THE SHOCK STATE OF ITOKAWA SAMPLES.

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Introduction: One of the fundamental aspects of any astromaterial is its shock history, since this factor elucidates critical historical events, and also because shock metamorphism can alter primary mineralogical and petrographic features, and reset chronologies [1]. Failure to take shock history into proper account during characterization can result in seriously incorrect conclusions being drawn. Thus the Hayabusa Preliminary Examination Team (HASPET) made shock stage determination of the Itokawa samples a primary goal [2]. However, we faced several difficulties in this particular research. The shock state of ordinary chondrite materials is generally determined by simple optical petrographic observation of standard thin sections. The Itokawa samples available to the analysis team were mounted into plastic blocks, were polished on only one side, and were of non-standard and greatly varying thickness, all of which significantly complicated petrographic analysis but did not prevent it. We made an additional estimation of the sample shock state by a new technique for this analysis - electron back-scattered diffraction (EBSD) in addition to standard petrographic techniques. We are also investigating the crystallinity of Itokawa olivine by Synchrotron X-ray diffraction (SXRD).

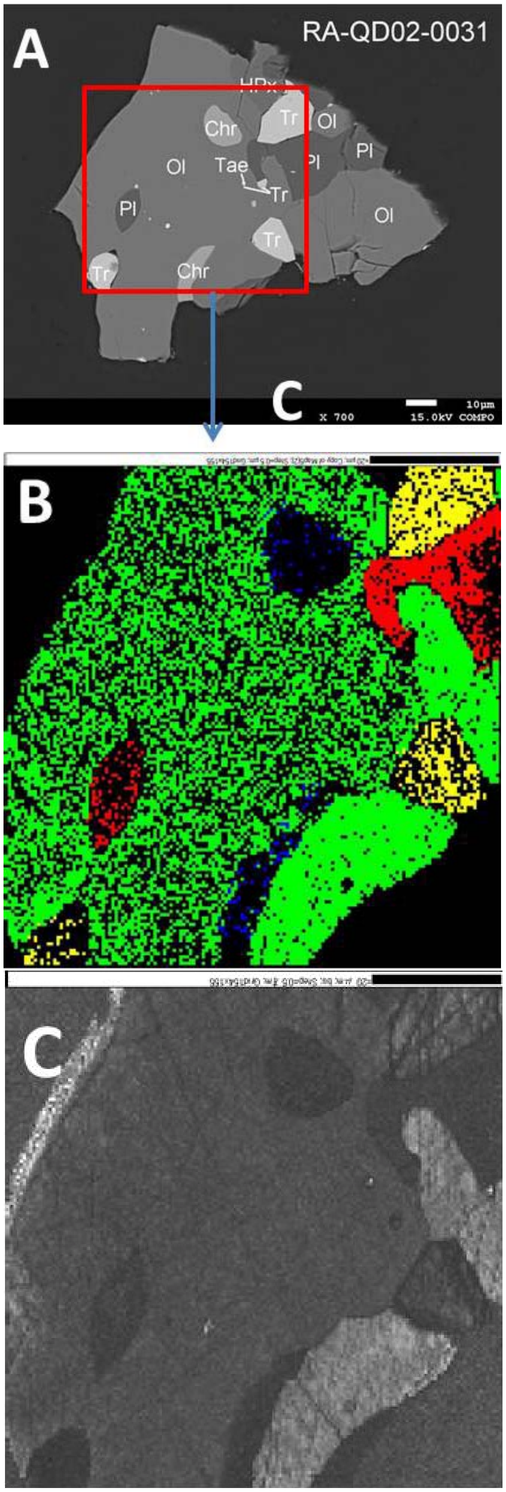
Experimental procedures: Each Itokawa grain was embedded in a block of epoxy, and polished using absolutely no water (to prevent terrestrial alteration). Since EBSD requires exceptionally well-polished samples we had to find a new procedure for the final polish. Rather than using water and colloidal silica, as is traditional for EBSD, we used a mixture of ethylene glycol, ethanol, glycerol, and 0.05 µm alumina, as recommended by polishing guru George Vandervoort (personal communication, 2010). The resulting sample finish was inferior to what could have been achieved by standard techniques, but was adequate. Samples were coated with 10 nm of carbon, and then were observed at Kyushu University in a JEOL JSM-7001F FEGSEM operated at 15 kV and 82 µA. We used an Oxford CHANNEL 5 EBSD system and associated software, in mapping mode. We found that optimal maps of entire grains were obtained in 10-120 minutes, each. However, for maps longer than 30 minutes stage movement was an irritation. We performed SXRD analysis of Itokawa olivine grains using energy scanning of monochromated radiation at SPring-8 beam line 37XU (see [3] for experimental details).

Results: We made EBSD maps of 6 equilibrated (LL5/6) Itokawa grains (RA-QD02-0010, -0013, 0030, 0031, 0057, 0058), and one unequilibrated (LL4) grain (RA-QD02-0011-1). Equilibrated Itokawa grain RA-QD02-0031 (hereafter 31), is shown in Fig. 1. The EBSD maps reveal that the degree of crystallite crystallinity significantly varies within individual grains. In the maps crystalline subdomains that produced indexable diffraction patterns are assigned a characteristic color (for example green for olivine), and poorly-crystalline domains are black (Fig. 1). Olivine crystallinity in grain 31 varies considerably within the space of a few microns, and likewise albite, troilite and chromite. Albite was sometimes better crystalline than adjacent olivine, counter to our expectations. However, local variations in degree of crystallinity is a hallmark of shock metamorphism [1,4].

