CAN SPACE WEATHERING SURVIVE LITHIFICATION? RESULTS OF A TEM STUDY OF LUNAR REGOLITH BRECCIA 10068

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Introduction: Space weathering processes are known to be important on the Moon. These processes both create the lunar regolith and alter its optical properties [1,2,3]. Like the Moon, the asteroids have no atmosphere to protect them from the harsh space environment and therefore it is expected that these bodies will also incur the effects of space weathering [1,3]. However, there are many important differences between the environment at the asteroid belt compared to the Moon. These environmental differences will almost certainly affect the weathering processes and the products of those processes. Understanding these weathering processes and their consequences is essential for evaluating spectral data obtained remotely.

The Space Weathering Environment: In the asteroid belt collisions are slower, so micrometeorite bombardment will cause less vaporization than on the Moon. Also, as the distance from the sun increases, the solar wind particle flux decreases, which means less sputtering and implantation should occur. Finally, the smaller size and lower gravity of these bodies means that it is more difficult to retain a regolith.

Despite these factors, there is a growing body of spectral evidence that indicates space weathering influences some asteroids enough to affect their optical properties. Binzel *et al.* [4] have identified near Earth asteroids with spectral properties covering the range from S-type to spectra similar to those of OC (ordinary chondrite) meteorites, suggesting an ongoing process is occurring that can alter the spectra of OC material to look like S-type asteroids. There is also evidence of regolith alteration from Galileo's flybys of Gaspra and Ida showing spectral differences at fresh craters [5]. Evidence from NEAR, an S-type asteroid, indicates that it has an OC-like composition [6]. Recent work, which illuminated the effects of $npFe^0$ on the optical properties of lunar soil grains, has demonstrated that the spectral properties of S-type asteroids directly mimic the effects predicted for small amounts of $npFe^0$ on grains of ordinary chondrite regolith [1,2,3]. These results predict that formation of $npFe^0$-rich weathered rims that are commonly found surrounding individual lunar soil grains will occur on asteroids as well and would provide the necessary optical effects to link S-asteroids with OC parent bodies.

No direct samples of asteroid regolith have yet been obtained. However, there is a class of meteorites, the gas-rich breccias (sometimes called regolith breccias), which are thought to be examples of lithified asteroid regolith.

Optical Properties of Regolith Breccias: Regolith breccias often exhibit a distinctive light/dark structure. Within the dark regions are found high levels of solar-wind implanted gasses, and thus it is assumed that the dark material represents regolith which was directly exposed at the surface [10]. The reflectance spectra of the dark material is much lower in albedo than the corresponding light material and also appears to exhibit band attenuation and possibly even a "modest red slope" [11]. The darkening is a result of *micron*-sized Fe and troilite distributed throughout the dark material [11]. Unlike the *nano*-scale Fe found in weathered rims, this larger Fe severely shortens the optical path length and results in darkening that overshadows all other space weathering effects. Reflectance spectra, therefore, is not the best way to look for space weathering products in these meteorites. They must be analyzed directly.

The First Step: Preliminary studies have been undertaken to determine whether or not the delicate weathered rims produced by cumulative space weathering processes and observed on lunar grains can survive lithification. Basu *et al*. de-lithified a lunar regolith breccia (10068) using a freeze-thaw technique [7]. Vis/NIR spectra were taken of the de-lithified breccia and compared to the spectra of mature lunar soil 10084. The spectra display the same characteristic "red" continuum of weathered soils. This was interpreted as indirect evidence that the weathering products, particularly the rims containing $npFe^0$, were not destroyed during lithification.

Methods: To further test whether rims can be maintained through lithification, we have studied the de-lithified breccia under transmission electron microscope (TEM). Small aliquots of 10-20 μm soil were placed in a low viscosity epoxy and thin sections ~70-80 nm thick were prepared using an ultramicrotome. The samples were analyzed on a Phillips 420 TEM equipped with a CCD camera and an EDS (energy dispersive spectrometer).

Results: In all, approximately 50 soil grains from the de-lithified regolith breccia (10068) were observed. Nearly all contained some weathered material. A wide range of weathering products were observed, including vapor/sputter deposited rims (figure 1), radiation damage, glass splashes (figure 2), and agglutinates (figure 3). In fact, as expected for a mature soil, about half of the observed grains were agglutinates. The majority of soil grains contained some $npFe^0$-bearing rim material (figure 1). A few were enclosed by nearly 360˚ of such rim material. Others contained rim material only on one or two sides, or in isolated regions. In some cases these grains may have originally had more extensive rim material but it was lost in the process of lithification and/or de-lithification. It is not surprising that some grains would be broken and some rim material lost in these processes. What is more surprising is how much is still intact. It is clear that these weathered rims are not as delicate as they may appear and are well attached to their host grain.

