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Evidence of space weathering in regolith breccias II: Asteroidal regolith breccias

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Abstract–Space weathering products, such as agglutinates and nanophase iron-bearing rims are easily preserved through lithification in lunar regolith breccias, thus such products, if produced, should be preserved in asteroidal regolith breccias as well. A study of representative regolith breccia meteorites, Fayetteville (H4) and Kapoeta (howardite), was undertaken to search for physical evidence of space weathering on asteroids. Amorphous or npFe^0-bearing rims cannot be positively identified in Fayetteville, although possible glass rims were found. Extensive friction melt was discovered in the meteorite that is difficult to differentiate from weathered materials. Several melt products, including spherules and agglutinates, as well as one irradiated rim and one possible npFe^0-bearing rim were identified in Kapoeta. The existence of these products suggests that lunar-like space weathering processes are, or have been, active on asteroids.

INTRODUCTION

Our understanding of space weathering comes almost exclusively from studies of lunar soils. In the lunar literature, the term ‘‘space weathering’’ has been used to describe an array of processes and products from solar wind sputtering to micrometeorite bombardment. One important product that has been described through detailed microanalytical studies (Keller and McKay 1997; Wentworth et al. 1999) are very thin (60–200 nm) patinas (rims) developed on individual lunar soil grains. These rims often contain single-domain metallic iron particles, commonly called nanophase iron (npFe^0) or submicroscopic iron (Keller and McKay 1993, 1997). It is known that space weathering, in particular this npFe^0, has distinct and predictable effects on the optical properties of lunar soils (Pieters et al. 1993; Hapke 2001; Noble et al. 2007). The optical effects have traditionally been described as threefold: npFe^0 causes the reflectance spectra to be darker and redder, and also results in an attenuation of the characteristic absorption bands. These effects combine to create a characteristic ‘‘space weathering continuum’’ (Noble et al. 2007). The exact shape of this continuum will vary depending on the properties of the particular target soil (e.g., the maturity of the soil, the FeO content, etc.) as well as the environmental conditions (e.g., rate and velocity of impacts, distance from Sun, reduced gravity, presence or absence of an atmosphere or magnetic field, etc.) in which it was produced.

On the Moon, these soil properties and environmental factors are well understood and npFe^0 is known to form largely through two mechanisms: melting and vapor deposition from micrometeorite impacts and sputtering from the solar wind (Hapke 1973; Hapke et al. 1975; Keller and McKay 1997; Pieters et al. 2000). In the asteroid belt, the environment is significantly different. Collisions are on average slower (Hörz and Schaal 1981), so micrometeorite bombardment will cause less melting and considerably less vaporization than on the Moon (Hörz and Cintala 1997). Also, as the distance from the Sun increases, the solar wind particle flux decreases, thus sputtering rates are lower. Finally, the impact rate is greater, comminuting fresh material at a faster rate. These arguments suggest that soils on asteroids should accumulate npFe^0 at a significantly lower rate than those on the Moon.

Despite these factors, there is a large body of spectral evidence that clearly indicates space weathering influences some asteroids enough to affect their optical properties. In general, the spectra of asteroids do not match the spectra of our collection of meteorites. Particularly, the spectra of S-type asteroids, the most abundant type, do not correspond well to the spectra of the most abundant type of meteorites, ordinary chondrites (OCs). The asteroid spectra tend to be redder than the meteorites with a steep curvature in the visible wavelengths. Binzel et al. (1996) have identified near-Earth asteroids with spectral properties covering the range from S-type to spectra similar to those of OC 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. With time, the spectra of Ida and Gaspra appear to redden and lose spectral contrast (Chapman 1996). Evidence from NEAR-Shoemaker's X-ray measurements of Eros indicates an OC composition despite an S-type spectrum, again suggesting that space weathering processes have altered the optical properties of the surface (Trombka et al. 2000; Clark et al. 2001). Similarly, the S-type asteroid Itokawa was shown to be of OC composition using data from the Hayabusa spacecraft (Okada et al., 2006; Hiroi et al. 2006).

