The origin of hydrogen in space weathered rims of Itokawa regolith particles.

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Introduction: Space weathering is the combined action of the solar wind, solar flares, micrometeorite impacts, and galactic cosmic rays [1]. These processes alter the physical and chemical properties of surfaces exposed to the vacuum of space. Within Itokawa particles, space weathering features include 20-40 nm thick amorphous and vesiculated rims and Fe nanoparticles ($_{np}$) [2, 3], as well as ~100-300 nm diameter micrometeorite impact craters [4]. Space weathering also implants elements contained within the solar wind, in particular the noble gases, He and Ne [5], as well as H [6]. Hydrogen is particularly important as it may react with Itokawa silicates to produce OH and H_2O; OH has been observed in space weathered rims of interplanetary dust particles [6]. The possibility of generating water through the interaction of solar wind with silicate minerals may have significant implications for the origin of water in the inner solar system. Therefore, it is important to quantify the abundance and distribution of these elements across these space weathering features, but also to ensure that such features are related to space weathering processes and not terrestrial contamination. Here we have combined field emission scanning electron microscopy (FE-SEM), transmission electron microscopy (TEM), time of flight secondary ion mass spectrometry (TOF-SIMS) and, for the first time, atom probe tomography (APT), to the study of space weathered rims in Itokawa regolith particles. For comparison, analyses were performed on San Carlos olivine reference materials that had been irradiated with low energy He or deuterium (D).

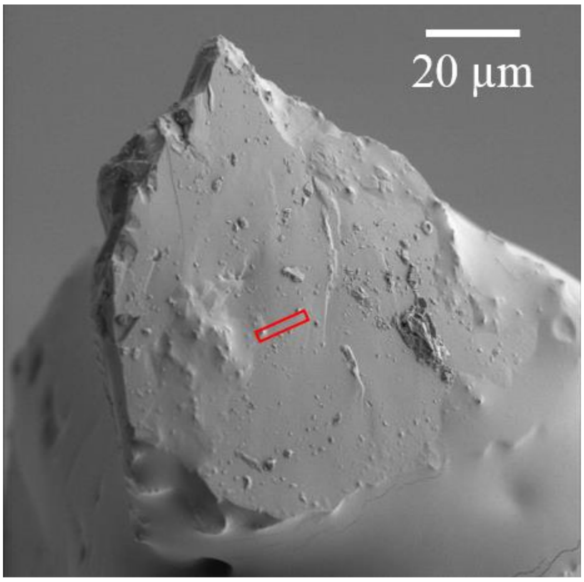

Figure 1: SE image Itokawa particle RA-QD02-0293. Atom probe specimens were extracted from the red box

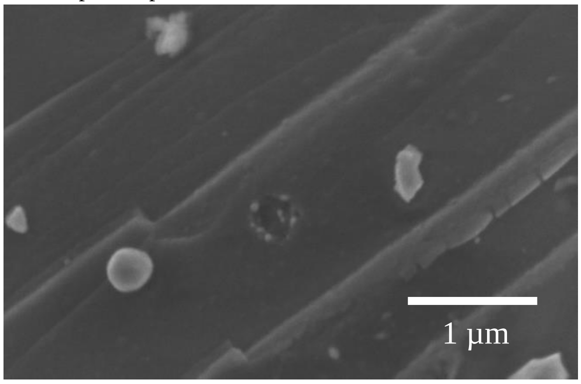

Figure 2: A SE image of a micrometeorite impact crater in Itokawa particle RA-QD02-0278.

Methods: Itokawa particle RA-QD02_0279 was mounted on a glass rod (Figure 1) and particles RA-QD02_0278 and RB-CV-0087 were mounted on carbon tape. RA-QD02_0278 and RB-CV-0087 were initially characterised at the Natural History Museum to identify mineral phases and space weathering features such as micrometeorite impact craters (Figure 2) using an FEI Quanta 650 FE-SEM with an annular Bruker energy dispersive X-ray spectrometer (EDS) inserted between the pole piece and the sample. This geometry allows non-destructive analysis at sub-micron resolution of uncoated samples with substantial surface topography by using ultra low beam current (25 pA) and low accelerating voltage (6kV) under high vacuum. The particles were then sputter coated with 200 nm of Cr to protect the sample from FIB-SEM sample preparation. Using a TESCAN LYRA3 FIB-SEM at Curtin University, APT needles were extracted by focussed ion beam (FIB) techniques [7], and TOF-SIMS ion maps were acquired from RA-QD02_0279 using both a negative and positive ion beam. The resulting 100 nm diameter APT needles were analysed at the geoscience atom probe facility (Cameca LEAP 4000X HR) at Curtin

University. Electron-transparent foils were also extracted from regions of the particles adjacent to the atom probe needles for correlative high resolution TEM and EDS. APT needles were also extracted from San Carlos olivine, both from pristine grains and from samples that had been implanted with He and D using a 10 kV Colutron accelerator.

