X-ray nano-CT and TEM-EDS Analyses of Impact Melt Splashes on Ryugu Samples

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Introduction: Ryugu samples are chemically and mineralogically similar to CI chondrites, and consist mainly of Mg-rich phyllosilicates, Fe-Ni-sulfides, magnetite, carbonates, hydroxyapatite, organic matters, and other minor minerals [1–5]. Some Ryugu particles experienced space weathering on the asteroid surface and exhibit amorphized and melted sample surfaces formed by solar wind irradiation and micrometeoroid bombardments [6]. A0067 and A0094 particles are among the space weathered Ryugu samples [6] and have flat sample surfaces which exhibit a lot of microcraters and impact melt splashes. In the present study, we investigated one relatively large microcrater (A0067-crater#1) and two impact melt splashes (A0067-melt#1 and A0094-melt#1) on the two particles (Fig. 1) by scanning electron microscope equipped with energy dispersive X-ray spectroscopy (SEM-EDS), X-ray nano-tomography (XnCT), and scanning transmission electron microscope (STEM) equipped with EDS to unveil the nature of the impactors hit on the asteroid Ryugu.

Results and Discussion: A0067-melt#1 shows round shape (~20 µm in diameter) and is composed of a Mg-Fe-rich glassy silicate main body and an Fe-rich opaque drop (~10 µm) attaching on the glassy silicate. It was extracted from the A0067 particle using focused ion beam technique and analyzed by XnCT and STEM-EDS. The analyses revealed that A0067-melt#1 is attached onto the saponite-rich coarse phyllosilicate layer (~1–4 µm in thickness) [2] developed along with the A0067 main body surface. Some gaps occur between the phyllosilicate sheets. These probably formed from shrinking of the phyllosilicate layers associated with volatile losses caused by the attaching of the hot impact melt splash. The glassy silicate in A0067-melt#1 has homogeneous Mg-Fe-rich composition with the ratio Mg/(Mg+Fe) in atom (hereafter Mg#) of ~0.64 and contains only small amounts of Fe-Ni metal–sulfide spherules (<100 nm). The Fe-rich opaque drop consists of dendritic crystals of α-(Fe-Ni) (~200–300 nm) embedded in the matrix composed mainly of troilite and minor pentlandite, and probably formed by a rapid cooling of an Fe-S-Ni melt.

A0094-melt#1 shows hourglass-like morphology (~15 × 5 µm) and is probably made of two Mg-Fe-rich glassy silicate drops connected to each other. XnCT–STEM-EDS analyses revealed that A0094-melt#1 is compositionally inhomogeneous and shows patchy structure with Fe-rich (Mg# 0.52–0.55) and Fe-poor (Mg#~0.79) glassy silicate regions (2–5 µm in size). The boundaries between the regions are unclear. Spherical voids (a few tens of nanometers to ~2 µm) are abundant both in the Fe-rich and the Fe-poor regions. The Fe-poor region contains almost no crystalline phase whereas the Fe-rich region contains spherical and irregular-shaped Fe-Ni sulfides (<500 nm) and olivine grains (1–2 µm). Some aggregates (0.3–1 µm) consisting mainly of spongy inorganic carbon, irregular-shaped Fe-Ni sulfides, and Mg-rich silicates were also observed in A0094-melt#1. The aggregates are textually similar to primitive organic materials reported in anhydrous chondritic IDPs and carbonaceous chondrites [7], and might have formed from such primitive organic matters through volatile losses caused by impact induced heating.

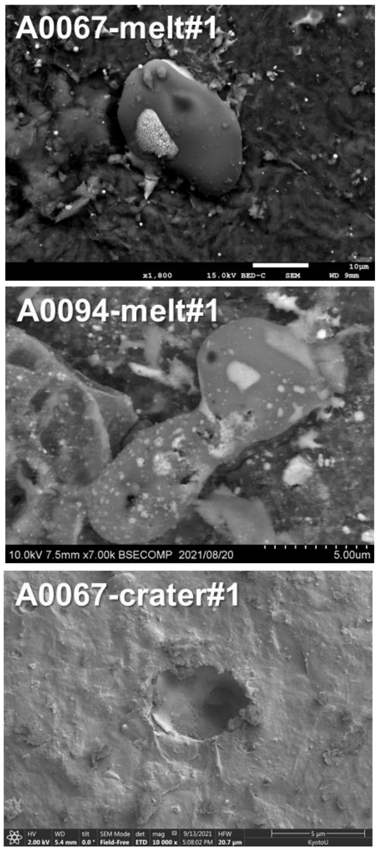

Fig. 1. FE-SEM images of A0067-melt#1, A0094-melt#1, and A0067-crater#1.

A0067-crater#1 is ~5 µm in diameter. XnCT–STEM-EDS analysis revealed that A0067-crater#1 is ~4 µm in depth and traps small amount of mixture of glassy silicate and troilite. The mixture should be an impact melt and shows flow structure consisting of glassy silicate and troilite layers (30–250 nm in thickness) stacking with each other. The glassy silicate layer is compositionally inhomogeneous and separated into Si-poor and Si-rich glasses. Both the silicate glasses contain spherical voids (<200 nm) and Fe-Ni sulfide spherules (<100 nm). The Si-poor glass (Mg#~0.72) is abundant compared to the Si-rich glass and compositionally similar to the glassy silicates in A0067-melt#1 and A0094-melt#1. The Si-rich glass selectively occurs along with the crater wall and probably formed *in-situ* from a Si-rich source material originally distributed on the A0067 particle surface. In the present study, we observed thin (<100 nm) Si-rich layers on A0067 and A0094 particle surfaces. These might correspond to the Si-rich vaper deposits previously reported on surfaces of some space weathered Ryugu particles [6] and may be the source of Si-rich glass in A0067-crater#1.

