Insights Into Regolith Evolution from TEM Studies of Space Weathering of Itokawa Particles.

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Exposure to solar wind irradiation and micrometeorite impacts alter the properties of regolith materials exposed on airless bodies [1]. However, estimates of space weathering rates for asteroid regoliths span many orders of magnitude [*e.g.*, 2, 3]. Timescales for space weathering processes on airless bodies can be anchored by analyzing surface samples returned by JAXA's Hayabusa mission to asteroid 25143 Itokawa. Constraints on timescales of solar flare particle track accumulation [4, 5] and formation of solar wind produced ion-damaged rims [6] yield information on regolith dynamics.

Multiple electron transparent thin sections of Itokawa particles RAQD02-0211 (0211), RA-QD02-0125 (0125), and RA-QD02-0192 (0192) were prepared using a hybrid ultramicrotomy-focused ion beam (FIB) technique [7] on a Leica EM UC6 ultramicrotome and an FEI Quanta 3D dual beam FIB-SEM. This technique results in whole slices of particles − preserving both edge and interior features (*e.g.*, Fig. 1a). Transmission electron microscope (TEM) analyses of the FIB sections, which allow for accurate determination of solar flare particle track densities and rim characteristics (*e.g.*, width, crystallinity), were done on the JEOL 2500SE 200kV field emission STEM. All instruments are housed at NASA JSC.

All three particles are olivine-rich (Fo_{70}) with minor sulfides and show features of space weathering: adhering mineral grains and melt particles, solar flare particle tracks, and continuous solar wind damaged rims. The rims are compositionally similar to the cores of the grains, structurally disordered, and nanocrystalline [8]. The rim thickness varies and track density gradients (fig. 2) are observed across the particles. The track density gradient across particle 0211 correlates with the rim thickness (Figs. 1b). The highest track density (3.4×10^9 tracks/cm^2) is on the side of the particle with the thickest rim (~80nm), while the lowest track density (9.2×10^8 tracks/cm^2) correlates with the thinnest rim (~40nm). Particle 0192 also shows a track density gradient (2.9×10^9 to 1.1×10^9 tracks/cm^2) and has comparable rim widths to particle 0211. Exposure ages, based on the track production rate of $4.1\pm1.2\times10^4$ tracks/cm^2/year at 1AU [4] are: ~80,000 years for 0211, ~70,000 years for 0192, and ~24,000 years for 0125.

The heterogeneous distribution of the space weathering effects on two Itokawa particles is consistent with both particles maintaining a relatively fixed orientation in the Itokawa regolith throughout the time they were being irradiated by incoming solar flare particles. 1.) Cosmic ray exposure ages for other Itokawa particles are relatively young (≤1−1.5 Ma) [9−11] when compared to other LL chondrites (8−50Ma) [12]. The CRE age indicates that the regolith was stable at meter depths over ~10^6 years. 2.) Based on track production rates in olivine at 1AU [4], Itokawa particles recorded solar flare tracks over timescales of <10^5 years. The track gradient indicates that over this timescale, the particles maintained a relatively stable orientation at mm to cm depths. 3.) Solar wind produced ion damaged rims are predicted to become amorphous and to reach thicknesses of 100nm within 10^3−10^4 years [6]. The rims on the Itokawa particles are not amorphous and have thicknesses of <60-70nm, suggesting a residence time on the surface (with direct exposure to the solar wind) of less than ~10^3 years. The continuous rims found on these grains, which have varying thicknesses, indicate that all sides of the particles have had direct exposure to the solar wind. The uppermost surface of the Itokawa regolith was sufficiently dynamic that while grain rotation must have occurred, the particles were not lost to space.

The Itokawa particles were shielded from direct exposure to the solar wind, at mm to cm depths, over timescales of 10^4–10^5 years. The track gradients in these particles suggest that the regolith in the Muses-C region of Itokawa experienced little overturn; rather, it was relatively stable at these depths. However, late in their history, over $<10^3$ years, all sides of the particles were directly exposed to the solar wind (as evidenced by continuous ion-damaged rims), which requires grain rotation on Itokawa's surface.

