Chondrule-like Objects in Ryugu: Evidence for Accretion of Ryugu in the Vicinity of the Outer Solar System Chondrule Factory

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We report the discovery of large abundances of chondrule-like objects within Ryugu sample A0180, including microchondrules and a large porphyritic chondrule. The primary phases within these objects have all been replaced by the products of aqueous alteration, however, their morphologies and shapes testify to an origin as sub-spherical molten droplets identifying them as chondrule-like objects (CLOs). The majority of CLOs found in A0180 were identified by X-ray Computed Tomography (XCT) and are microchondrules <30 μm in size.

Results: Sample A0180, like other Ryugu samples [1-3], has a mineralogy and texture that closely resembles CI chondrites, and is dominated by phyllosilicates, framboidal magnetite, pyrrhotite and carbonates (mainly dolomite), with small abundances of apatite. Numerous sub-spherical silicate-dominated objects (181) were identified within sample A0180, which are considered as CLOs (Fig.1). All but one CLO are <30 μm in diameter and were identified in XCT data by virtue of mantles of sulphides with high X-ray attenuation. These form near complete sub-spherical shells surrounding a silicate core. In section these micro-CLOs were observed to have partial rims of polycrystalline Ni-bearing pyrrhotite, surrounding a silicate core with a composition and texture suggesting they consist primarily of phyllosilicates. The majority of silicate cores have homogeneous textures, however, some are similar to matrix. One broken, hemispheric micro-CLO was observed (Fig.1f), and one was a composite with two interpenetrating shells (Fig.1g). The abundance of micro-CLOs in sample A0180B is 350 ppm.

A large CLO was also identified in the sample as a spherical cap truncated by the external surface of the particle. It comprises clusters of euhedral crystals of dolomite within a matrix of phyllosilicates with minor magnetite and sulphide. The phases were identified by quantitative comparison of their X-ray attenuation with phases exposed in the plane of section. Dolomite crystals have orthorhombic symmetries suggesting they are pseudomorphs of pre-existing phases. The diameter of the object, reconstructed from its curvature, is 550 μm.

Discussion: The CLOs are suggested to represent microchondrules, with metallic or sulphide-rims, and a porphyritic chondrule that have been replaced by aqueous alteration. The observation of broken and composite microchondrules suggest these were liquid droplets and formed prior to accretion. The occurrence of small numbers of altered and unaltered microchondrules in Ryugu has previously been noted [3,4]. This study shows that Ryugu contains higher microchondrule abundances than all but one meteorite (Semarkona, 800 ppm [5]), and the highest microchondrule to chondrule ratio. It also demonstrates that Ryugu contains small numbers of large chondrules.

Chondrules in carbonaceous chondrites are most likely to have formed in the outer Solar System since their ages post-date the formation of the Jovian gap at 800 kyr after CAIs [6,7]. The most likely location for the chondrule factory is where mm-sized dust is concentrated, in the pressure bump 1AU outside the Jovian gap. The occurrence of abundant microchondrules and small numbers of chondrules suggests accretion in proximity to the chondrule factory, rather than at a large distance, since radial transport by viscous spreading is limited after formation of the gap [8], furthermore the predominant flow beyond the pressure bump is inwards owing to gas drag on dust particles [7].

The large microchondrule to chondrule ratio within Ryugu implies a concentration mechanism for small particles relative to chondrules. The turbulent concentration of particles of this size requires gas densities higher than in the solar nebula at 30 AU [e.g. 7], but could be achieved sunwards of the pressure bump in the region of the nebula affected by the turbulent wake of Jupiter. Furthermore, although CO_2-rich inclusions in Ryugu have been interpreted as formation beyond the CO_2-snow line [3], these inclusions are found in phases formed during aqueous alteration at much higher temperatures than the

sublimation of CO_2 ices. Abundant carbonates within some Ryugu samples [1-3] testify to the presence of water saturated with carbonate that could exsolve CO_2, similar to naturally carbonated springs. The highly primitive nature of Ryugu, and the CI chondrites, could be a consequence of their fine-grain size, since small particles are likely to have escaped significant processing. CI chondrites, therefore, may not be fine-grained because they are primitive, but primitive because they are fine-grained.

