

METEORITIC MATERIAL FROM PERMANENTLY SHADOWED APOLLO 17 SOIL. K.D. Burgess¹, B.A. Cymes² and R.M. Stroud^{1†}, ¹U.S. Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC 20375 USA (kate.burgess@nrl.navy.mil); ²NRC Postdoctoral Research Associate, U.S. Naval Research Laboratory, Washington DC 20375; [†]Present Address: Arizona State University, Tempe, AZ 85287.

Introduction: The Moon has undergone extensive bombardment throughout its history, as evidenced by craters ranging from massive impact basins to microcraters on individual soil grains. However, only a limited number of samples containing fragments of exogenous material have been identified in the Apollo and Luna collections [1,2]. Few of the impactor fragments are likely to survive collision in their original form, but debris incorporated in the regolith can maintain clear chemical differences from normal lunar material [2].

The serendipitous identification of a soil particle with clear non-lunar chemistry adds to the growing list of meteoritic material located on the Moon. The exotic nature of the phases present in the particle compared to lunar material could aid in linking it to a specific meteoritic source. Soil 76241 is part of a sample collected from under the overhang of a boulder where it was permanently shadowed, which provides additional constraints on the timing of impact that was the source of this particle.

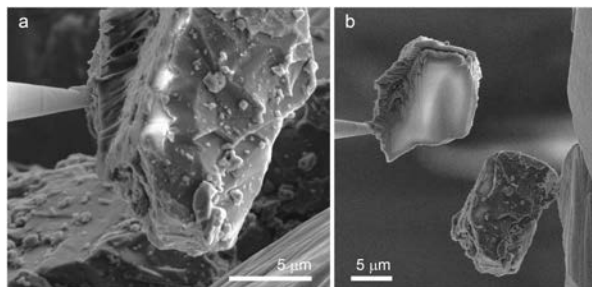


Figure 1. Secondary electron SEM images of particle from soil 76241. The particle was split into multiple sections.

Methods: Particles from soil 76241 were mounted on carbon tape and carbon-coated for imaging in the SEM. FIB samples were prepared with an FEI Helios G3 equipped with an Oxford 150 mm² SDD energy dispersive X-ray spectrometer (EDS). After imaging, protective straps of C were deposited on regions of interest. A section suitable for STEM analysis was extracted using standard techniques and mounted on a Cu half-grid (Fig. 1). The particle of interest was ~15 µm × 15 µm × 10 µm and was divided into three sections, each attached to the grid. Only one section has been thinned to <100 nm; two others remain thicker than 1 µm. STEM analysis was performed with

the Nion UltraSTEM200-X at NRL. The microscope is equipped with a Gatan Enfium ER spectrometer for EELS and a windowless, 0.7 sr Bruker SDD-EDS detector. Data were collected at 200 kV.

Results and Discussion: The bulk grain is a silicate glass with Al, Ca, Mg, K, and Na but no Fe or Ti, which is inconsistent with the composition of common lunar phases. The surface of the grain in SEM images was coated with tiny adhered grains, as seen on most lunar soil particles. However, the surface coatings in the extracted FIB section are complex and very different from classic space weathering features in both form and composition. Of particular note are the Fe-Ni-P and (Fe-)Ca-S materials. These are present generally in rounded, layered deposits several hundred nanometers across and 150-300 nm thick (Fig. 2 & 3).

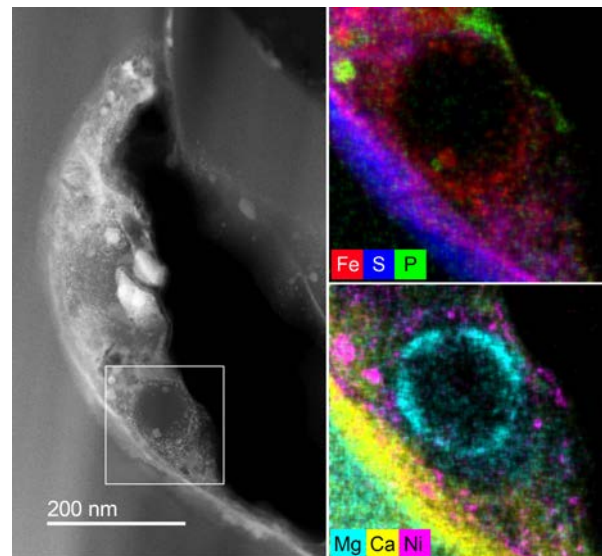


Figure 2. EDS map showing complex surface structure with S- and P-bearing phases. The interior of the Mg-rich ring is silica.

