SPACE EROSION OF RYUGU EVIDENCED BY NANO-TOPOGRAPHY. L. Daly[1,2,3], M. R. Lee[1], P. A. Bland[4], W. Smith[5], S. McFadzean[5], P-E. Martin[1], P.A.J. Bagot[3], D. Fougerouse[4], D.W. Saxey[4], S. Reddy[4], W.D.A. Rickard[4], T. Noguchi[7,8], H. Yurimoto[9], T. Nakamura[10], H. Yabuta[11], H. Naraoka[12], R. Okazaki[12], K. Sakamoto[9], S. Tachibana[13], S., Watanabe[14], Y. Tsuda[15], and the Min-Pet Fine Sub-team. [1]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK. (luke.daly@glasgow.ac.uk). [2]Australian Centre for Microscopy and Microanalysis, The University of Sydney, Sydney, NSW, Australia, [3]Department of Materials, University of Oxford, Oxford, UK. [4]Space Science and Technology Centre, School of Earth and Planetary Sciences, Curtin University, Perth, WA, Australia. [5]Materials and Condensed Matter Physics, School of Physics and Astronomy, University of Glasgow, Glasgow, UK. [6]Geoscience Atom Probe Facility, John de Laeter Centre, Curtin University, Perth, WA, Australia. [7]Division of Earth and Planetary Sciences, Kyoto University; Kitashirakawaoiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan. [8]Faculty of Arts and Science, Kyushu University; 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan. [9]Department of Earth and Planetary Sciences, Hokkaido University; Kita-10 Nishi-8, Kita-ku, Sapporo 060-0810, Japan. [10]Department of Earth Science, Graduate School of Science, Tohoku University; 6-3 Aoba, Aramaki, Aoba-ku, Sendai 980-8578, Japan. [11]Earth and Planetary Systems Science Program, Hiroshima University; 1-3-1 Kagamiyama, Higashi-Hiroshima City, Hiroshima, 739-8526, Japan. [12]Department of Earth and Planetary Sciences, Kyushu University; 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan. [13]UTokyo Organization for Planetary and Space Science, University of Tokyo; 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan. [14]Department of Earth and Environmental Sciences, Nagoya University; Furo-cho, Chikusa-ku, Nagoya 464−8601, Japan. [15]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency; 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan.

Introduction: The Hayabusa2 mission returned 5.4 g of material from the surface of the water-rich C-type asteroid 162173 Ryugu in December 2020 [1]. Preliminary characterization indicates that the mineralogy of Ryugu is consistent with that of highly aqueously altered CI chondrites [1]. One of the primary goals of the sand team is to understand how the surfaces of small (< 200 µm) grains from Ryugu are modified by space weathering, a combination of processes including the solar wind, micrometeoroid impacts and galactic cosmic rays [3]. Space weathering processes affect all airless worlds, and result in physical and chemical modifications of mineral exteriors and consequently changes the reflectance spectra obtained from asteroid surfaces.

Intriguingly, reflectance spectra of returned grains do not match the spectra acquired from Ryugu by the Hayabusa2 probe [1,2]. In addition, preliminary observations of fine grained Ryugu particles from chamber A and C of the Hayabusa2 sample canister indicate that space weathered grains are rare ~6 % [4]. Given that over half of Itokawa grains exhibit surface modification from space weathering [5] the scarcity of space weathering features in Ryugu grains is puzzling.

The low abundance of space weathered grains may be because only grains at the very surface of Ryugu are altered in such a way and the kinetic sampling mechanism would result in the majority of sampled material to have come from deeper parts of the regolith. However, regolith gardening processes are likely to result in overturn of the surface bringing up fresh material from depth and burying space weathered grains. Thus, even a sample exclusively from beneath the surface of the asteroid should also contain space weathered grains. An alternative explanation is that grain surfaces have been eroded either by natural processes on the asteroid or by the sample capture mechanism destroying any surficial space weathering features. Here we look for evidence of abrasive processes on Ryugu grain surfaces.

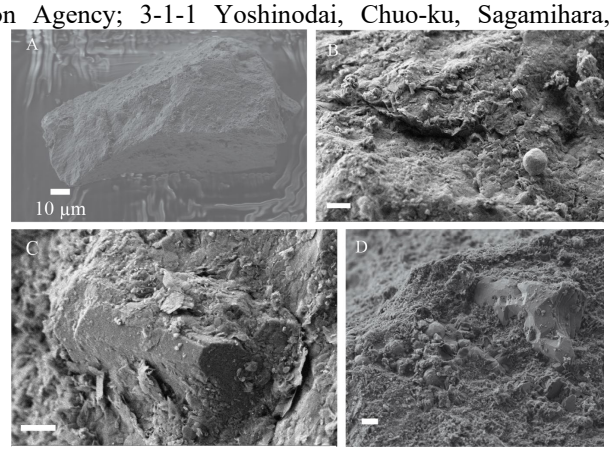

Figure 1. Low kV SEM images of two grains of Ryugu showing rounded grain and mineral edges and nano-topography of competent mineral grains relative to the weaker matrix. White scale bars are 1 um unless stated.

Methods: Two <100 µm Ryugu grains were mounted on sticky Cu tape using a micromanipulator. The surface morphology of the grain was imaged using secondary electron (SE) and backscattered electron (BSE) detectors in a scanning electron microscope (SEM) at the University of Glasgow. A low accelerating voltage of 2 kV was used for high resolution surface imaging. The grain was then sputter coated with a 200 nm thick layer of Cr to protect the grain surface and act as a fiducial layer in subsequent transmission electron microscopy (TEM) and atom

probe tomography (APT) measurements [6]. Regions of interest were extracted for APT from the grain surface using a Ga-focused ion beam (FIB) at the University of Glasgow following the approach of Daly et al., [6]. Electron transparent lamellae were extracted for TEM from specific regions of interest identified in the low kV SEM imaging following the approach of Lee et al., [7]. TEM and APT analyses are ongoing with further APT measurements planned.

