POST-HYDRATION COMPACTION OF RYUGU FROM MATRIX PETROFABRICS.

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Introduction: Grains that have been collected from the regolith of the C-type asteroid 162173 Ryugu by the Hayabusa2 spacecraft provide a unique opportunity to understand the accretion and subsequent alteration of the Solar System's most primitive bodies. Preliminary analysis of the returned samples shows that they are most similar to CI carbonaceous chondrites [1], and so will have undergone extensive parent body aqueous alteration. They may also contain evidence for shock heating and mechanical deformation by impacts, and space weathering (i.e., alteration mediated by the solar wind, solar and galactic cosmic rays, and micrometeoroid impacts). Indeed, both shock heating and space weathering have been proposed as possible explanations for results of near-IR spectroscopic measurements of Ryugu by the Hayabusa2 spacecraft [2]. Here we have characterized the petrography and mineralogy of a regolith grain for evidence of aqueous alteration, shock deformation, and space weathering.

Materials and methods: The grain studied is 70×90 μm in size, and all analytical work was undertaken at the University of Glasgow (UoG). The outer surface of the grain was characterized by secondary electron imaging using a Zeiss Sigma SEM operated at 2 kV, then a wafer was cut and extracted from it using a Ga-FIB. Bright-field (BF) diffraction-contrast TEM images and selected area electron diffraction (SAED) patterns were acquired from the wafer using a FEI T20 TEM at 200 kV, and both BF and high angular annular dark-field (HAADF) images were obtained using a JEOL ARM STEM operated at 200 kV. Grains were chemically analysed by energy-dispersive X-ray spectroscopy (EDX) and electron energy loss spectroscopy (EELS) using the same STEM.

Results: SEM shows that the outer surface of the grain is covered by very thin platy crystals of phyllosilicate that are up to ~1 μm in length. Projecting through them are euhedral grains of dolomite several micrometers in size, and objects composed of radiating arrays of close-packed magnetite needles.

The FIB wafer contains relatively coarse grains within a fine-grained phyllosilicate-rich matrix (Fig. 1). The coarse grains comprise two magnetite spherules, one grain of pyrrhotite and one dolomite. The magnetite spherules are composed of closely packed acicular crystals 2–4 μm in length by ~50–70 nm in width (Fig. 2a), and BF images show that these crystals contain abundant ~100 nm size pores or inclusions (Fig. 2b).

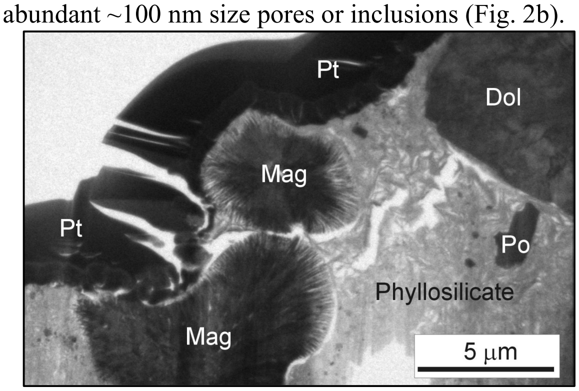

Figure 1. BF TEM image of the Pt-coated FIB wafer that contains magnetite (Mag), pyrrhotite (Po) and dolomite (Dol) in a porous phyllosilicate-rich matrix.

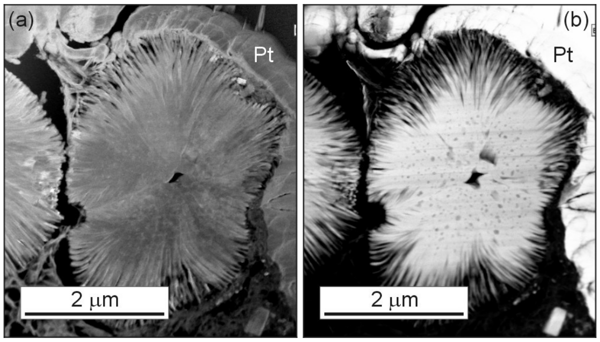

Figure 2. HAADF (a) and BF (b) STEM images of a magnetite spherule. (b) shows that the constituent magnetite needles contain numerous small pores or inclusions. Pt denotes the FIB-deposited Pt strap.