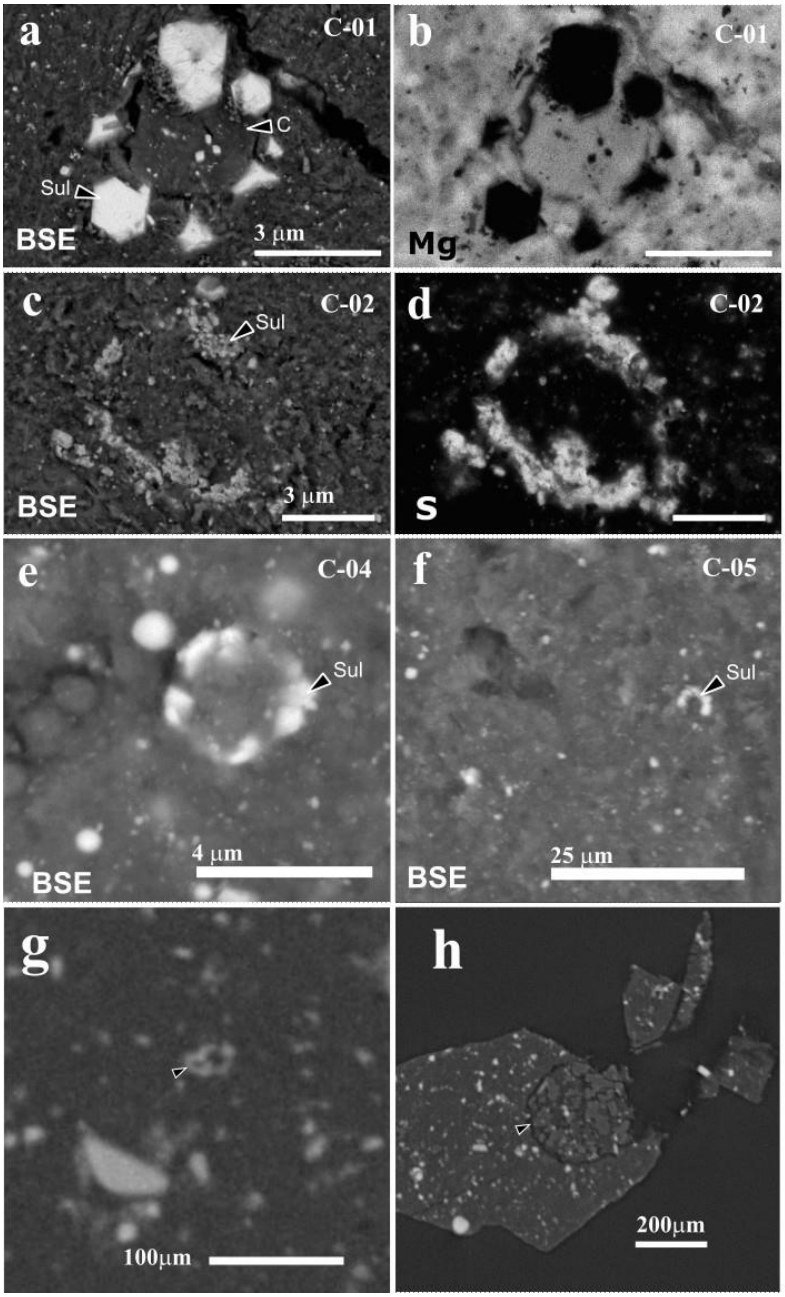

Figure 1. Showing backscattered electron (BSE), element maps (labelled with element) and XCT images of CLOs within sample A180. (a-g) Show microchondrules with sulphide (Sul) rims and silicate cores (C). (f) Illustrates a broken microchondrule. (g) Shows a composite microchondrule in XCT data. (h) Shows a large altered porphyritic chondrule.

References

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