Results: The two grains studied have irregular surfaces with angular-sub-rounded edges (Fig 1). The grains are predominantly comprised of a fine-grained phyllosilicate matrix with embedded euhedral sulphide, magnetite, and carbonate grains. TEM and low kV SEM imaging reveal no evidence of space weathering (neither amorphization by solar wind nor melt layers from micrometeoroid impacts [3]) on either grain's surface. In the same way imaging of the grain's surfaces reveal: phyllosilicate crystals exhibit a preferred alignment forming a foliation texture; oxide, sulphide, and carbonate grains exhibit topography relative to the matrix and protrude from the grain's surface; the matrix curves upwards and onlaps onto the edge of the protruding grains (Fig. 1). In addition, some magnetite and carbonate crystal facets are slightly rounded where the crystal is exposed at the grain's surface (Fig. 1). In particular, spherulitic magnetite needles are rounded where present at the grain's surface and sharp below the surface (Fig. 2).

Discussion: The nano-topography of competent minerals like magnetite relative to the soft weak phyllosilicate matrix, the rounding of crystal edges at grain surfaces and the sub-rounded surface of the grains themselves are consistent with abrasion of the grains and preferential erosion of the weaker matrix.

There are two plausible explanations for these surface features: 1) Fresh surface generation and grain fracturing during sample collection, 2) natural abrasion and erosion of the grain's surfaces on Ryugu.

The samples were recovered from the regolith of Ryugu by firing a Ta projectile at the asteroid's surface and ejecting grains into the sample container. In this brief high-energy environment it is likely that grains will fragment and new fresh surfaces will be produced. However, this process would not completely destroy space weathered surfaces on the majority of grains and may produce many smaller grains that exhibit space weathering on one or more faces from the fragmentation of larger grains.

Natural abrasion of grains in Ryugu's regolith during impacts and regolith gardening would slowly remove the grain's outer surface preferentially eroding phyllosilicate matrix, rounding the grain's and exposed competent mineral's edges. This abrasive process would also serve to destroy any space weathering features that were originally present on the grain from any time spent previously at the surface of Ryugu.

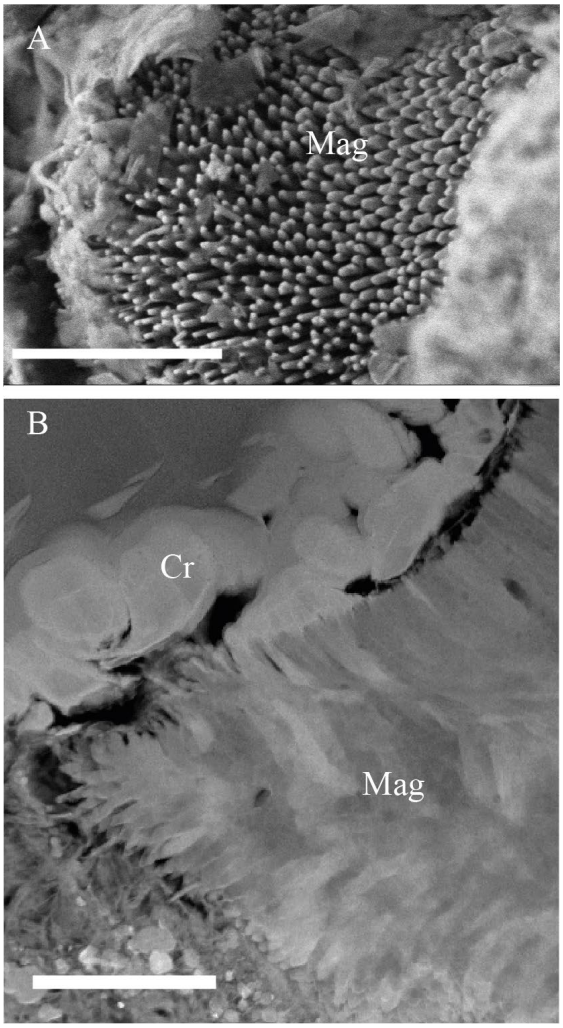

Figure 2. A) Low KeV SEM and B) HAADF STEM image of the surface morphology of a spherulitic magnetite grain in Ryugu showing rounded magnetite needles at the grain surface. White scale bar is 1 µm.

The preferential removal of weak material by abrasion may also explain observations of solar wind irradiated olivine grains in Ryugu situated next to phyllosilicates that exhibit no evidence of space weathering [4]. In conclusion, abrasion of the weak incompetent grain surfaces of Ryugu in the regolith of the asteroid may explain the scarcity of space weathered surfaces on collected Ryugu regolith grains.

References: [1] Yada T., et al., (2021) *Nat. Astro.* 1-7. [2] Kitazato K., et al., (2019) *Sci.* 364, 272-275. [3] Chapman C.R., (2004), *Ann. Rev. Earth Planet. Sci.*, 23, 539-567. [4] Noguchi T., et al., (submitted) *Sci.* [5] Noguchi T., (2011) *Sci.* 333, 1121-1125. [6] Daly L., et al., (2021) *Nat. Astro.* [7] Lee, M.R., et al., (2003). *Mineralogic. Mag.* 67(3), 581-592.