MINERALOGY AND SPACE WEATHERING OF FINE FRACTION RECOVERED FROM ASTEROID (162173) RYUGU. T. Noguchi[1,2], T. Matsumoto[3], A. Miyake[1], Y. Igami[1], M. Haruta[4], H. Saito[5], S. Hata[6], Y. Seto[7], M. Miyahara[8], N. Tomioka[9], H. A. Ishii[10], J. P. Bradley[10], K. Ohtaki[10], E. Dobrică[10], H. Leroux[11], C. Le Guillou[11], D. Jacob[11], M. Marinova[11], F. de la Peña[11], F. Langenhorst[12], D. Harries[12], P. Beck[13], T. H. V. Phan[13], R. Rebois[13], N. M. Abreu[14], J. Gray[15], T. J. Zega[16], P.-M. Zanetta[16], M. S. Thompson[17], R. Stroud[18], K. Burgess[18], B. A. Cymes[18], J. C. Bridges[19], L. Hicks[19], M. R. Lee[20], L. Daly[20], P. A. Bland[21], M. E. Zolensky[22], D. R. Frank[10], J. Martinez[23], A. Tsuchiyama[24,25], M. Yasutake[26], J. Matsuno[24], S. Okumura[1], I. Mitsukawa[1], K. Uesugi[26], M. Uesugi[26], A. Takeuchi[26], M. Sun[24], S. Enju[27], A. Takigawa[28], T. Michikami[29], T. Nakamura[30], M. Matsumoto[30], Y. Nakauchi[31], H. Yurimoto[32], K. Nagashima[10], N. Kawasaki[32], N. Sakamoto[32], R. Okazaki[33], H. Yabuta[8], H. Naraoka[33], K. Sakamoto[31], S. Tachibana[34], S. Watanabe[35] Y. Tsuda[31], [1] Div. Earth Planet. Sci., Kyoto U. (email: noguchi.takaaki.2i@kyoto-u.ac.jp), [2]Faculty Arts Sci., Kyushu U., [3]Hakubi Center Adv. Res., Kyoto U., [4]Inst. Chem. Res., Kyoto U., [5]Inst. Mat. Chem. Eng., Kyushu U., [6]Dept. Adv. Mat. Sci., Kyushu U., [7]Dept. Planet., Kobe U., [8]Earth Planet. Sys. Sci. Prog., Hiroshima U., [9]Kochi Inst. Core Sample Res., JAMSTEC, [10]Hawai'i Inst. Geophys. Planet., U. Hawai'i at Mānoa, [11]U. Lille, CNRS, INRAE, [12]Inst. Geosci., U. Jena, [13]IPAG, U. Grenoble Alpes, [14]Langley Res. Cent., NASA, [15]Mat. Charact. Lab, Penn. State U., [16]Lunar Planet. Lab., Dept. Mat. Sci. Eng., U. Arizona, [17]Dept. Earth Atmos. Planet. Sci., Purdue U., [18]Mat. Sci. Tech. Div., U.S. Naval Res. Lab., [19]Space Res. Cent., U. Leicester, [20]Sch. Geogr. Earth Sci., U. Glasgow, [21]Sch. Earth Planet. Sci., Curtin U., [22]ARES, NASA, [23]Jacobs Engineering, [24]Res. Org. Sci. Tech., Ritsumeikan U., [25]CAS Key Lab. Mineral. Metal., Guangzhou Inst. Geochem., CAS, [26]Japan Synchr. Rad. Res. Inst., [27]Dept. Math, Phys. Earth Sci., Ehime U., [28]Dept. Earth Planet. Sci., U. Tokyo, [29]Faculty Eng., Kindai U., [30]Dept. Earth Sci., Tohoku U., [31]ISAS, JAXA, [32]Dept. Earth Planet. Sci., Hokkaido U., [33]Dept. Earth Planet. Sci., Kyushu U., [34]UTOPSS, U. Tokyo, [35]Dept. Earth Env. Sci., Nagoya U.

