Ice and Liquid Water in Asteroid Ryugu – Constraints from Sample A0180

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Carbonaceous asteroid 173163 Ryugu has a mineralogy and petrology similar to CI chondrites and thus experienced intense aqueous alteration early in its history. Samples of Ryugu returned by the Hayabusa 2 mission (Sawada et al., 2017) reveal the presence of abundant phyllosilicates, carbonates, sulphides and magnetite generated by aqueous processing of the progenitor asteroid in the early Solar System (Ito et al., 2022, Nakamura et al, 2022a,b, Yada et al., 2022). We report the results of a combined electron beam and nano-XCT study of Ryugu sample A0180 that allow the evolution of water within the sample to be traced from the growth and accretion of ice within the nebula to its melting and migration within the progenitor asteroid.

Several textural features were observed within A0180 that reflect the history of aqueous processing. Cavities are abundant within the sample (0.17 vol%) and vary from small equant voids several µm in diameter to large re-entrant cavities containing highly porous assemblages of coarse-phyllosilicate, sulphides and magnetite. Many voids have drusy rims of phyllosilicate indicating they were fluid-filled voids. Some have rims of organic matter, including composite cavities in which only one cavity has an organic rim, suggesting these were originally ice grains with pre-accretional organic mantles. Cavities in sample A0180 thus represent nebula ice grains that were accreted into the progenitor asteroid. Reconstruction of nano-XCT data allows the size distribution of nebula ice grains and grain growth mechanisms to be determined.

Veins and fractures are also present within sample A0180. Networks of discontinuous veins containing mixtures of framboidal magnetite and phyllosilicate were observed in polished sections and within nano-XCT data and formed curved, cuspate veins. These veins must represent pathways of aqueous fluids during alteration. Fracture networks are also present in A0180 as both isolated fractures, bounded by crack tip terminations, and larger fractures that extend across the entire sample (~1 mm). Fracture-filling Ni-bearing sulphide, phyllosilicate and organic matter are observed in places. Fractures are also surrounded by metasomatic aureoles of altered material that are more homogeneous than the rest of the matrix. The presence of fracture-infilling phases and the presence of aureoles suggests these fractures were present during aqueous alteration. Cross-cutting relationships indicate that fractures postdate magnetite-bearing veins. Both fractures and magnetite veins have similar tortuosity.

The occurrence of cavities, veins and fluid-filled fractures allows the evolution of water during the accretion and aqueous alteration of Ryugu to be traced. Cavities represent fossil ice grains and reveal size distributions consistent with bimodal growth of dirty ice grains within the outer solar system. The presence of organic rims suggests these were irradiated in low-opacity regions of the nebula. Likewise, the volume of ice is less than required to explain the observed abundance of phyllosilicates, suggesting the region of the progenitor sampled by A0180 accreted in an ice-depleted region compared with other parts of the asteroid.

Magnetite veins and fractures testify to the influx of distal water during heating of the asteroid by short-lived radionuclides (Weidenschilling, 2019) and record several pulses of compositionally distinct fluids migrating into the region (c.f. McCain et al., 2023). The similar morphologies of veins and fractures suggest these were formed by the same process, however, their cuspate morphologies are not consistent with either shock (Tomioka et al., 2023, Hamann et al., 2023) or thermal fracturing. In contrast, we performed freeze-thaw experiments that confirm that cuspate morphologies form as a result of the expansion and contraction of ice during repeated freeze-thaw episodes. The experiments also reveal that ice grains can be preserved with relatively minor shape and volume modification over 2-3 episodes of melting if temperatures are close to the freezing point of water.

The observations made on sample A0180 suggest that ice plays a crucial role in the alteration of carbonaceous asteroids. Ice grains are accreted from the solar nebula into a porous matrix of primitive µm-sized grains in asteroids. Internal heating by the decay of short-lived radionuclides causes the melting of ice within the interior and outwards migration of a shell of melt water. Hydrous alteration of primitive silicate grains and precipitation of phyllosilicates, however, seals the porous network forming a barrier to fluid migration. The increase in fluid pressure caused by the trapping of melt water can cause hydraulic fracturing and periodic escape of pulses of fluids outwards within the asteroid. At the margins of these plumes of rising liquid water temperatures will be at the freezing point leading to multiple episodes of freeze-thaw. Fracturing caused by freeze-thaw will then occur ahead of rising plumes providing important migration pathways for fluids. Freeze-thaw at the fringes of asteroid water reservoirs, therefore, is likely to be important in the dispersion of hydrated materials throughout asteroids.