In the impact melts, different source materials such as impactors and Ryugu surface materials would have been mixed. The impact melts studied consist mainly of Mg-Fe-rich glassy silicate parts whose major element compositions (including Fe-Ni sulfide and olivine grains) are plotted along with an extension of a line connecting the CI (solar) composition [8] and the Fe-vertex in a (Si+Al)–Mg–Fe ternary diagram (Fig. 2). This suggests the impact melts studied have common source materials and the compositional trend seems to represent a mixing line of the source materials. A0094-melt#1 shows compositional inhomogeneity suggesting an incomplete mixing of the source materials, and the Fe-poor and the Fe-rich regions might be proximate to the original source materials. The Fe-poor region is compositionally similar to the Mg-rich phyllosilicate matrix in the Ryugu samples (Fig. 2) [2] , which consists >80 vol.% of Ryugu samples, and probably sourced from Ryugu surface materials. On the other hand, the Fe-rich region has CI-like composition which deviate from the compositions of Ryugu's phyllosilicates and other Ryugu components (Fig. 2). This suggests that Ryugu is not the source of the Fe-rich region and that the Fe-rich region was probably sourced from the impactors. The known small planetary materials having CI-like compositions are interplanetary dust particles (IDPs) and micrometeorites derived from asteroids and comets. Among those, anhydrous chondritic IDPs have bulk compositions which match well with the compositional range of the impact melts studied (Fig. 2) [9], and might be the source of the Fe-rich region. This is consistent with the presence of the carbonaceous aggregates, which might have formed from primitive organic matters, in A0094-melt#1. These mean that the impact melts studied might have formed by anhydrous chondritic-IDPs impacts on the Ryugu's surface. Further study of many more impact melt splashes and microcraters will give important information about the variation and flux of the impactors that hit on asteroid Ryugu.

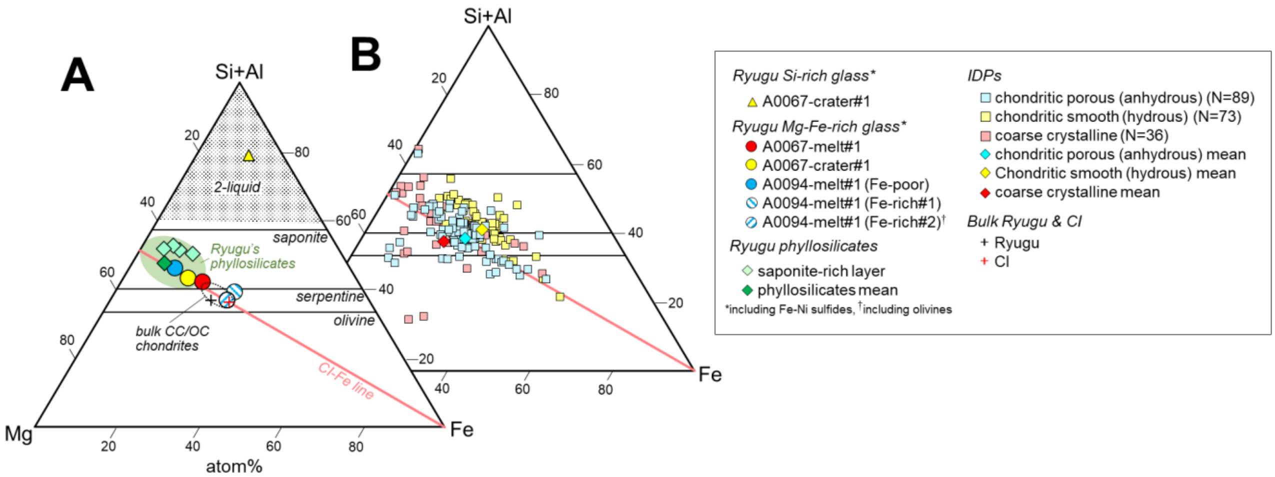

Fig. 2. (Si+Al)–Mg–Fe atom% ternary diagram of compositions of the melt splashes. (A) The major element compositions of the melt splashes studied and (B) those of IDPs. The compositions of IDPs are from [9], Ryugu's bulk composition is from [1], and the composition of the phyllosilicates in the Ryugu samples is from [2]. The compositional field of Ryugu phyllosilicates (774 analyses) [2] is shown as a green colored oval.

Reference: [1] Yokoyama et al. (2023) *Science*, **379**, eabn7850. [2] Nakamura et al. (2023) *Science*, **379**, eabn8671. [3] Ito et al. (2022), *Nat. Astron.* **6**, 1163–1171. [4] Nakamura et al. (2022) *Proc. Jpn. Acad. Ser.* B 98:227. [5] Yamaguchi et al. (2023), *Nat. Astron.* **7**, 398–405. [6] Noguchi et al. (2023) *Nat. Astron.* **7**, 170–181. [7] Matrajt et al. (2012) *Meteorit. Planet. Sci.* **47**, 525–549. [8] Lodders (2021) *Space Sci. Rev.* **217**, 44. [9] Schramm et al. (1989) *Meteoritics* **24**, 99–112.