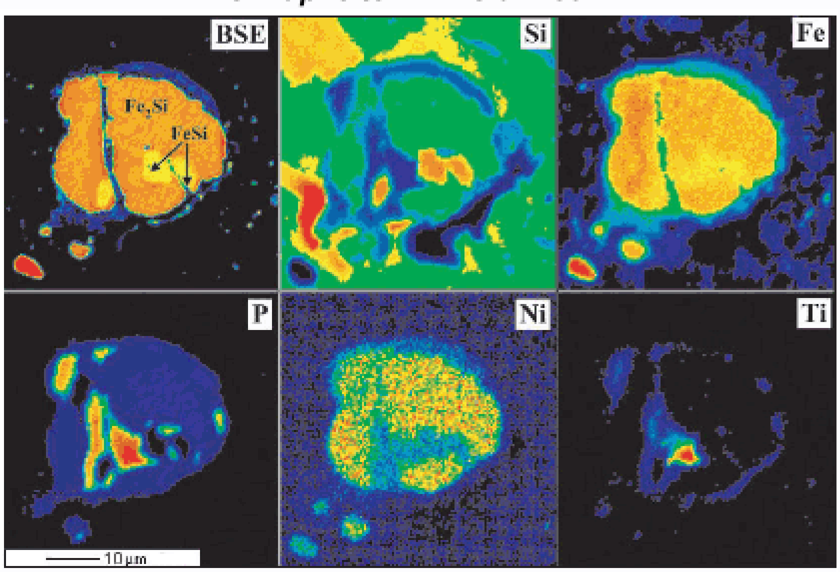
One of the breccia clasts in the meteorite contains opaque minerals 2-30 microns in size that have a slight tarnish appearance. Upon closer inspection with the electron microprobe, Mahesh Anand and Larry Taylor discovered that the grains are actually compounds of iron silicides. The largest such grain (~35 microns) turned out to be Fe_2Si, and its discovery in Dhofar 280 is the first documentation of its natural occurrence. Similar chemical structures have been created synthetically in the lab and other related minerals have been known to form on Earth under unique conditions when lightening strikes sandy soil forming glassy fulgurites. Naming the new Fe_2Si mineral hapkeite seemed fitting to Larry Taylor and his colleagues as they consider it to be a direct product of impact-induced vapor-phase deposition in the lunar regolith. Hapkeite is the third iron silicide identified in this lunar meteorite. The other two minerals remain to be formerly named, FeSi and $FeSi_2$. Anand and colleagues consider SiO_2 in the vapor phase from energetic impact-induced melts to be an important source of SiO^{2+} and Si^0, which would combine in various proportions in the vapor with Fe^0 to condense out as the observed Fe-Si metal grains. Although hapkeite has not yet been identified in Apollo regolith samples, the research team concluded that Fe-Si phases are probably more common in the lunar regolith and may be more closely related in origin to nanophase iron than previously thought.



(From Anand *et al.*, *PNAS*, v. 101, p.6848.)

Reflected-light image of the breccia clast in Dhofar 280 showing hapkeite and some smaller FeNi metal grains.

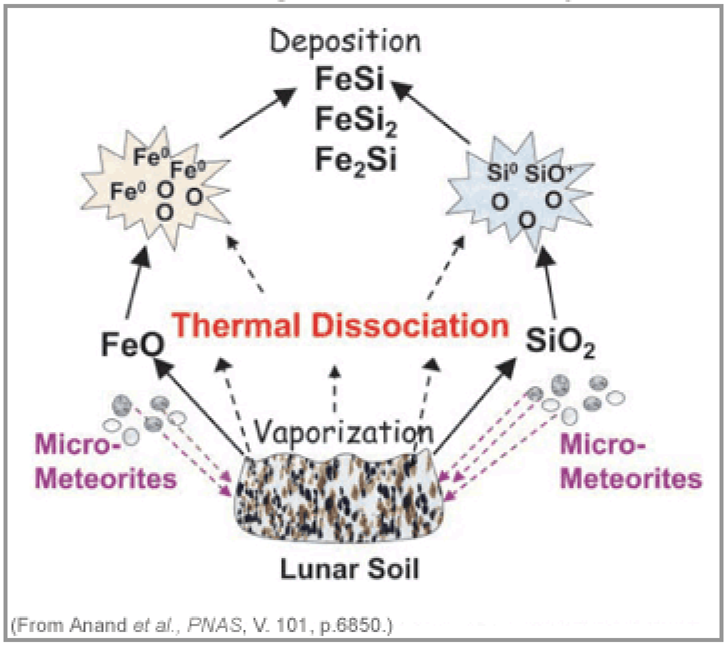
Backscatter electron (BSE) and x-ray elemental maps of hapkeite in Dhofar 280



(From Anand *et al.*, *PNAS*, v. 101, p.6848.)

