FORMATION OF FE WHISKERS THROUGH SIMULATED MICROMETEOROID BOMBARDMENT.

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Introduction: Space weathering, driven by solar wind irradiation and micrometeoroid bombardment, alters the morphological, microstructural, chemical, and spectral characteristics of grains on the surfaces of airless bodies [1,2]. Our model for space weathering is built in the framework of silicate minerals, which comprise the majority of our returned sample collection from the Moon. Space weathering characteristics identified in lunar silicates include amorphous rims, chemically heterogeneous melt and vapor deposits, vesiculated textures, and nanophase Fe (npFe) particles, e.g., [3]. However, remote sensing observations of asteroids (e.g., Eros) [4], which can be more mineralogically complex than the Moon, and analyses of returned samples from diverse parent bodies (e.g., Itokawa, Ryugu) [5,6] have revealed that sulfide minerals play a critical role in the evolution of asteroidal surfaces. For example, remote X-ray fluorescence observations of Eros revealed surface S-depletion, and the analysis of samples returned by the JAXA Hayabusa and Hayabusa2 missions showed npFeS and npFeNiS particles in grain rims, suggesting that S plays an active role in the development of space weathering characteristics on asteroids. Analysis of these returned samples has also revealed the presence of morphologically unique S-depleted Fe-whiskers on sulfide grain surfaces, e.g., [7,8]. Several formation mechnisms have been proposed for these microstructures, including as a decomposition product from sustained solar wind H^+ irradiation [7,8]. To understand the origin of space weathering characteristics unique to sulfide minerals, here we report results of in situ heating of pentlandite and pyrrhotite grains to simulate micrometeoroid bombardment inside the transmission electron microscope (TEM).

Methods: We suspended grains of pentlandite and pyrrhotite in isopropanol and dropcast samples onto microelectromechanical systems (MEMS) chips with supporting SiN films (Norcada) for in situ heating using the Hitachi Blaze heating holder under vacuum in the 200 keV aberration-corrected Hitachi HF5000 scanning TEM (STEM) at the University of Arizona. The HF5000 is equipped with bright-field (BF), dark-field (DF), and secondary electron (SE) detectors as well as dual Oxford 100 mm^2 windowless silicon-drift energy dispersive X-ray spectroscopy (EDX) detectors. We subjected sulfide grains to two distinct thermal regimes: 1) fast (<0.5 s) repeated thermal pulses from room temperature to 1100 °C and back to simulate the short-duration high-temperature effects of micrometeoroid impacts and 2) slow, step-heating with a ramp rate of 100 °C/s, holding the sample for two minutes each at 200 °C, 550 °C, 610 °C, 750 °C, 950 °C, and 988 °C to investigate the behavior of sulfides at several known, relevant exsolution and eutectic temperatures [9]. We imaged the samples before and after heating, collected EDX maps to understand changes in chemistry resulting from heating, and recorded videos of the thermal events.

Results and Discussion: Sulfide samples that experienced a single rapid thermal pulse to 1100 °C formed Fe-Ni-rich and S-depleted pillars/whiskers with near-identical morphology (e.g., striated cones up to 1 μm in length and 500 nm in width) to those observed in space weathered Apollo, Itokawa, and Ryugu samples [7,8]. Subjecting whisker-bearing grains to a subsequent thermal pulse up to 1100 °C resulted in the complete destruction of all identified pillars. The implications for these results are that micrometeoroid bombardment alone may enable the formation of these morphologies on sulfide grains exposed on airless surfaces, and that these textures would not be preserved in grains experiencing multiple impacts/high-temperature events. Our step-heating regime provides insight into the mobility of sulfur during thermal events. Heating to 610 °C (below which pentlandite/pyrrhotite exsolves) resulted in the complete loss of sulfur from some grains while others formed core-shell structures with Fe-S-rich rims and S-depleted, Fe-Ni-rich cores. This microstructure was maintained until EDX maps showed all sulfur was lost from the remaining grains at the Fe–FeS eutectic at 988 °C leaving an Fe-rich rim and Fe-Ni-rich core. These results may provide a pathway for the formation of S-depleted rims via micrometeorid bombardment in addition to solar wind irradiation, as has been proposed for other returned samples, e.g., [10]. In situ heating experiments of this type may also provide insight into the nature of S mobility on asteroidal parent bodies under a variety of thermal conditions.

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