Introduction: The JAXA Hayabusa2 spacecraft returned 5.4 g of samples from near-Earth C-type asteroid (162173) Ryugu to Earth on December 6th, 2020 [1]. The returned samples give us a unique opportunity to investigate material from the surface of a C-type asteroid that is expected to record evidence of space weathering. Here, we report the mineralogy of the fine fraction of the Ryugu grains and microstructural and chemical features related to space weathering.

Samples and Methods: Surface morphologies of ~600 small Ryugu grains were observed by field emission scanning electron microscopy (FE-SEM) and focused ion beam (FIB)-SEM at Kyoto and Kyushu Universities. Thin foil samples were prepared by FIB-SEM at both universities. In addition, a polished sample of a fragment originating from a large grain A0058 (~3 mm wide) was also investigated. To understand mineralogy and petrology down to the nanometer scale and to clarify the detailed structural and chemical characteristics of space weathering, we performed transmission electron microscopy (TEM), synchrotron radiation X-ray absorption fine structure (XANES and EXAFS) spectroscopy, nanotomography, and atom probe analysis at 16 universities and laboratories spread across the world. Nine abstracts are presented for this meeting by our Min-Pet Fine sub-team.

Results: *Mineralogy of fine fraction of the Ryugu samples.* Major minerals of the small Ryugu grains are phyllosilicates (saponite and serpentine), Fe-Ni sulfides, magnetite, dolomite, and breunnerite. It is obvious that asteroid Ryugu experienced aqueous alteration as comparable to C1 chondrites and did not experience enough heating to produce secondary anhydrous minerals such as olivine, pyroxene, and Fe metal.

Space weathering of Ryugu samples. Recognizable surface modifications of the phyllosilicate-rich matrix were found on 3% and 10% of the observed grains in Chambers A and C, respectively. Chambers A and C contained particles obtained at the first and second touchdown sites, respectively. A variety of surface modifications are observed: melt splashes, amorphous layers (Fig. 1), and melt layers (Figs. 1, 2) (definitions of these terms are described below). In the most extreme case, a partially melted grain and a grain enclosed by a continuous melt layer are observed.

The amorphous layers form a continuous sheet ~0.1 μm thick composed of amorphous silicate material at the top surface. Their bulk chemical compositions are indistinguishable from those of the underlying phyllosilicate-rich matrix, but they have a higher ratio of Fe^{2+} relative to Fe^{3+} than the interior phyllosilicate-rich matrix. The melt layers have bubbles and numerous submicroscopic (<100 nm) rounded Fe-Ni sulfide beads (bright spots as shown in Fig. 2). These data suggest that both silicate and Fe-Ni sulfides were melted and immiscibly separated into silicate and sulfide melts. Such melt layers have higher Fe and lower Si+Al and Mg ratios, as well as a higher ratio of Fe^{2+} relative to Fe^{3+} than the interior phyllosilicate-rich matrix.

Discussion and conclusion: The mineralogy and petrology of the Ryugu FIB sections investigated are similar to CI chondrites, but the samples lack ferrihydrite and sulfates, commonly found in CI chondrites [3]. Considering the effects of terrestrial weathering of CI chondrites, we infer that the mineralogy of investigated Ryugu grains is similar to that of CI chondrites prior to their weathering upon arrival on Earth.

The surface morphology of the amorphous layers resembles the surface of an experimental product of Orgueil CI chondrite that was irradiated by 4 keV He^+ at a fluence of 1.3×10^{18} ions/cm^2, irrespective of the almost six order-of-magnitude difference in flux between experiments and natural conditions. This textural similarity might have resulted from effective escape of volatiles from the radiation-damaged phyllosilicates under both experimental and natural conditions. To a first approximation, it appears that solar-wind irradiation likely played an important role in modifying the surface of the phyllosilicate-rich matrix.

