EXPOSURE CONDITIONS OF SAMPLES COLLECTED ON RYUGU'S TWO TOUCHDOWN SITES DETERMINED BY COSMOGENIC NUCLIDES 10BE AND 26AL.

K. Nishiizumi[1], M. W. Caffee[2], K. Nagao[3], J. Masarik[4], R. Okazaki[5], H. Yurimoto[6], T. Nakamura[7], T. Noguchi[8], H. Naraoka[5], H. Yabuta[9], K. Sakamoto[10], S. Tachiban[10,11], S. Watanabe[10,12], Y. Tsuda[10], and Hayabusa2 Initial Analysis Volatile Team, [1]Space Sci. Lab., Univ. of California, Berkeley, CA 94720-7450, USA., kuni@berkeley.edu), [2]Dept. of Phys. & Astro., Purdue Univ., West Lafayette, IN, USA., [3]KOPRI, Incheon, Korea, [4]Comenius Univ., Slovakia, [5]Kyushu Univ., Fukuoka, Japan, [6]Hokkaido Univ., [7]Tohoku Univ., [8]Kyoto Univ., [9]Hiroshima Univ., [10]ISAS/JAXA, [11]Univ. of Tokyo, [12]Nagoya Univ.

Introduction: Hayabusa2 arrived at the C-type asteroid 162173 Ryugu in June 2018, and successfully collected surface samples from two sampling sites, returning ~5.4 g of samples to Earth on December 6, 2020. Surface samples stored in Chamber A were collected by the 1st touchdown (TD) on Ryugu's surface on February 21, 2019. A crater (diameter of ~14 m) on Ryugu's surface was made using a collision device - denoted "Small Carry-on Impactor (SCI)" - on April 5, 2019 [1]. Samples in Chamber C were collected proximal to this artificial crater and are possibly ejecta from the north side of the crater by the 2nd TD on July 11, 2019 [2].

Our studies are based on the measurement of those nuclides produced in asteroidal surface materials by cosmic rays - both solar (SCR) and galactic cosmic rays (GCR). Cosmic-ray-produced (cosmogenic) nuclides are used to determine the duration and nature of the exposure of materials to energetic particles. Our goals are to understand both the fundamental processes on the asteroidal surface and the evolutionary history of its surface materials. With this information we hope to better understand asteroid-meteoroid evolutionary dynamics. For Hayabusa2 samples, there are several specific questions we aim to address: (1) are the Chamber C samples, collected during the 2nd TD ejecta deposits from the artificial crater, (2) if so, what is the original depth of each recovered sample in the Ryugu regolith, and (3) what is the surface exposure time, mixing rate, and erosion/escape rate of Ryugu's surface? To answer these questions, we were allocated and received 2 particles from Chamber A (A0105-19 and -20) and 6 particles from Chamber C (C0106-09, -10, -11, -12, C0002-V01, and -V02) for measurements of cosmogenic radionuclides and noble gases. Each sample is several hundred µm in size.

Experimental Methods: Each sample was gently crushed by a mortar and pestle made from sapphire and then divided into two fractions, one fraction for cosmogenic radionuclides and one for noble gases measurement. The samples were individually transferred to a small Al weighing boat and the masses were determined using an ultra-micro balance. For cosmogenic radionuclide analysis, the sample was transferred to a Teflon bomb from the Al boat and dissolved with a few drops of HF-HNO_3 mixture in the presence of clean Be, Al, Cl, and Mn carriers. After Cl was separated as AgCl, a small analysis aliquot was taken for chemical analysis by ICP-OES. Beryllium, Al, and Ca were separated by ion chromatography, using 1 mL anion and cation ion exchange columns, and purified for accelerator mass spectrometry (AMS) measurements. To serve as a baseline comparison, three grains of the Nogoya CM2 chondrite were analyzed using the same protocols.

Beryllium-10 ($t_{1/2}$ = 1.36 x 10^6 yr) and preliminary ^{26}Al (7.05 x 10^5 yr) AMS analyses were performed at PRIME Lab, Purdue University [3] and results were shown in Table 1. Analyses of ^{36}Cl (3.01 x 10^5 yr) and ^{41}Ca (1.04 x 10^5 yr) as well as noble gases will be done in the near future.

Results and Discussion: To validate our procedures we measured the ^{10}Be and ^{26}Al concentrations in 3 individual grains from Nogoya. The ^{10}Be concentrations from the Nogoya grains are nearly identical and in good agreement with our previous measurement of 2.22 ± 0.10 dpm/kg (unpublished) and 2.44 ± 0.29 dpm/kg [4]. The measurements reported here used ~3 orders of magnitude less sample mass than the measurements made years ago and have essentially the same uncertainties. For Ryugu, we were able to obtain high quality ^{10}Be measurements using a ~100 µg sample. The preliminary ^{26}Al AMS results scattered somewhat due to interference by an impurity.

The surface of Ryugu is bombarded by cosmic rays in a 2π exposure geometry, similar to surface of the Moon. On the Moon, the production profile of cosmogenic radionuclides, ^{10}Be, ^{26}Al, ^{36}Cl, and ^{41}Ca, from the surface to a depth of over 400 g/cm^2 is well established by measurements of those nuclides in the Apollo 15 drill core and 15008/7 core [e.g., 5, 6, 7]. For this work, we performed new calculations using the MCNP Code System [8] to obtain GCR production rates of cosmogenic radionuclides and noble gases for a body having a 2π geometry with Ryugu's chemical compositions [e.g., 9]. The calculated ^{10}Be and ^{26}Al depth profiles of Ryugu are shown in Fig. 1 and 2; the dashed lines indicate ±5% uncertainties. The measured ^{10}Be and ^{26}Al concentrations from our Ryugu samples are also shown; the intersection of the measured activities with the calculated curves - shown by the rectangles - indicates the irradiation depths of the samples on Ryugu. SCR produced ^{26}Al at the surface is also shown in Fig. 2.