Our recent work detailing 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 OC regolith (Pieters et al. 2000; Noble et al. 2007). This is in agreement with the modeling of Hapke (2001), who arrives at the same conclusion. We have shown that the precise expression of space weathering-induced changes will vary as a function of npFe^0 content. Adding significant amounts (>0.3 wt%) of npFe^0 to a soil results in an overall reddening and darkening throughout the Vis/NIR region. By contrast, adding only very small amounts (<0.1 wt%) of npFe^0 results in a steep convex curvature in the visible region, while leaving the near infrared spectrum virtually unaffected.

This pattern was first noticed in the finest fraction of weathered lunar soils (Noble et al. 2001). Because npFe^0 is concentrated in rims on grain surfaces, the optical properties of the finest fraction of soils, with their greater surface to volume ratio, are dominated by space weathering effects. Immature and submature highland soils and immature mare soils display this distinct curvature in the visible spectrum, whereas more mature soils with higher npFe^0 contents have spectra that are significantly darker and nearly linear in shape. In Fig. 1 are examples of two submature (defined as those soils with an I_s/FeO maturity index between 30 and 60—see Morris 1978) lunar soils: a highland soil with a highly curved continuum and a mare soil with a much darker and more linear spectrum. Although these two soils share similar exposure ages, the lower npFe^0 content of the highland soil results in a significantly different continuum shape. The typical curvature of many asteroid spectra versus meteorite spectra is exactly what would be expected if a small percentage of asteroid regolith grains were surrounded by npFe^0-bearing rims.

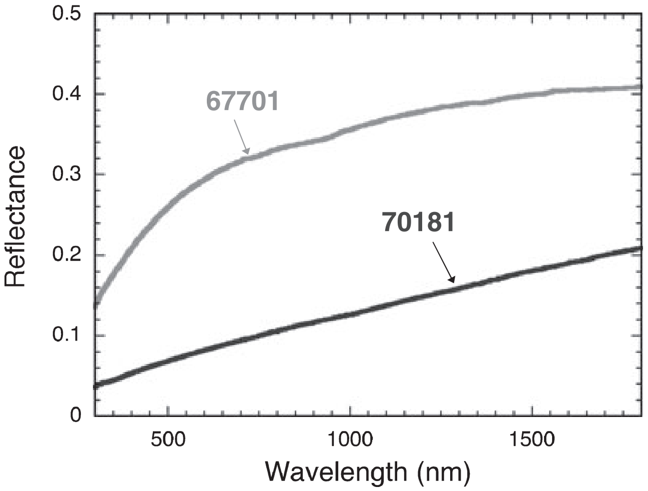

Fig. 1. Reflectance spectra of the <10 μm fraction of two submature lunar soils. The highlands soil, 67701 (I_s/FeO = 39), displays the curvature in the visible region of the spectrum characteristic of small amounts of npFe^0. The mare soil, 70181 (I_s/FeO = 47), has more npFe^0 and thus its continuum is darker and more linear.

In contrast to the lunar case, there are no direct asteroidal regolith samples to investigate for physical evidence of space weathering processes. Thus, we use the next best alternative, regolith breccia meteorites. These meteorites (commonly called gas-rich meteorites) have high solar gas concentrations, which indicate that a significant fraction of the grains that constitute them have been directly exposed to the space environment (i.e., in the regolith on an asteroid body). They are created when regolith is bonded together by shock from a nearby impact.

Our study of *lunar* regolith breccias (Noble et al. 2005) demonstrates that space weathering products, including npFe^0-bearing rims, can be preserved in regolith breccias. All together, four distinct types of rims were identified in the lunar breccias (Fig. 2). NpFe^0-bearing rims and amorphous (radiation damage) rims were common in the breccias, just as they are common in lunar soils (Keller and McKay 1997). Two other rim types were identified which are thought to be related to the breccia-forming process itself and are only rarely seen in lunar soils: glass rims and vesicular rims. Glass