Both the surface morphology and the internal texture of the melt layers resemble those of the products from the laser irradiation experiments that simulate micrometeoroid impacts [3], suggesting that they had an important role in forming the melt layers. Reduction of Fe^{3+} to Fe^{2+} occurred in amorphous and melt layers, and only a small amount of nanophase (np) Fe^0 was formed on the surface of the melt layer. The low abundance of np Fe^0 in Ryugu samples contrasts starkly with those in Itokawa and lunar samples [e.g. 4-8]. These differences may be related to the high relative abundances of Fe^{3+} to Fe^{2+} in Ryugu grains compared to Itokawa and lunar grains. The H_2O in phyllosilicates may be also related to the difference.

To discuss the space weathering processes affecting the C-type asteroid Ryugu, we make the hypotheses, which are common to S-type asteroids: 1) space weathering induced by solar wind irradiation is a rapid process, while that induced by micrometeoroid impacts is a slow process [9], 2) impacts of larger meteoroids are less frequent than those from smaller ones due to the rarer abundance of larger meteoroids.

Based on these assumptions, four stages of the surface modification of the phyllosilicate-rich matrix can be classified. In Stage I, no detectable change was found on the surfaces of the phyllosilicate-rich matrix. In Stage II, an amorphous layer is formed on the phyllosilicate-rich matrix by progressive damage from solar wind irradiation. In Stage III, the effects of micrometeoroid impact overprint the effects of solar wind irradiation. In Stage IV, the effects of multiple micrometeoroid impact are clearly observable. The natural overturn or gardening of regolith grains on the asteroid parent body interrupts these stages so that the weathering process on any one grain does not progress linearly. However, our results imply that the Ryugu surface has experienced space weathering longer than Itokawa.

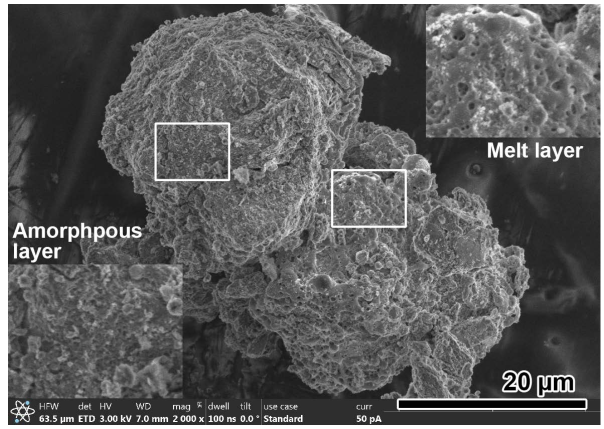

Fig. 1 Secondary electron image of a space-weathered grain C0105-03003800. The upper left part of this grain has an amorphous layer and the lower right part has a melt layer.

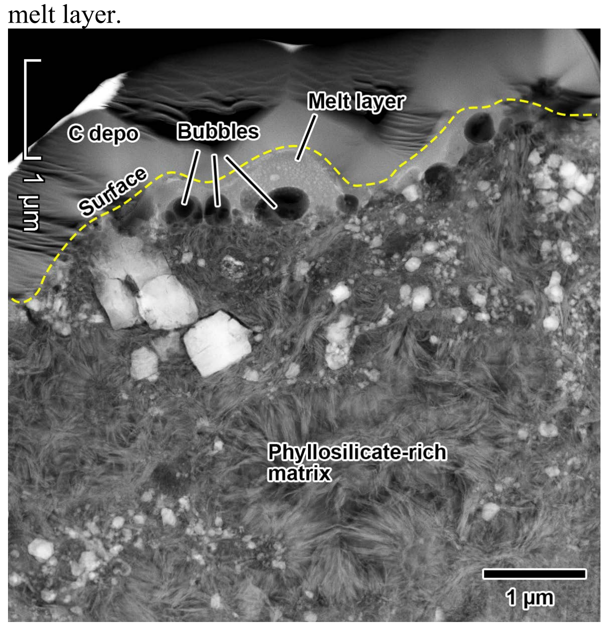

Fig. 2 HAADF-STEM image of a cross section of A0104-02203703. This grain has a melt layer containing abundant bubbles; Most of the tiny bright spots in the melt layer are Fe-Ni sulfide beads.

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