Results and discussion: SEM imaging indicates that particle RA-QD02_0278 has several circular features on its surface that we interpret as micrometeorite impact structures (Figure 2), whereas RA-QD02_0279 and RB-CV-0087 lack such structures (Figure 1). EDS maps collected from the circular features in RA-QD02_0278 indicate that they have a similar chemical composition to the host olivine grain and so are likely to have been formed by secondary impact ejecta. Four APT datasets, each containing over 50 million ions, were collected from RA-QD02_0279 and one APT data set through a micrometeorite impact crater was collected from RA_QD02_0278. In all APT datasets evaporation commenced in the Cr coating, giving confidence that the outermost surfaces of the particles were measured, which have been potentially altered by space weathering features. The bulk chemistry derived from the APT data from RA-QD02_0279 indicate it is olivine (Fa_{30}). He and Ne were not observed in the mass spectrum and no Fe_{np} were detected. However, nanoscale domains of heterogeneous densities were observed in the outermost 20-30 nm (Figure 3). The high-density regions are enriched in Mg. Three of the four RA-QD02_0279 APT datasets show an enrichment of up to ~1.2 at. % in OH and H_2O ions that extends inwards for ~50 nm from the outer surface of the olivine particle. None of these features were observed in the pristine San Carlos olivine. TEM measurements of Itokawa, and APT data collection from the irradiated San Carlos olivine reference materials are ongoing and these results along with the implications of these new atomic scale observations will be presented at the meeting.

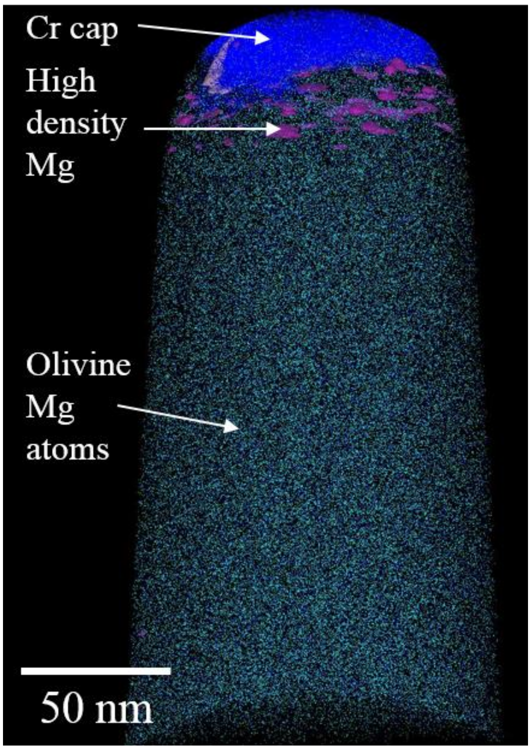

Figure 3: Atom probe needle of a space weathered rim of Itokawa. The blue and teal dots represent individual atoms of Cr and Mg, respectively. The protective Cr cap is clearly visible where the blue atoms are concentrated at the top of the needle. Pink isosurfaces depict Mg-rich, high-density regions close to the surface of the olivine grain.

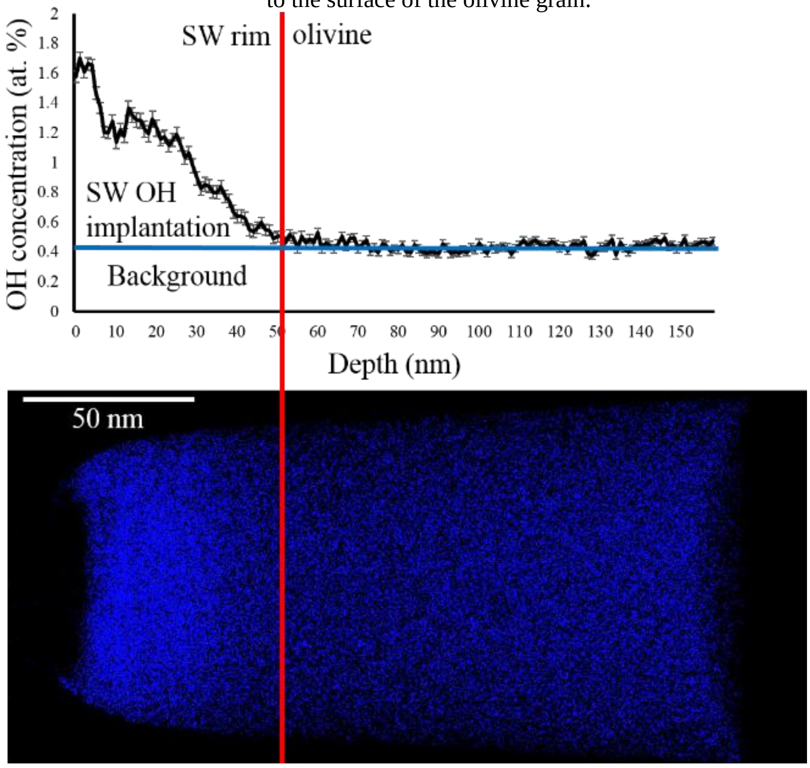

Figure 4: Atom probe needle of a space weathered rim of Itokawa. The blue dots represent OH ions, which are enriched up to 1.2 at. % in the outer 50 nm of the particle (left hand side).

References:

[1] Chapman C.R., (2004) *Ann. Rev. of Earth & Planet. Sci.,* 32, 539-567. [2] Noguchi T., et al., (2011), *Science,* 333, 6046, 1121-1125. [3] Noguchi T. et al., (2014) *MAPS,* 49, 2, 188-214. [4] Harries D., et al., (2016), *EPSL,* 450, 337-345. [5] Nagao K., et al., (2011) *Science,* 333, 6046, 1128-1131. [6] Bradley J.P., et al., (2014) *PNAS,* 111, 5, 1732-1735. [7] Thompson K., et al., (2007), *Ultramic.,* 107(2), 131-139.

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