In order to determine the relative shock degree of the Itokawa grains we duplicated the EBSD analysis using grains from the Kilabo LL6 (shock stage S3) and Alfianello L6 (S5) ordinary chondrites. We used completely equilibrated type 6 chondrites in order to avoid potential complications from variable mineral compositions. For this to work the standard meteorite chips had to be polished and observed under exactly the same conditions as the Itokawa samples. It is desirable to put this analysis on a firm quantitative basis, and this can be achieved through use of band slope (BS) images, which are processed from the raw EBSD maps. Band slope maps can be considered to indicate the degree of crystallinity, which varies directly as brightness in BS maps, as illustrated in Fig. 1c. BS maps lend themselves to more ready quantification. By visually comparing the overall crystallinity of samples from EBSD and BS maps we estimated that Itokawa samples should be assigned to be intermediate between Kilabo and Alfianello, therefore shock stage S4 by EBSD.

We also determined the shock state of the Itokawa samples in the conventional manner under crossed polars in a standard petrographic microscope. Despite the irregular and non-standard specimen thickness this was surprisingly easy to do. Our biggest problem was the fact that we only attempted this analysis after SIMS measurements had been completed for many of the samples, which had excavated holes measuring several microns surrounded by thin amorphous regions, which we had to ignore. We examined 29 separate grains. As an example, three images of grain 31, taken at different rotation angles, are shown in Figure 1D. Practically all crystallites in the Itokawa grains exhibited minor to pronounced undulatory extinction. Some grains displayed distinct mosaicism. We saw no instances of shock veins in the equilibrated (LL5-6) grains, but there were amorphous regions in the unequilibrated LL4 grains. We observed no obvious parting or planar deformation features. Given the natural variability of shock effects [Stoffler et al], these petrographic observations indicate shock stage S2, which is considerably lower than that suggested by EBSD images (S4), but consistent with tentative results in [5].

To verify that shock levels were lower than S4 we have begun collecting SXRD data on larger Itokawa olivine grains. Grain RA-QD02-0049-2 consists almost entirely of olivine, and its diffraction pattern was very sharp, indicating insignificant shock metamorphism for this particular grain.



Conclusions: Before proceeding it is worth considering the fact that asteroid Itokawa (0.1-0.5 km across) is a reassembled beanbag which probably includes only a very small fraction of the initial progenitor asteroid (which measured at least 10s of km across) as it existed before destruction. It is not known how lithologically representative Itokawa is of this progenitor asteroid. Further, the total recovered mass of Itokawa is on the order of 1 mg, and it is not known how representative this mass is of Itokawa, or the progenitor asteroid. In terms of the sampling of Itokawa, arguments can be made that the grains are representative, but also that they are not representative. Nevertheless, we conclude that the majority of the Itokawa samples are shock level S2.

Shock effects can be effectively studied from even the tiny Itokawa grains, and by multiple techniques. It would be interesting to examine IDPs and lunar regolith grains in the same manner. However, EBSD and standard petrographic techniques are not equally sensitive to very fine-scale shock effects. EBSD appears to have greater potential to elucidate shock effects at the finest scale, and if EBSD data only are used to assign a shock stage the results may not be directly comparable to those obtained by petrographic techniques.

References: [1] Stöffler D. et al. (1991) *Geochim. et Cosmochim. Acta* **55**, 3845-3867; [2] Nakamura T. et al. (2011) *Science* **333**, 1113-1116; [3] Hagiya K. et al. (2010) *Meteorit. Planet. Sci.* **45**, A73; [4] Stöffler D. et al. (1992) *Meteoritics* **27**, 292; [5] Noguchi T., *Bunseki*kagaku, in press.

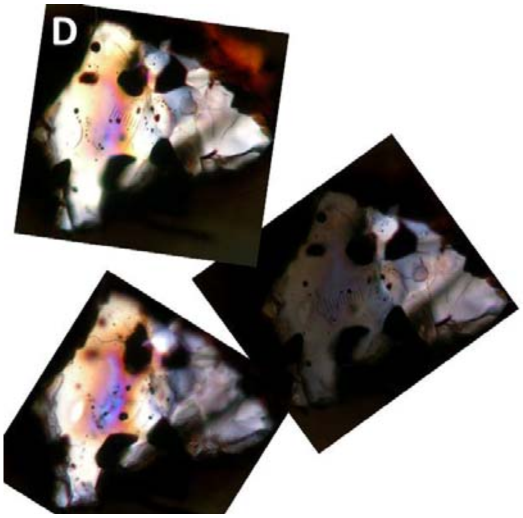


Figure 1. Images of grain 31. **1A:** BSE image of the entire grain. Ol: olivine, Pl: albite, Tr: troilite, Tae: taenite, Chr: chromite, HPx: high-calcium pyroxene. **1B:** EBSD map of the portion of 31 indicated by the red box. Olivine is green, albite is red, troilite is yellow, chromite is blue. **1C:** Band slope map produced from the EBSD map in 1B. The brightest crystallites are highly-crystalline olivine, and most of the chromite and albite are poorly crystalline, but one crystallite of troilite and the largest olivine mass has intermediate degree of crystallinity, due to variable shock effects at the micron scale. The white stripe under the "C" is an artifact. **1D:** Three cross polar petrographic images, taken at different rotation angles, indicating slight mosaicism and irregular extinction of the olivine crystallite on the right.