Lithological variation of asteroid Ryugu samples returned by the Hayabusa2 spacecraft: Assessment from the 18 particles distributed to the initial analysis "Stone" team

T. Mikouchi[1], H. Yoshida[1], T. Nakamura[2], M. Matsumoto[2], A. Tsuchiyama[3,4], J. Matsuno[3], K. Tsutsui[2], M. E. Zolensky[5], D. Nakashima[2], M. Masuda[1], K. Hagiya[6], M. Kikuiri[2], T. Morita[2], K. Amano[2], E. Kagawa[2], H. Yurimoto[7], T. Noguchi[8], R. Okazaki[9], H. Yabuta[10], H. Naraoka[9], K. Sakamoto[11], S. Tachibaba[1,11], S. Watanabe[12] and Y. Tsuda[11]
[1]*University of Tokyo, Japan (mikouchi@um.u-tokyo.ac.jp),* [2]*Tohoku University, Japan,* [3]*Ritsumeikan University, Japan,* [4]*Guangzhou Inst. of Geochemistry, Chinese Academy of Sciences, China,* [5]*NASA John Space Center, USA,* [6]*University of Hyogo, Japan,* [7]*Hokkaido University, Japan,* [8]*Kyoto University, Japan,* [9]*Kyushu University, Japan,* [10]*Hiroshima University, Japan,* [11]*ISAS/JAXA, Japan,* [12]*Nagoya University, Japan*

Introduction: JAXA's Hayabusa2 spacecraft successfully returned ~5.4 g of C-type asteroid Ryugu materials on Dec. 2020 [e.g., 1] and the recovered samples were extensively analyzed by initial analysis teams and Phase2 curation teams. The reported results show that Ryugu samples are similar to CI chondrites in chemistry and mineralogy, showing evidence for aqueous alteration in the parent body [e.g., 2,3]. As a "stone" team of the initial analysis, we received 18 coarse particles (>1 mm) of Ryugu samples to characterize their mineralogy and petrology. We found that the samples were breccias of mm-to-sub mm size clasts. All of the clasts are mainly composed of Mg-Fe phyllosilicates, but the alteration degree appears slightly different from one clast to another [3]. Here we report a lithological variation of Ryugu samples to propose their reasonable lithological classification based upon different mineral assemblages and associated mineralogy, which will provide important information to elucidate the formation and evolution of the Ryugu parent body.

Samples and Methods: We analyzed 18 coarse particles that are 7 Chamber A particles (A0026, A0055, A0063, A0064, A0067, A0094 and A0106) and 11 Chamber C particles (C0002, C0023, C0025, C0033, C0040, C0046, C0055, C0061, C0076, C0103 and C0107), respectively. Chamber A particles are from the first touchdown site while Chamber C particles are from the second touchdown site where the SCI impact experiment was carried out to attempt to collect subsurface materials [4]. In total 52 polished sections were prepared from all particles. The JEOL JXA-8530F field emission electron microprobe (FE-EPMA) at Univ. of Tokyo was employed for both WDS X-ray mapping and quantitative analyses of constituent minerals using well-characterized natural and synthetic standards after observation using back-scattered electron (BSE) images. X-ray mapping was carried out with a 1-3 μm interval to understand distribution of constituent minerals.

Results: Most of the analyzed polished sections show brecciated textures on a scale of mm to μm (Fig. 1). In spite of such brecciation, all clasts are mainly composed of Mg-Fe phyllosilicates that are TEM-scale mixtures of serpentine and saponite [3]. Other minor phases include carbonates (Ca-carbonates, magnesite ("breunnerite") and dolomite), magnetite, Fe,Ni sulfides (pyrrhotite and pentlandite), Ca phosphate, olivine, pyroxene, Mg,Na phosphate, Mn-rich ilmenite, spinel, chromite, Fe,Ni phosphide and Fe,Ni metal.

Among these accessory phases, carbonates exhibit the most remarkable mineralogy because they are present as different mineral species in each clast, which appears to be related to the degree of aqueous alteration [3]. When Ca carbonates are present, olivine and pyroxene are also associated, suggesting that

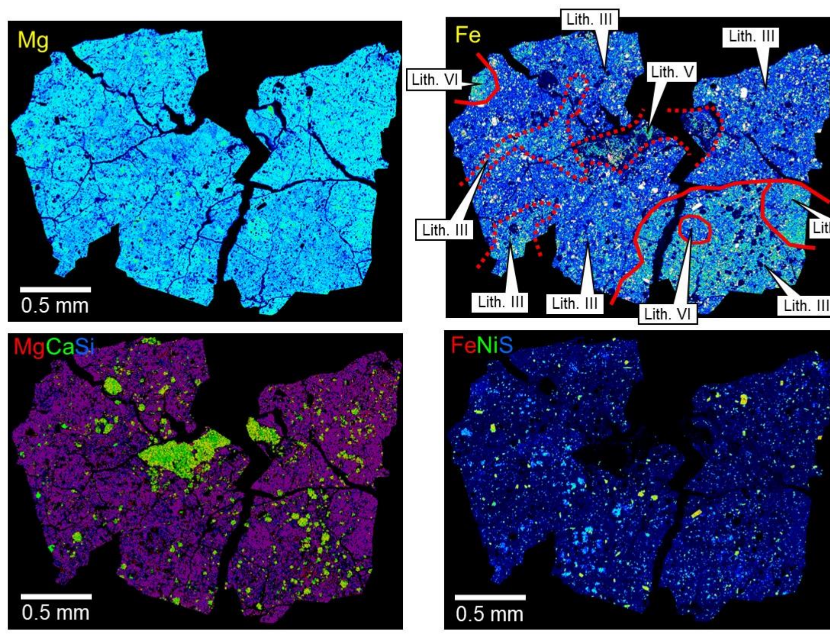

Fig. 1. Mg and Fe X-ray maps (above) and MgCaSi and FeNiS composite RGB maps (below) of the A0055-01 polished section. In this section lithologies III, V and VI were found (noted in the Fe map (upper right)). Yellow~green phases in the MgCaSi map are dolomites. The same analysis was done for all other polished sections.