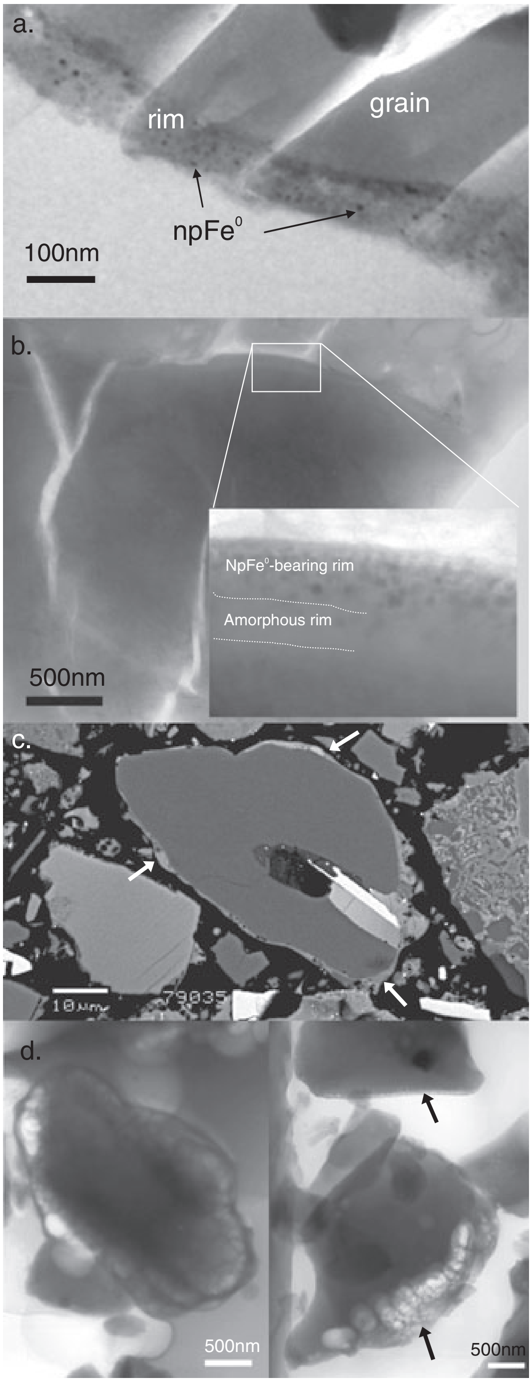

Fig. 2. TEM bright-field images of lunar breccia rims: a) $npFe^0$-bearing rim from breccia 10068. b) Amorphous rim from breccia 15505. c) Glass rim (indicated by arrows) from breccia 79035. d) Vesicular rims (indicated by arrows) also from breccia 79035 (after Noble et al. 2005).

rims were identified in every lunar breccia examined. They are rich in $npFe^0$ and share the same wide range of compositions as agglutinitic glass. Vesicular rims, in contrast, are generally compositionally indistinguishable from their host grain. Rather than being acquired, it appears that vesicular rims are a result of the evolution of implanted gasses from within the host grain. A more complete description of glass and vesicular rims can be found in Noble et al. (2005).

METHODS

Two different regolith breccia meteorites were selected for this study, Fayetteville (H4 OC) and Kapoeta (howardite). Two thin sections of Fayetteville were acquired from the Smithsonian Institution. Samples of Kapoeta were acquired from both the American Museum of Natural History and the Field Museum. Demountable (superglue) polished thin sections of Kapoeta were prepared at the NASA Johnson Space Center. Scanning electron microscope (SEM) analysis was performed on all thin sections on a JEOL 5910LV SEM equipped with an IXRF thin-window energy-dispersive X-ray (EDX) detector. Electron microprobe analysis was performed using a Cameca SX100 microprobe with five wavelength dispersive detectors. Following the SEM analysis, we identified several regions of interest from each of the thin sections. Copper TEM grids were glued to the regions of interest and removed from the thin sections by soaking in acetone. The samples were ion milled to electron transparency using a Gatan Duo-Mill and carbon coated for analysis in the transmission electron microscope (TEM). The TEM analyses were performed on a JEOL 2000FX 200 kV STEM equipped with a Link thin-window EDX detector.

Fayetteville

The Fayetteville OC is a Class A regolith breccia which has experienced only low shock pressures (1–5 GPa) and little to none of its matrix material has melted (Bischoff et al. 1983). It has well-developed light/dark structure with high levels of trapped noble gasses (Black 1972), which implies surface exposure. Fayetteville is also one of only two meteorites that have previously been found to contain "true analogs of agglutinates" (Basu and McKay 1983), further attesting to its "weathered" status.