Within these unique features, Ca-sulfide is in contact with the silicate, although the thickness of this “rim” varies significantly between deposits. Inside the rim are complex nanoscale inclusions including Fe-Ni-phosphide, Fe-sulfide, Fe metal, chromite, and amorphous silicate. The small nature of the inclusions makes precise determination of chemistry challenging. In the phosphides, (Fe+Ni):P ranges from 2 to 4, and Fe:Ni ranges from 7 to 15, but small sulfides and metal

inclusions are generally associated spatially with the phosphides and could contribute to this range. The inclusions range from euhedral to subhedral to spherical in shape. Fig. 2 shows a spherical silicate inclusion within the deposit that has a rim rich in Mg. The interior of the inclusion is almost pure silica, while Fe-rich nanoparticles are also present in the rim. The EDS maps in Fig. 3 clearly show the lack of O and Si in the Ca-sulfide and phosphide inclusions. The Ca-sulfide rim in Fig. 3 has Ca/S~1, with ~5 at% F and ~7 at% C.

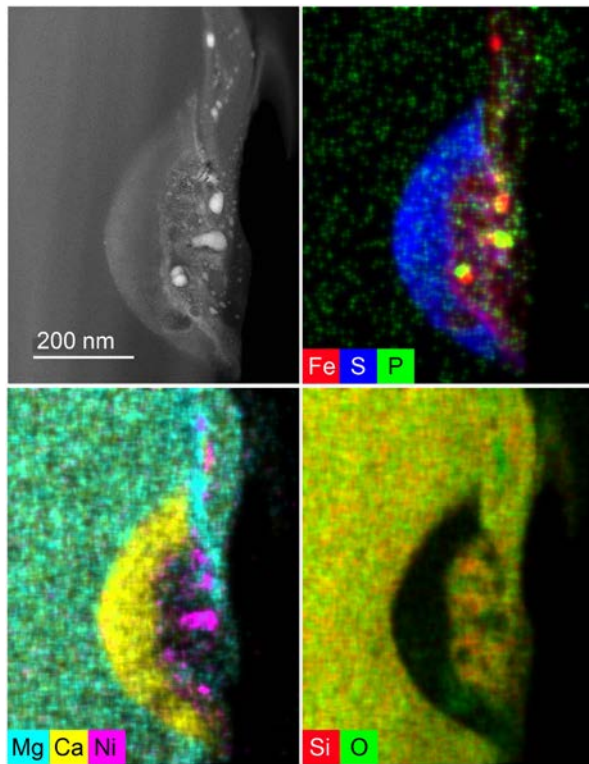


Figure 3. (a) HAADF image of surface lunar particle. (b-d) EDS maps showing complex chemistry of exogenous material, including Ca-sulfide and Fe-Ni-phosphide as well as variations of Mg within the silicate.

The sulfide and phosphide material were observed along only one side of the particle, but their shapes indicate clear interaction with the main silicate particle, rather than just surface deposits. Additionally, although all observed along the exposed surface of the grain, they do not display any “classic” features of space weathering, such as layers with uniform nanophase iron inclusions. Whether these are deposits that formed with the CaS rim only on one side or represent spherules that are now fragmented is unclear from the current data. Other exposed surfaces of the

larger grain show only uniform Ca-Mg-Na-K-Al-silicate with no evidence of space weathering.

Given the unique material present in this grain, the chemistry could provide direct links to its source. Oldhamite (CaS) is found in a limited range of meteorites, specifically enstatite chondrites and aubrites [3], which may make it possible to constrain the source material for this exotic particle. Phosphides such as schreibersite ((Fe,Ni)₃P) are also not very common within meteorites, and could also be consistent with an enstatite chondrite or aubrite origin. Interestingly, one of the exogenous samples identified in Apollo samples is the Hadley Rille enstatite chondrite [4].

However, the rounded shape of these deposits and their presence only along one side of this particle could indicate they are not the original phases in the source material. Melting and vaporization on the lunar surface due to impacts is known to lead to reduction of the deposited material, as in the Fe-Si phases noted in lunar meteorite Dhofar 280 [5]. Further thermodynamic work is needed to determine if the phases in this particle could form during vaporization of phosphate-bearing material.

Conclusions: The exogenous material in this particle is potentially from a reduced meteoritic source such as enstatite chondrite, but impact processes such as vaporization could also lead to the presence of otherwise unexpected phases at the nanoscale. Identifying the link the specific source of the material on the lunar surface is important for understanding lunar surface evolution. Given the small size of the original particle, such source identification is challenging, but potentially valuable. The emplacement time of the boulder shading this soil, which could be determined from thermoluminescence of the frozen soil 76240, will provide constraints on the timing of the impact. The limited amount of material here, although clearly distinct from “normal” lunar soil, means that further discovery of such material will continue to be serendipitous and any systemic search would be highly labor intensive, as noted by Joy et al. [2].

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References: [1] Demidova, S.I., et al. (2022) *Nat Astron*, 6, 560. [2] Joy, K.H., et al. (2016) *Earth, Moon, and Planets*, 118, 133. [3] Rubin, A.E., and Ma, C. (2017) *Geochemistry*, 77, 325. [4] Rubin, A.E. (1997) *Meteor Planet Sci*, 32, 135. [5] Anand, M., et al. (2004) *Proc Nat Acad Sci*, 101, 6847.