Backscatter electron and x-ray elemental maps of hapkeite. Analyses show that 95 wt% of hapkeite is composed of Fe and Si with spots of Ti- and P-rich areas.

Cartoon showing formation of Fe-Si phases

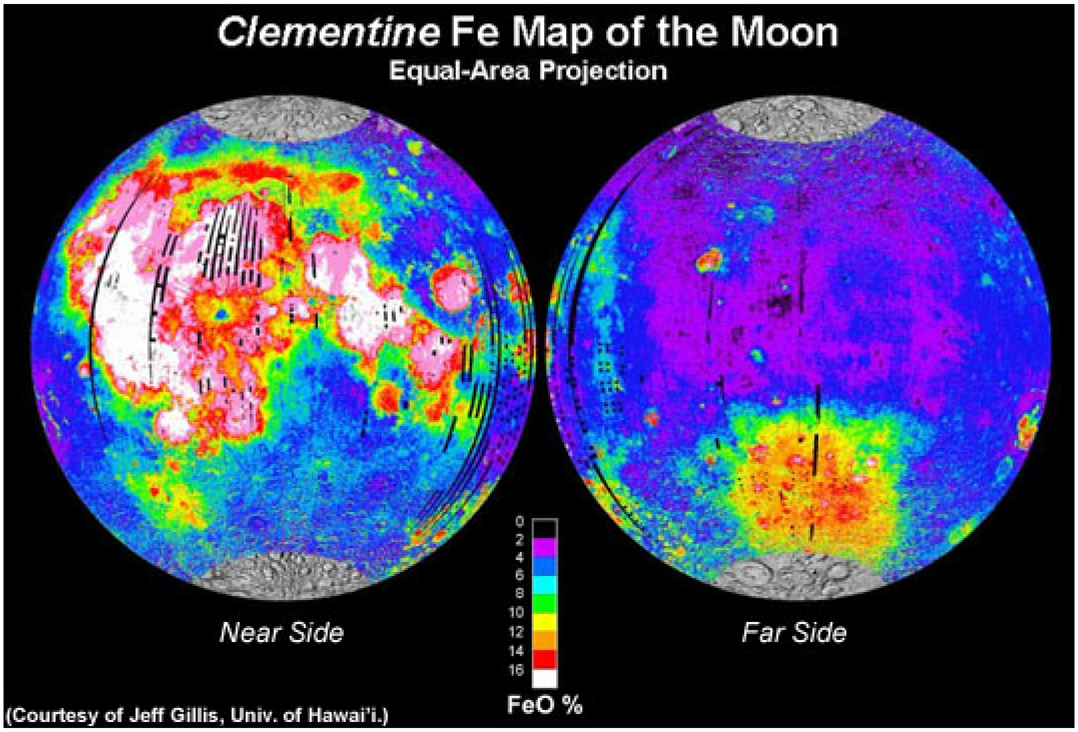


This cartoon shows the researchers' interpretation of how the iron silicides may form on the Moon. After vaporization by micrometeorite impact, Fe and Si recombine from the vapor phase to form various Fe-Si compounds such as those found in Dhofar 280.

Implications for Remote Sensing

As the **Lunar Sourcebook** (p.286) says, "The regolith is the source of virtually all our information about the Moon." Covering practically the entire surface to a depth of about 3 to 10 meters the regolith is the source of our Apollo samples and dominates what our remote sensing instruments analyze. Since Hapke's predictions, cosmochemical analyses of samples have helped to explain how the formation and accumulation of nanophase iron and Fe-Si phases have changed the physical, optical, chemical, and mineralogical properties of the lunar regolith.

Much of what we know today about the global properties of the Moon stems from the early work by scientists like Hapke, Tom McCord (Emeritis Professor at University of Hawaii), and their colleagues on the effects of vapor-phase depositional processes and the effects on the chemical and optical properties of the lunar regolith. Building on this knowledge of space weathering, researchers are developing new mineral mapping techniques in visible and near infrared wavelengths. For example, Paul Lucey (Univeristy of Hawaii) and colleagues have used Clementine multispectral data to determine the concentrations of FeO and TiO_2 on the lunar surface. [See **PSRD** articles Moonbeams and Elements and The Surprising Lunar Maria.]



Map of the FeO content on the lunar surface determined from the intensity of light reflected in two wavelengths. The FeO technique was invented by Paul Lucey and is based on our current understanding of space weathering.

Experts in lunar sample analysis are collaborating with experts in remote sensing to address outstanding questions in lunar science. One such group, for example, the Lunar Soil Characterization Consortium, is working to better understand the effects of space weathering on the surfaces of airless planetary bodies. They are characterizing the mineralogy and chemistry of the finest-sized fractions of the lunar regolith in order to better understand remotely sensed reflectance spectra of the Moon. (See data.)

The discovery of hapkeite in a lunar meteorite has helped improve our understanding of space weathering on the Moon and how space weathering plays a major role in affecting remote sensing studies of airless planetary bodies.

Additional Resources

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