Like most regolith breccias, Fayetteville is composed of light and dark regions. The dark regions, where the noble gasses are concentrated, contain numerous micrometer-scale Fe-metal and FeS particles, consistent with earlier findings (Britt and Pieters 1994). TEM analysis reveals that within these dark areas are many small regions of melt glass that contain abundant nano-scale Fe-metal and FeS particles. In Fig. 3 are shown several examples of these nano-scale features. The glassy material is largely located along cracks and

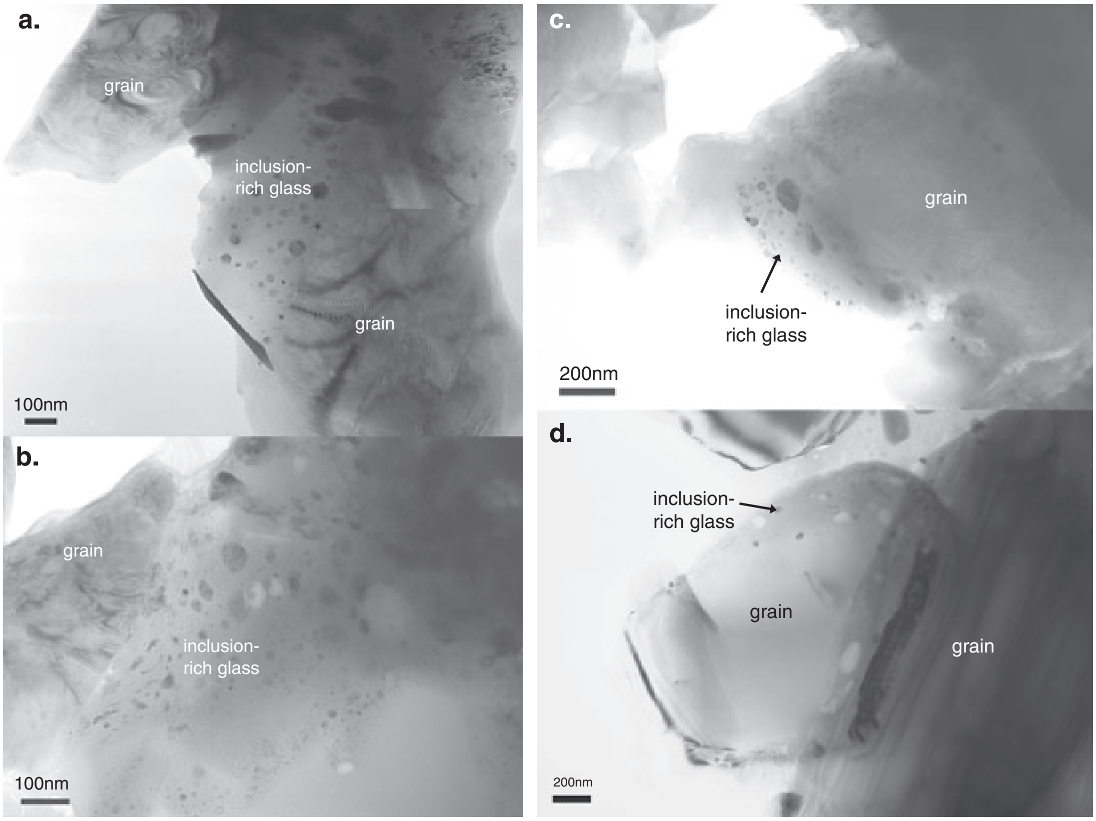

Fig. 3. TEM bright-field images of inclusion-rich glasses in Fayetteville. The glass in images (a) and (b) are clearly filling in cracks between grains. Images (c) and (d) represent more ambiguous cases where the glass may be surrounding individual grains.

between grain boundaries (Figs. 3a and 3b) and therefore is likely to be formed in the breccia as a result of friction melting (van der Bogert et al. 2001), rather than by sputtering and/or micrometeorite impact-induced vaporization/melting in the regolith. Some glass regions, however, are more ambiguous. Figures 3c and 3d are two examples of cases where inclusion-rich glass appears to be surrounding grains. These ''rims'' are rather thick (200 nm in places), and their large inclusions and discontinuous nature are inconsistent with an origin as vapor-/sputter-deposited rims. They could, however, be analogous to the glass rims observed on lunar breccia grains (Noble et al. 2005).

Despite the low shock experienced by this meteorite, the effects of friction melting are pervasive. There is so much inclusion-rich glass throughout the sample that the positive identification of true space weathering products is made nearly impossible.

