3D MORPHOLOGIES OF MAGNETITE, SULFIDES, CARBONATES AND PHOSPHATES IN RYUGU SAMPLES AND THEIR CRYSTALLIZATION SEQUENCE DURING AQUEOUS ALTERATION.

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Introduction: The mineralogy, petrology and chemical properties of the samples collected from the asteroid 162173 Ryugu by the Hayabusa2 spacecraft show that the samples correspond to CI meteorites not affected by terrestrial weathering (e.g., [1,2]). Our analysis using SR-based X-ray nanotomography (XnCT) is also consistent CI meteorites [3]. Here we report the morphologies of major mineral phases in 3D to discuss their crystallization conditions in aqueous alteration together with their crystallization sequence based on their textures.

Methods: We examined 75 particles (10 ~ 180 μm in apparent size) by XnCT at BL47XU of SPring-8 [3]. Most of them were imaged by DET-SIXM method combined with absorption and phase-shift tomography to discriminate mineral phases with the voxel size of 50 ~ 110 nm, their Mg# and densities. Some samples were imaged by absorption tomography with higher resolution (voxel size: 15 ~ 18 nm).

Results and Discussion: The matrix of analyzed particles is mainly composed of Mg-rich phyllosilicates (serpentine and saponite, 82 vol.%) with different features (fine to coarse aggregates, Mg# = 0.75 ~ 0.92 (mean: 0.83±0.04), density = 1.2 ~ 2.1 (mean: 1.7±0.26) g/cm^3), IOMs (0.7 vol.%) and voids (12 vol.%). The major minerals in the matrix are magnetite (2.5 vol.%), Fe(-Ni)S (1.4 vol.%; pyrrhotite >> pentlandite), dolomite (1.2 vol.%), breunnerite and apatite (0.2 vol.%). The data here should show the representative feature of Ryugu samples through the 3D analysis of abundant particles without selection bias but may have large uncertainties for the modal abundance in particular IOMs due to insufficient spatial resolution and thresholding of the XnCT analysis.

3D morphologies. Magnetite has a variety of morphology (typically a few ~ 10 μm); spherulite and its aggregate, framboid composed of mono-dispersed grains of a few 100s nm ~ a few μm, plaquette, large equant grains composed of {311} and elongated grains. Transitional morphologies were also observed. Whiskers (~0.5 μm thick and 20 μm long) and cube (~1 μm) are rarely present as well. In contrast, pyrrhotite is mostly separated hexagonal plates ({100} and {001} in the hexagonal setting) with different size (longest length: <1 ~ 60 μm). The width/length ratio ranges from 0.06 to 0.98 (mean: 0.43±0.20) and is independent of the size. Pentlandite (<~5 μm) is embedded in pyrrhotite or present as fragmented grains in the matrix. Nano-sized pyrrhotite and pentlandite grains were also observed in some matrix by TEM [4] although their morphologies were not clearly known. Dolomite is usually present as aggregates of subhedral ~ euhedral grains (<1 ~ 50 μm). Some are euhedral grains of flattened rhombohedron probably composed of {101}. Separated breunnerite grains (30 ~ 100 μm) are thin rhombohedron of possibly {012}. Apatite is usually present as aggregates of subhedral ~ euhedral grains (<1 ~ 50 μm) and one hexagonal prism of {100} (or {110}) and {001} was observed.

Crystallization sequence. The crystallization sequence of the major minerals estimated based on inclusions and their relative enclosing relations, which can be easily recognized in 3D, is follows; magnetite → Fe(-Ni)S (pentlandite → pyrrhotite) → apatite → dolomite/breunnerite. For magnetite, the sequence is likely spherulitic → plaquette/framboidal (from fine to coarse) → equant/elongated. This indicates that magnetite crystallization condition changed from high to low supersaturations. The overall sequence can be explained by aqueous alteration of primitive solar materials such as GEMS-like materials. The high supersaturation for magnetite was probably caused by abrupt dissolution of relatively Fe^0 or FeO-rich amorphous silicates followed by precipitation of magnetite and Mg-rich phyllosilicates. In contrast, pyrrhotite hexagonal plates with different size might be formed by dissolution and reprecipitation from original Fe(-Ni)S nanograins at relatively low supersaturation. Dolomite and apatite having equilibrium shapes [5,6] indicate that they precipitated at relatively low supersaturations in the late stage.

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