The pyrrhotite is a faceted crystal 2.5×1.2 μm in size. Its SAED pattern shows that it is 4C-pyrrhotite and there is evidence for twinning in both the pattern and the TEM image (Fig. 3). Matrix phyllosilicate crystals range widely in size through the sample. Those adjacent to the pyrrhotite are lath-shaped and up to ~1 μm in length by ~15 nm in thickness. Some of these crystals show clear evidence for having been fractured, and those between the pyrrhotite and dolomite grain have been tightly compacted, and wrap around the sulphide (Fig. 3).

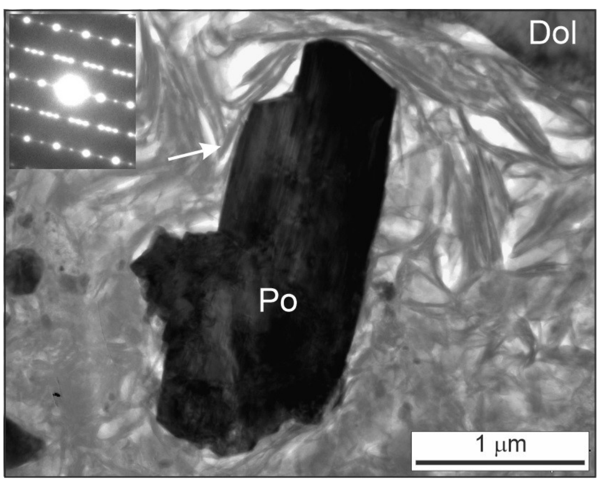

Figure 3. BF TEM image of the pyrrhotite (Po) crystal with SAED pattern inset. The pyrrhotite is surrounded by phyllosilicate crystals, some of which have undergone brittle fracturing (arrowed). The edge of the dolomite grain (Dol) is in the top right-hand corner.

Discussion: The phyllosilicate-magnetite-dolomite-pyrrhotite mineralogy of this grain is very similar to the CI carbonaceous chondrite meteorites, thus supporting conclusions from the initial analysis [1]. The magnetite spherules are also closely comparable to those in CI meteorites, e.g. Orgueil [3].

The arrangement of the phyllosilicate crystals in the vicinity of the pyrrhotite grain is indicative of late-stage (post aqueous alteration) compaction (i.e., after phyllosilicate and dolomite crystal growth). The brittle fracturing of the phyllosilicate crystals shows that they were deformed at a high strain rate as can result from impact shock, rather than at a low strain rate that can accompany lithostatic compaction in the interior of a large asteroid, or the semi-viscous flow of water-saturated matrix [4]. Although further work is required on their crystallographic properties, the twins in the pyrrhotite grain could be further evidence for shock deformation. The dolomite is also another target for future analysis of shock deformation because carbonate microstructures have been used to identify mild shock deformation of the Orgueil meteorite [5].

The impactor responsible for deformation of the matrix may have been a large meteoroid/asteroid either pre or post parent body break up, one or more micro-meteoroids that were responsible for space weathering, or the sampling device (a tantalum projectile [6]). An argument against micro-meteoroids is that there is no evidence for space weathering of the grain's outer surface, such as a vesicular melt or micrometeoroid impact craters, although such features could have been lost during natural 'regolith gardening' or sample collection [7, 8].

Conclusions: The Ryugu grain studied is mineralogically closely comparable to the CI meteorites. The fabric of the phyllosilicate matrix shows that the grain has undergone high strain-rate deformation, which could have been in response to a meteoroid impact, or sample collection. Further microstructural work to seek evidence for shock deformation of the pyrrhotite and dolomite crystals may help to answer this question.

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