Kapoeta

Because of their high metal content, OC regolith breccias are vulnerable to micro- and nano-scale dispersion of metal by shock and/or friction. This dispersion of fine-grained metal makes identifying weathering products problematic, if not impossible. To avoid this problem, a howardite was selected. Howardites, part of the howardite, eucrite, and diogenite (HED) meteorite group, come from the surface of a differentiated body, probably 4 Vesta (McCord et al. 1970). Because howardites are basaltic in nature, they do not have the high metal content of OC and they are more directly comparable to the lunar mare regolith breccias previously investigated.

Like Fayetteville, Kapoeta is also a Class A regolith breccia, indicating low shock. It has, in fact, been classified as ''friable'' (Warren 2001) and therefore would be expected to have retained any weathering products acquired before and/or during lithification (Noble et al. 2005). Despite being highly variable, Kapoeta has high noble gas content (e.g., Black 1972). In addition, microcraters have been identified in the meteorite (Brownlee and Rajan 1973), which provides direct evidence of surface exposure. Sedimentary structures such as laminae and accretionary lapilli have also been described (Pedroni 1991). While clearly some of the constituent grains of Kapoeta have been directly exposed at the surface, the majority likely have not. It has been estimated based on cosmic ray exposure that not more than about 20% of grains in most meteorite regolith breccias have been directly exposed at the surface (Macdougall 1981). This is in significant contrast to lunar regolith breccias in which nearly all grains have experienced surface exposure.

Vesta, the probable parent body of Kapoeta, is unusual among the asteroid population in that its Vis/NIR spectrum actually does match reasonably well with meteorites in our collection, the HEDs (i.e., it does not appear to be significantly space weathered). There are two possible explanations for this: Vesta either weathers very slowly, or it has been recently resurfaced. As was previously mentioned, the surface of Vesta is largely basaltic, similar to the lunar mare. We know that lunar basalts weather, thus there is no reason to think that Vesta would be immune to weathering. What we do not know is the *rate* at which such a surface in the asteroid environment will weather. Experimental data suggest that pyroxene weathers more slowly than olivine under the same conditions (Yamada et al. 1999; Hiroi and Sasaki 2001; Sasaki et al. 2003), thus Vesta's basaltic surface may weather at a slower rate than the surface of a more olivine-rich chondritic body. There is also evidence from UV spectral data that suggest that Vesta's western hemisphere is space weathered, but to such a small degree that the weathering effects can only be seen in the UV spectrum and are not apparent in the Vis/NIR spectral range (Hendrix et al. 2003). It takes very little npFe^0 to begin to affect the Vis/NIR spectral properties of a soil (Noble et al. 2007); noticeable changes in the Vis/NIR spectral continuum should occur even if only 1% or 2% of grains have npFe^0-bearing rims. Thus, the current surface must be below this threshold. It is possible that Vesta was more weathered at one time. A large impact crater on Vesta suggests the possibility that Vesta may have been thoroughly resurfaced in the recent past, effectively resetting the weathering clock (Pieters and Binzel 1994).

The lithification age of Kapoeta is difficult to determine. From radiometric dating of individual clasts, we know that the breccia must have formed more recently than its youngest known clast, approximately 3.5 Ga (Bogard 1982), and it must be older than its exposure age of approximately 3 Ma (Caffee and Nishiizumi 2001). By calculating the shielding from the systematics of the distribution of several noble gas isotopes, Caffee and Nishiizumi (2001) inferred that the breccia was buried for approximately 10 Ma before being ejected from its parent body. Therefore, the age of the formation of the breccia can only be constrained to between approximately 3.5 billion and 13 million years ago.

If Kapoeta is at the older end of that range and was assembled during a period when impact rates were higher (Hartmann et al. 2007), particularly rates of larger impactors (Chapman and Davis 1975), that environment would result in shorter gardening times and therefore less time for space weathering products to build up in the regolith. In this case, weathering products in Kapoeta should be extremely rare.

If instead, we assume that Kapoeta is younger and that conditions on Vesta were similar when the breccia was formed to current conditions and therefore approximately 1% of surface grains had npFe^0-bearing rims, and that roughly 20% of the grains in Kapoeta were directly exposed at the surface, then we should expect to find one npFe^0-bearing rim for every approximately 500 grains.