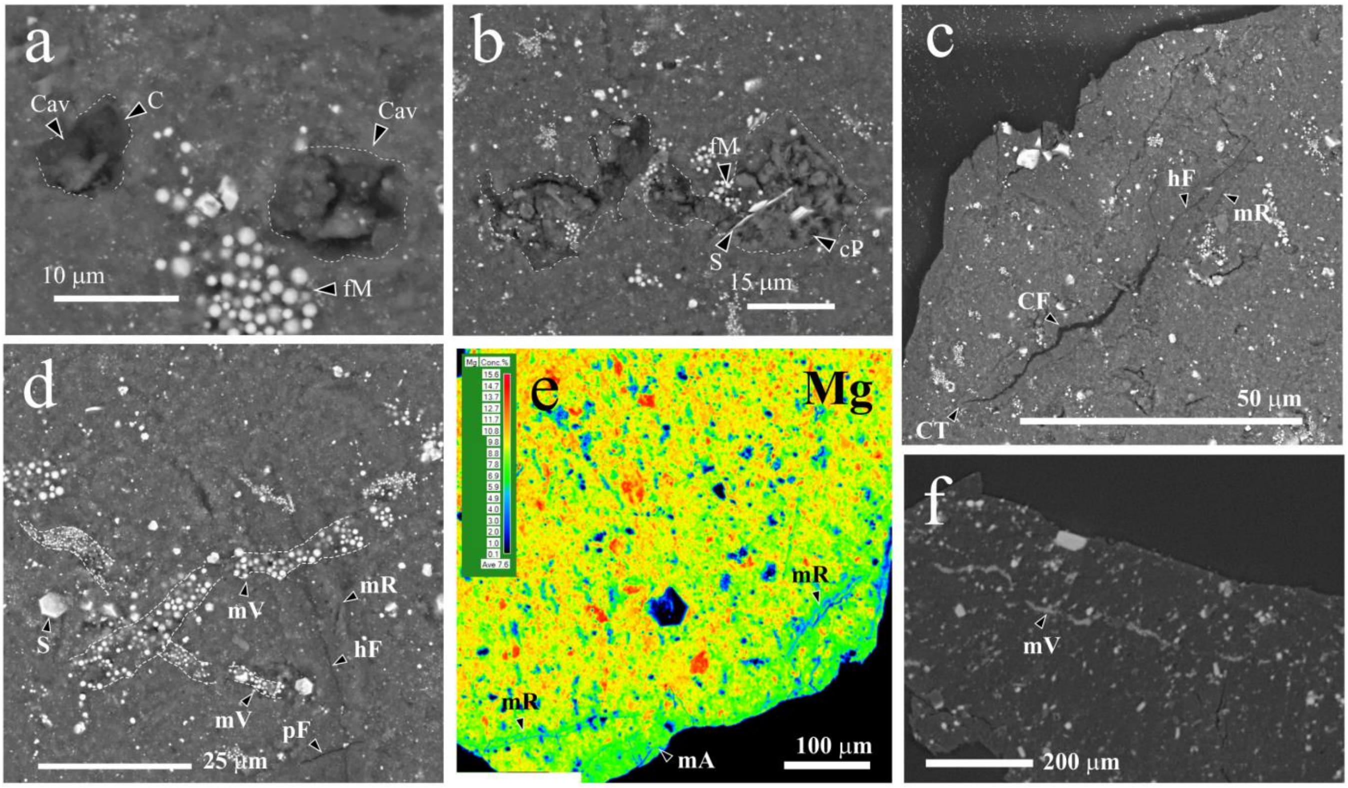

Figure 1. Images of cavities, veins and fractures in Ryugu sample A0180. (a) Shows two cavities (Cav), one with an organic rim (C). (b) A large re-entrant cavity containing porous phyllosilicates (cP), framboidal magnetite (fM) and sulphides (S). (c) A cuspate fracture (CF) with one end partially healed by infilled phyllosilicate (hF). The fracture terminates at a crack tip (CT). A metasomatic rim (mR) surrounds the fracture. (d) Cross-cutting, discontinuous magnetite veins (mV). Partially healed fractures surrounded by metasomatic rims are also present. (e) A Mg-element map showing metasomatic rims (mR) surrounding fractures. (f) A nano-XCT slice showing a cuspate magnetite rim.

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