

### New Lunar Mineral HAPKEITE<sup>\*</sup>: Product of Impact-Induced Vapor-Phase Deposition in the Regolith?

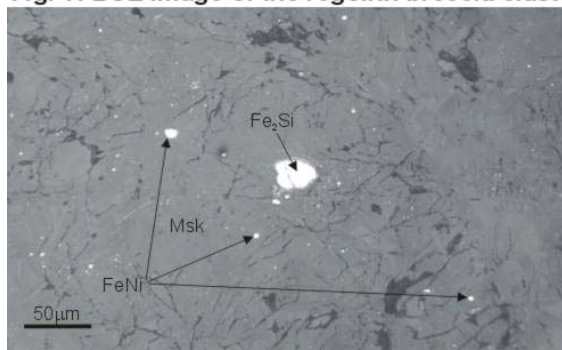
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**Introduction:** Dhofar 280 (Dh-280) is a lunar fragmental breccia meteorite found in the Dhofar region of Oman, in April, 2001 [1,2]. A regolith-breccia clast in this meteorite contains some small (e.g. 10-20  $\mu\text{m}$ ) opaque minerals that optically appear to be FeNi metal with a slight tarnish. Closer inspection with electron microprobe (EMP) revealed these grains to be consisting of *three distinct new lunar mineral phases* -- *FeSi*, *Fe<sub>2</sub>Si*, *FeSi<sub>2</sub>* [2]. We report here the results of *in-situ* single-crystal study of one of the phases, Fe<sub>2</sub>Si. We have named this mineral – HAPKEITE – after Prof. Bruce Hapke (U Pittsburgh), who was far-sighted in his predictions of the effects of space weathering on the formation of lunar soil and its effects upon reflectance spectra [3].

**Meteorite Host:** Dhofar-280 is a fragmental

**Fig. 1: BSE image of the regolith breccia clast**

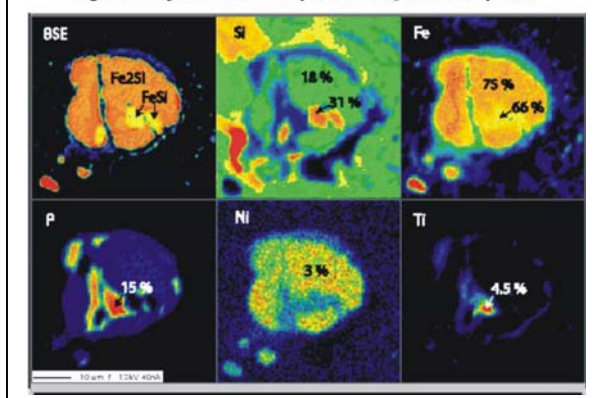


highland breccia with well-preserved primary igneous clasts and negligible terrestrial alteration. The An content of plagioclase feldspars from several clasts show a restricted range of An 94-98, typical of highland breccias. As reported in [2], the majority of the feldspar and mafic minerals plot either in the FAN region or in the gap between the FAN and HMS groups, thus establishing the highlands origin for this meteorite.

**New Mineral Phase:** Grains of three new Fe-Si phases from 2 to 30  $\mu\text{m}$  in size were discovered in a regolith-breccia clast in Dh-280 [2]. This clast also contains numerous small (0.5-10  $\mu\text{m}$ ) FeNi metal grains, similar to an agglutinitic-glass-rich soil (Fig. 1). X-ray maps of the Fe<sub>2</sub>Si grain (Fig. 2) revealed hotspots of Ti- and P-rich areas in this grain (4.6 and 15 wt%, resp.). In general, more than 95 wt% of this mineral is composed of Fe and Si with only minor amounts of Ni, P, and Cr [2].