KAPOETA SEM RESULTS

Glass Rims

The most common type of rims found in lunar regolith breccias are glass rims (Noble et al. 2005). An example of a lunar glass rim is shown in Fig. 2c. These rims are rich in npFe^0, but are distinguished from npFe^0-bearing soil rims by their thickness, obvious flow features, and other characteristics, which indicate that they were deposited as a melt and not via vapor or sputter deposition as the soil rims are. Glass rims are not commonly found in lunar soils but only in regolith breccias, and thus are assumed to be part of the breccia-forming process itself. As such, they are not, strictly speaking, space weathering products, but they still provide important clues about the conditions on the surface of an airless body.

In Fig. 4 are several examples of glass rims which were identified in Kapoeta. Rims in the meteorite are less extensive than what was found in the lunar breccias. Not only are there fewer rims but, the rims that we find tend to be less continuous than they were for the lunar case. The abundance of rims in lunar breccias varies from breccia to breccia, in some soils 10–20% of grains are at least partially rimmed; in others, only a handful of rims (<1%) were identified in an entire thin section (Noble et al. 2005). In Kapoeta, dozens of rims were identified in each of the three thin sections studied via SEM.

Other Glass Products

We have identified three agglutinates in our Kapoeta sample (Fig. 5). Agglutinates have been previously identified in at least two other regolith breccia meteorites—in Fayetteville, as mentioned above, and also in Bununu, another howardite (Basu and McKay 1983), but they appear to be generally very rare in asteroidal materials. We also found at least two spherules in Kapoeta. Images of these glass droplets are

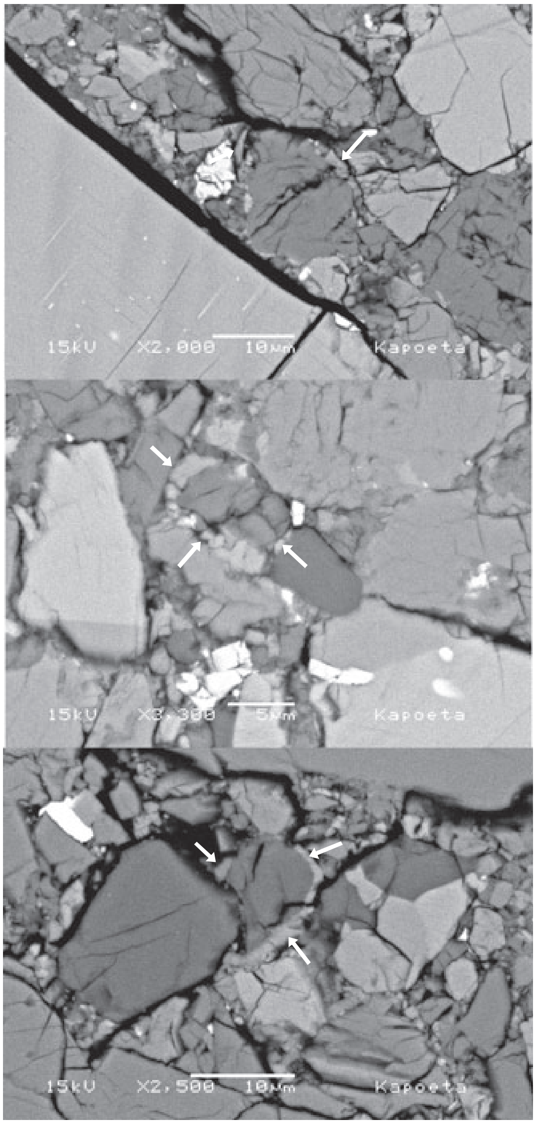

Fig. 4. SEM backscatter images of examples of glass rims (indicated by arrows) in Kapoeta.

shown in Fig. 6. The presence of spherules, agglutinates, and glass rims confirms that melting does occur during impact on asteroids, as has been discussed by others (e.g., Hörz and Schaal 1981).

KAPOETA TEM RESULTS

Remarkably little glass was observed at this scale despite the glass products seen in SEM. Three TEM sections were thoroughly examined, representing approximately 1000 grains. Only one possible $npFe^0$-bearing rim was identified. This rim is shown in Fig. 7. The amorphous rim material surrounds $>50\%$ of the grain and is about 25 nm thick, thinner than a typical lunar rim, but within the range observed on lunar grains. It contains abundant opaque nanoparticles in the approximately 2–5 nm range, consistent with $npFe^0$. Finding only a single rim is consistent with our prediction of one rim per approximately 500 grains. In addition, one amorphous rim (with no $npFe^0$) was also identified (Fig. 8). Such amorphous rims are also common in lunar soils and are a result of solar wind-induced radiation damage (Keller and McKay 1997).