such clasts are less altered compared to the others. In fact, the modeling calculation of progressive aqueous alteration of chondritic anhydrous minerals predicts that only Ca carbonates form when the water to rock ratio is low [3], resulting in less aqueous alteration. Such modeling is in accordance with the Ryugu sample observation that olivine and pyroxene are absent in clasts when Ca carbonates are absent and only dolomite and/or magnesite are present. This observation indicates that olivine and pyroxene are unaltered phases that survived aqueous alteration in the parent body. The more water-rich alteration condition forms dolomite and subsequently magnesite [3]. Rimming of magnesite on dolomite is observed, further supporting this proposal (Fig. 2). Similarly, Mg,Na phosphate is absent when Ca carbonates are absent. The presence of Fe,Ni phosphide and Fe,Ni metal is associated with the presence of olivine and pyroxene. In clasts with these phases, Ca phosphate is rare, suggesting that Ca phosphate formed by aqueous alteration of Fe,Ni phosphide and Ca-bearing phases. As noted in [3], there is the rare presence of olivine-rich clasts that appears to be the least altered clasts in Ryugu samples. In these clasts, dolomite and magnesite are rare and GEMS-like material is present [3].

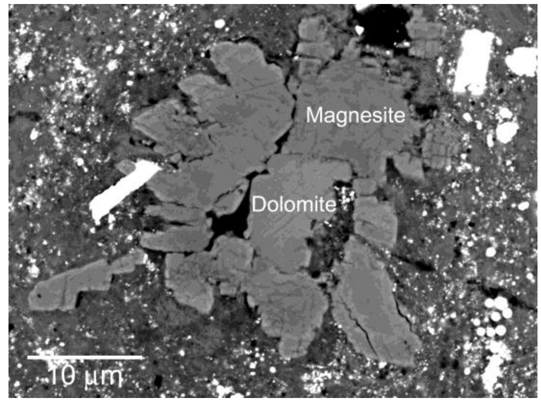

Fig. 2. BSE image of carbonates in A0067-02. Magnesite surrounds the dolomite core, suggesting formation of magnesite after dolomite.

Discussion and Conclusion: In summarizing the above observations, we tried to classify lithological variations of our coarse Ryugu particles based upon mineral assemblages and associated mineralogy, mostly using X-ray mapping results of FE-EPMA. The key mineral phases for this classification are olivine and carbonates. The presence/absence of olivine can broadly divide the clasts into two lithologies: olivine-bearing and olivine-free lithologies, corresponding to less altered and altered lithologies, respectively. Because olivine-bearing lithologies are rarer, olivine-free lithologies are major lithologies of Ryugu samples [3]. We assigned rare olivine-rich clasts as "lithology I" and the other olivine-bearing clasts as "lithology II". For olivine-free lithologies, the carbonate mineralogy can further divide them into four: dolomite-bearing ("lithology III"), dolomite+magnesite-bearing ("lithology IV" (Fig. 2)), carbonate aggregates ("lithology V") and carbonate-poor ("lithology VI"). We assigned lithology V clasts when carbonates show aggregate textures that are larger than 100 μm in size. Because we frequently found carbonate-poor clasts, we assigned lithology VI when carbonates are only ~<1 vol.% in abundance and small in size (~<10 μm). Except for these six types of different lithologies, there are exceptional lithologies such as coarse isolated mineral grains. The lithologies I to IV appear related to the degree of aqueous alteration by this order since the calculation of progressive aqueous alteration by increasing water to rock ratios predicts different carbonate species (Ca carbonate → dolomite → magnesite) matching with the observed carbonate mineralogy in these lithologies [3]. The lithologies V and VI would have been formed at somewhat different conditions other than lithologies III and IV, respectively. We checked the phyllosilicate compositions of different lithologies and found that phyllosilicates in olivine-bearing lithologies (I and II) were more Fe and Na-rich compared to those in olivine-free lithologies (III-VI). There are no clear compositional differences among phyllosilicates in lithologies III-VI, except that phyllosilicates in lithology VI are slightly poorer in Fe and Na compared to those in lithologies III-V.

Thus, we propose that the lithology of Ryugu samples can be divided into 7 types (lithology I, II, III, IV, V, VI and others) based upon mineralogy of constituent minerals in different clasts due to the brecciated nature of Ryugu samples. When we looked at 18 coarse Ryugu particles that we analyzed, we found that olivine and pyroxene are absent in our Chamber A particles, namely Chamber A particles include only lithologies III, IV, V, VI and others. In contrast, most of Chamber C particles contain olivine and pyroxene, which is lithology II in many cases. The largest section in our sample (C0002 plate 5) contains rare type lithology I clasts although they are small (~100 μm). Therefore, we clearly see that there is a mineralogical difference between Chamber A and C particles. This observation may suggest heterogeneous distributions of materials with different degrees of aqueous alteration at the two different sampling sites. However, we cannot rule out the possibility of sampling bias because the samples analyzed are small. Also, it is unclear whether such lithological differences are related to the subsurface sampling at the second touchdown site by artificial crater formation.

References: [1] Yada T. et al. (2021) *Nat. Astron.* 6:214. [2] Yokoyama T. et al. (2022) *Science* 10.1126/science.abn7850. [3] Nakamura T. et al. (2022) *Science* 10.1126/science.abn8671. [4] Kadono T. et al. (2020) *Astrophys. Jour. Lett.*, 899, L22.