We have used the synchrotron energy dispersive single-crystal X-ray diffraction to determine the crystal structure of one of the largest Fe-Si phase (Fe<sub>2</sub>Si; Table 1). Cell parameters obtained by this technique are listed

**Fig. 2: x-ray elemental map of the Fe<sub>2</sub>Si & FeSi phase**



in Table 2, matching well with those of synthetic Fe<sub>2</sub>Si phase [4] and confirm the first natural occurrence of this mineral. The single-crystal study on the surrounding host mineral yielded data that match with plagioclase, consistent with results from petrography and EMP that also indicated maskeleynite as the host mineral. Previously, the only other Fe-Si minerals reported are suessite, Fe<sub>3</sub>Si, as described from an ureilite [5] and perryite, (Ni,Fe)<sub>5</sub>(Si,P)<sub>2</sub>, in enstatite achondrites [6]. Such metal grains are also rich in Si.

**Mode of origin:** The presence of these Fe-Si minerals in Dh-280 indicates extreme reducing conditions, whether on the Moon or on an asteroid. Inasmuch as they do occur in a fragmental lunar breccia, an extra-lunar origin is possible. If from a meteorite, these phases may have an origin similar to that postulated by [5,6]. It is important to note, however, that the Fe-Si phases in Dh-280 only occur in the lunar regolith-breccia clast that has not undergone extensive high-temperature metamorphism, as witnessed by the abundant minute Fe-metal grains (<1-2  $\mu\text{m}$ ).

It has been an axiom for years that solar-wind hydrogen in lunar soils

**Table 1: Fe<sub>2</sub>Si composition**

wt%	Avg.	SD
Fe	75.3	0.16
Si	18.4	0.54
Co	0.12	0.05
Ni	3.14	0.12
P	1.85	0.46
Cr	0.37	0.05
<b>Total</b>	<b>99.2</b>	
<b>At %</b>		
Fe	63.4	0.06
Si	30.8	0.82
Co	0.09	0.04
Ni	2.51	0.10
P	2.82	0.71
Cr	0.33	0.05
<b>Total</b>	<b>99.9</b>	

provides the extreme reducing conditions for the formation of the Fe metal in agglutinitic glass [7]. However, TEM studies of lunar soils have failed to detect the presence of even minute quantities of water, to be expected as a byproduct of oxide reduction [8]. In fact, the entire hydrogen-reduction axiom has recently been seriously questioned [7]. Thus, this mode of origin is not considered viable in the present case.

Alternatively, our preferred scenario for the indigenous lunar formation of these phases involves the

**Table 2: Single crystal data**

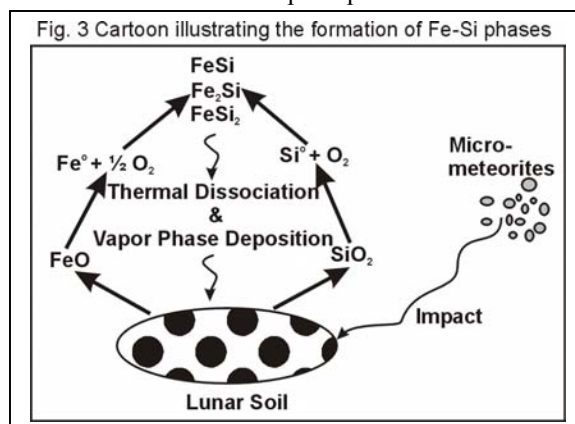
<b>Method:</b> Synchrotron Energy - Dispersive Single Crystal X-Ray Diffraction	
<b>Crystal System:</b> Cubic	
<b>Space Group:</b> Pm3m (221)	
<b>Cell Parameters:</b>	
a ...2.831...(4)Å	$\alpha$ ...90..
b ...2.831...(4)Å	$\beta$ ...90..
c ...2.831...(4)Å	$\gamma$ ...90..
V ...22.69...(64)Å <sup>3</sup>	