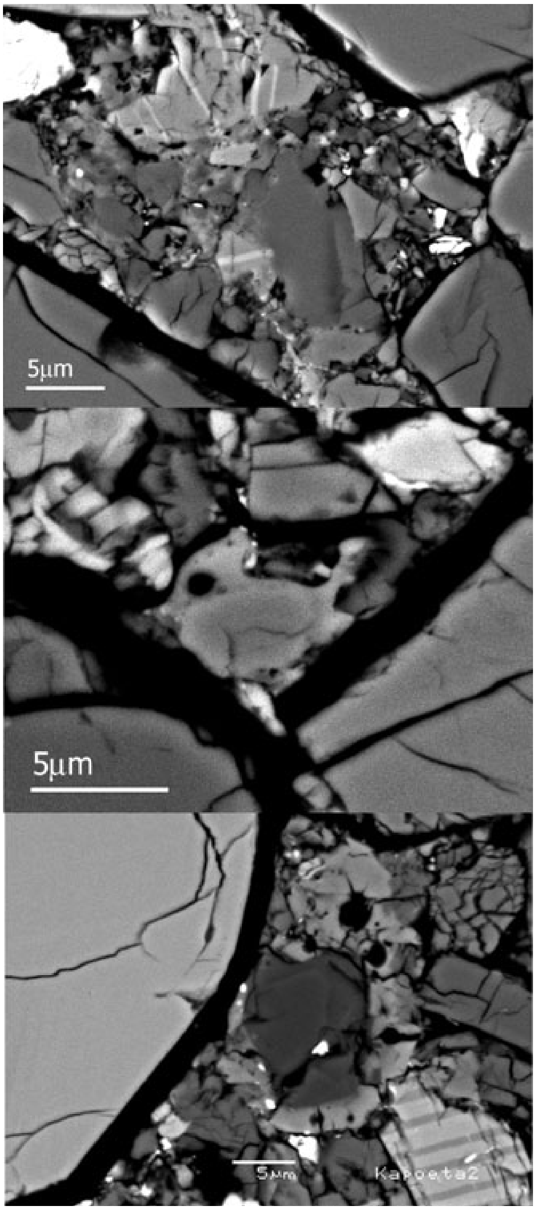

Fig. 5. SEM backscatter images of Kapoeta agglutinates, note the abundant vesicules.

DISCUSSION

A variety of space weathering products have been identified in the howardite Kapoeta that represent direct

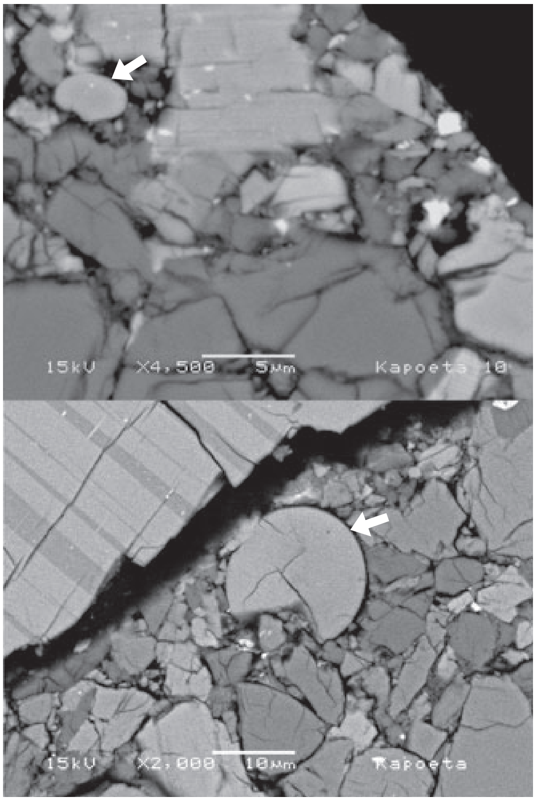

Fig. 6. SEM backscatter images of Kapoeta spherules (identified with white arrows).

evidence of many of the same space weathering processes that we understand from the lunar case. The amorphous rim is the result of solar wind irradiation and agglutinates and spherules are evidence of melt formation due to micrometeorite (and larger) impact. NpFe^0-rich rims can be formed either through vapor deposition or sputtering, although sputtering is more likely here due to the lower impact velocities expected in the Main Belt. While the environmental conditions and target compositions are significantly different on asteroids compared to the Moon, there is no need to invoke exotic processes to account for weathering on asteroids; rather we need to work to understand how those compositional and environmental differences affect the manifestation of different components of space weathering.