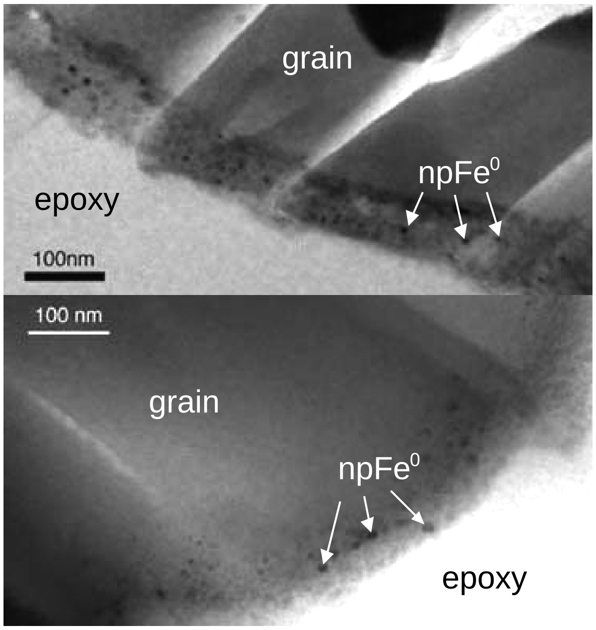

Figure 1. TEM bright field images of soil grains from de-lithified breccia 10068 displaying npFe^0 inclusion-rich rims.

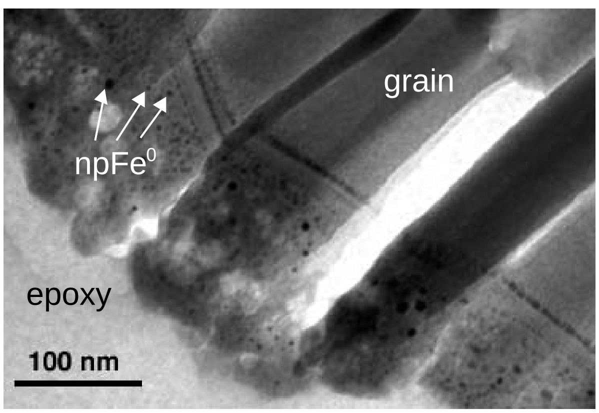

Figure 2. TEM bright field image of another soil grain from the breccia displaying a very complex rim, likely deposited as a glass splash.

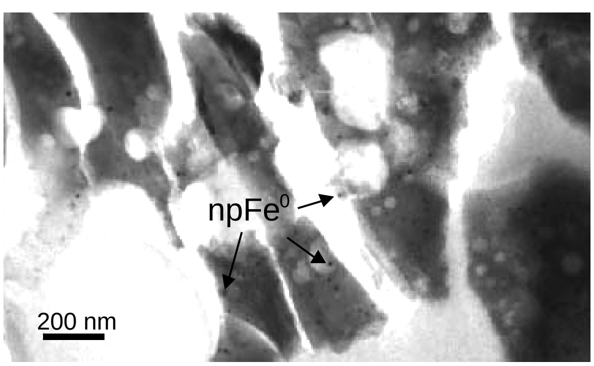

Figure 3. TEM bright field image of agglutinitic glass from the breccia. Note the large vesicules (light) and the abundant npFe^0 (black).

Visual inspection indicates that the size range of npFe^0 in the inclusion-rich rims is similar to the size range found in other typical lunar soil [8]. In fact, the rims seen on the regolith breccia grains are essentially indistinguishable from those found in ordinary lunar soil, particularly the inclusion-rich rims described by Keller and McKay [9].

Implications: These TEM studies confirm that weathered rims and their associated npFe^0 can be preserved intact through the process of lithification. Thus if npFe^0 is created in asteroid regoliths by space weathering processes, we can expect it might be preserved in regolith breccia meteorites.

The Next Step: Detailed TEM studies of meteorite regolith breccias should reveal to us any weathering products, if they exist. For this project, two regolith breccias have been selected, Fayetteville and Kapoeta. These meteorites were selected for several reasons. They are both Class A regolith breccias, which means that they have experienced only low shock pressures (1-5 GPa) and little to none of their matrix material has melted [12]. They have well developed light/dark structure with high levels of trapped noble gasses [13], which implies surface exposure. Fayetteville is also one of only 2 meteorites that has been found to contain “true analogs of agglutinates” [14], further attesting to its “weathered” status.

Finding weathered material (npFe^0 in particular) in these regolith breccias would provide the so-called “smoking gun” that space weathering processes occur on asteroids. More importantly, we will be able to compare and contrast meteoritic weathering products to those found on the Moon, allowing us to gain a deeper understanding of the effects of changing environment on the space weathering process.

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