melting and vaporization of lunar soil by micrometeorite impact. As well demonstrated by Keller and McKay [9], the surfaces of many lunar-soil particles consist of thin (0.1-0.5  $\mu\text{m}$ ) patinas and rims of silica-rich glass containing abundant nanophase-size Fe<sup>0</sup> metal. Most of this nanophase Fe<sup>0</sup> and silica glass is from the vaporization of FeO and SiO<sub>2</sub> from impact-melted soil. The FeO in the vapor further dissociates to Fe<sup>0</sup> and O, and the Fe<sup>0</sup> is condensed onto the soil particles along with the silica glass. Little consideration of the role of SiO<sub>2</sub> in the vapor-phase has been made. We suggest that with extreme heating, SiO<sub>2</sub> in the vapor dissociates further to SiO<sup>2+</sup> and Si<sup>0</sup>. It is thermodynamically feasible that the Fe<sup>0</sup> in the vapor combines with various proportions of Si<sup>0</sup>, also in the vapor, and condenses as small Fe-Si grains. A cartoon illustrating this scenario is shown in Fig. 3. If these Fe-Si phases are the result of impact-produced vaporization of lunar soil components, then it is likely that many of the small, micron-sized Fe<sup>0</sup> metal grains occurring in lunar soil may well contain Si<sup>0</sup> and Fe-Si phases.

**Naming the new mineral:** We have named this mineral HAPKEITE\*, after Prof. Bruce Hapke, who has just retired from University of Pittsburgh, at age 70 (born 1932). He agrees to this mineral name in his honor. Dr. Hapke was the first (1973) person [e.g., 3] to predict vapor-deposition of elemental Fe on the surfaces of lunar soil grains. It took thirty years [10] before this prediction was confirmed. It has been the discovery of these nanophase Fe<sup>0</sup> particles on the rims on most particles of mature lunar soil that has

permitted the explanation of the spectral reflectance properties of surfaces on airless bodies, such as the Moon, a truly significant discovery.

**Discussion:** Single-crystal data of the new lunar mineral (Fe<sub>2</sub>Si) matches well with the XRD data on the synthetic Fe<sub>2</sub>Si phase, confirming the first natural occurrence of Fe<sub>2</sub>Si in a lunar rock. Such reduced phases have previously been described from fulgurites [11, 12], where metallic phases were found in association with abundant carbon compounds from charred plant detritus. Other reduction mechanisms, such as degassing of oxygen or formation of nitrogen oxide gases, have also been considered. In the present case, reducing conditions could have been brought about by the presence of an extreme reductant OR the thermal dissociation of vapor species into elemental



components, such as we have put forth. These observations suggest that transient ultra-high temperature processes can produce extreme reducing conditions and on the Moon, where extremely energetic micrometeorite impacts have been prevalent. Additionally, the scavenging of dissociated oxygen from the vapor phase was probably aided by the lack of lunar atmosphere and the low escape velocity, both of which acted to give oxygen a low sticking coefficient. This may have facilitated oxygen scavenging from the vapor phase and have helped in the formation of the Fe-Si compounds.

**References:** [1] Nazarov (2001) *Met Bull*, No. 85, A295; [2] Anand et al. (2002) *LPSC XXXIII Abstract# 1653*; [3] Hapke et al. (1973) *Moon* 13; [4] *JADE 5 (SPI)*, Material Data Inc.; [5] Keil et al. (1982) *Amer. Mineral.* 67; [6] Wasson & Wai (1970) *GCA* 34; [7] Taylor (2002) *New Views II*, Abstract #3092; [8] Taylor et al. (1995), *LPSC XVI*, 1399-1400; [9] Keller & McKay (1997) *GCA*, 2331-2340. [10] Keller & McKay (1993) *Science*, 261, 1305-1307; [11] Essene & Fisher (1986) *Science*, 234, 189-193; [12] Wasserman et al. (2002), *LPSC XXXIII*, Abstract #1308.

\* Awaiting approval from Commission on New Minerals and Mineral Names of the IMA.