Vernazza et al. (2009) suggest that due to the rapid time scales for spectral changes associated with space weathering, solar wind must be the dominant factor in asteroid weathering over micrometeorite bombardment. If that is the case, one would expect to find amorphous and npFe^0-rich rims in asteroidal regolith, but only rarely agglutinates, spherules, or other glass products. Although we found several such melt products and only one npFe^0-rich rim and one amorphous rim in our study, our results are not necessarily contradictory. Because of their size, agglutinates and spherules are easily identified using SEM; rims, on the other hand, can only be seen on a TEM scale. Therefore our results are biased in favor of melt products because they are so much easier to find.

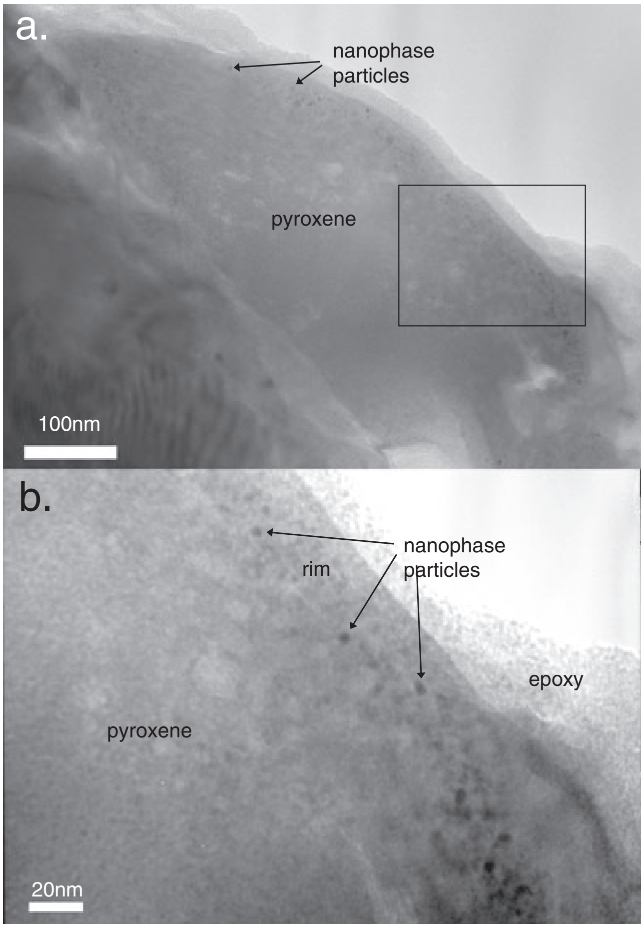

Fig. 7. a) TEM bright-field image of possible npFe^0-bearing rim in Kapoeta. b) Close-up of the region outlined in (a) showing npFe^0 inclusions.

Fig. 8. TEM bright-field image of an irradiated rim (indicated by arrows) in Kapoeta.

CONCLUSIONS

Rare end products of space weathering processes were identified in two meteorite regolith breccias. The H4 OC Fayetteville lacks the typical space-weathered materials observed in lunar samples such as agglutinates, melt spherules, and grain rims. Impact-related friction melts at grain contacts were commonly observed and complicate the search for amorphous rims and agglutinitic glasses. Although they could not be confirmed as distinct from the friction melt, several possible glass rims were identified in the breccia.

The howardite Kapoeta was found to contain impact-related glass products in the form of agglutinates, glass rims, and melt spherules. One probable vapor- or sputter-deposited rim and one amorphous rim were identified. The identification of a single $npFe^0$-bearing rim and a single amorphous rim underscores three points: (1) such rims are created on asteroids; (2) they are extremely rare in regolith breccias; and (3) both solar wind irradiation and micrometeorite bombardment contribute to space weathering on asteroid regoliths.

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