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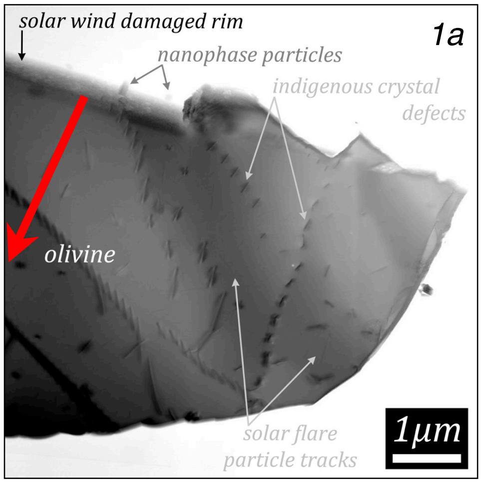
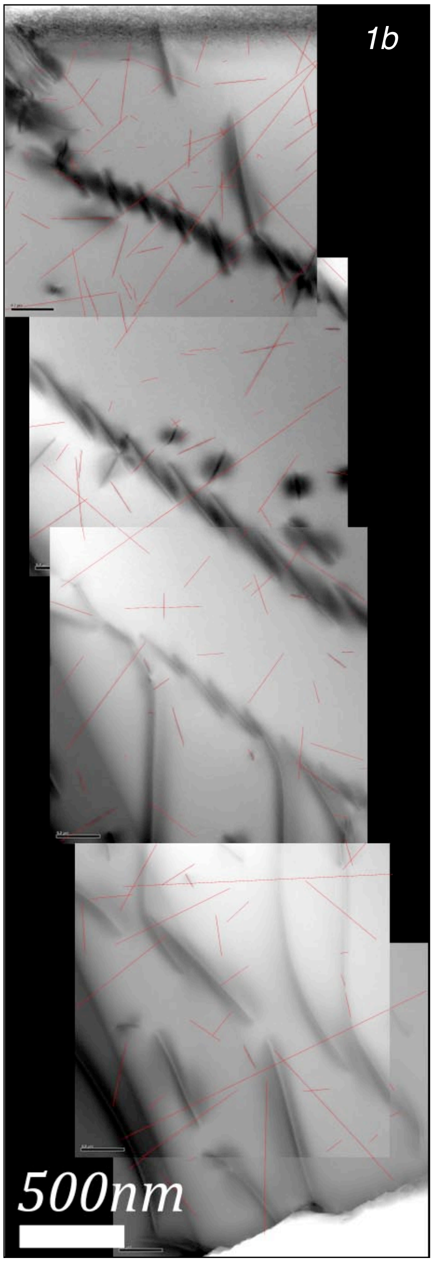


Fig. 1a. Bright field image (BFI) of Itokawa 0211, FIB section 1. 1b. BFI mosiac from 0211 (red arrow in fig. 1a). The thickest rim and highest track density are at the top, while the thinnest rim and lowest track density are at the bottom. Tracks are highlighted in red for ease of viewing.



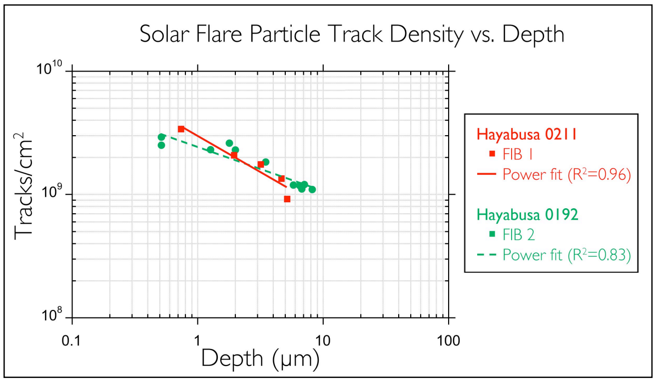


Fig. 2. Track density vs. depth. The trend line slopes are consistent with the Itokawa particles experiencing only mild tumbling while exposed on the surface of the asteroid; see [4, 5].