Table 1. Cosmogenic nuclide ^{10}Be and ^{26}Al concentrations in Ryugu samples and Nogoya CM2 chondrite.

Sample	Mass (µg)	^{10}Be (dpm/kg)	^{26}Al* (dpm/kg)
A0105-19	242.9	12.76±0.37	27.1±1.1
A0105-20	206.1	12.75±0.29	33.3±1.8
C0106-09	122.8	7.10±0.30	23.3±1.4
C0106-10	154.3	7.48±0.26	25.7±1.3
C0106-11	189.8	7.21±0.43	25.5±1.2
C0106-12	959.8	7.36±0.33	23.8±0.7
C0002-V01	45.3	8.29±0.95	24.9±1.9
C0002-V02	11.1	7.87±1.80	21.9±5.1
Nogoya CM2	459.4	2.09±0.13	-
Nogoya CM2	343.7	2.12±0.09	7.7±0.5
Nogoya CM2	204.9	2.00±0.13	9.1±0.6#

*preliminary results; #high interference

The ^{10}Be concentrations in all Chamber C samples are all the same but are lower than those of the Chamber A samples. The sampling location of the 2nd TD is close to the "ejecta ray 3" described by [1]. If the Chamber C samples were shielded during their exposure to cosmic rays and were part of the ejecta deposits from the artificial crater created by the SCI impact, we can calculate the depth at which they were irradiated.

Although the depth estimations from ^{10}Be and ^{26}Al overlap (Fig. 1 and 2), those based on ^{26}Al are shifted toward shallow depths. One possible explanation is undersaturation of ^{10}Be due to short exposure age of Ryugu surface. Using the ^{10}Be concentration in A0105 together with the maximum ^{10}Be production rate we obtain a minimum ^{10}Be exposure age of 4.1 Myr. The ^{26}Al concentration in A0105-19 does not indicate much SCR production. For a minimum exposure age of 4.1 Myr, we estimate sampling depths of 10-15 g/cm^2 for A0105-19 and 5-12 for A0105-20. Chamber C samples were ejected from a depth of 90-160 g/cm^2 from Ryugu for C0002 and 125-150 for C0106. This depth corresponds to 0.7-1.3 m, assuming the regolith density is the same as Ryugu's bulk density of 1.2 g/cm^3 [10]. Using a digital elevation map (DEM) the depth of the crater floor from the initial surfaces was estimated to be 1.7 m [1]. Our data indicates that all Chamber C samples which we measured were ejected from the lower portions of the crater.

Based on our depth estimation and new production rate calculation, we obtained ^{21}Ne exposure age of 4.2 Myr for bulk ^{21}Ne measurements of Ryugu samples [11]. This age is in good agreement of the minimum ^{10}Be age of 4.1 Myr, implying that the surface of Ryugu was exposed just over 4 Myr ago and that the surface has been quiescent since then. Future measurements of neutron captured ^{36}Cl and ^{41}Ca as well as noble gases in aliquot grains will further constrain the exposure conditions and depth reconstruction.

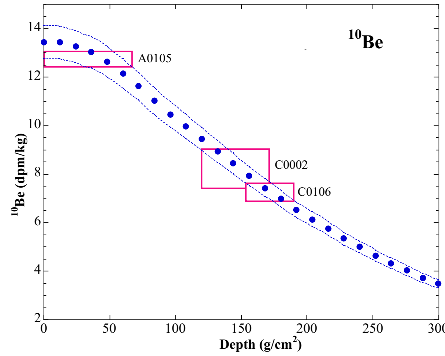

Fig. 1. Calculated ^{10}Be production profile on Ryugu and possible exposure depths of Ryugu samples.

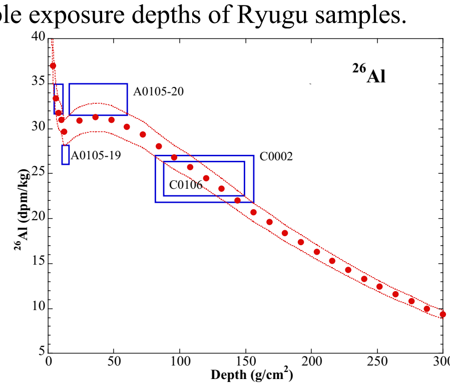

Fig. 2. Calculated ^{26}Al production profile on Ryugu and possible exposure depths of Ryugu samples.

Acknowledgments: We thank the Hayabusa2 project and initial analysis teams, especially the Hayabusa2 curation members. Z. Nett and K. C. Welten aided with laboratory tasks. Nogoya was obtained from the Field Museum of Natural History. This work was supported by NASA's LARS program.

References: [1] Arakawa M. *et al.* (2020) *Science 368,* 67-71. [2] Tsuda Y. *et al.* (2020) *Acta Astronautica 171,* 42-54. [3] Sharma P. *et al.* (2000) *NIM B 172,* 112-123. [4] Moniot R. K. *et al.* (1983) *GCA 47,* 1887-1895. [5] Nishiizumi K. *et al.* (1984) *EPSL 70,* 157-163. [6] Nishiizumi K. *et al.* (1984) *EPSL 70,* 164-168. [7] Nishiizumi K. and Caffee M. W. (2019) *Meteor. Planet. Sci. 54,* 6087 [8] Masarik J. and Reedy R. C. (1994) *GCA 58,* 5307-5317. [9] Yokoyama T. *et al.* (2022) *Science submitted.* [10] Watanabe S. *et al.* (2019) *Science 364,* 268-272. [11] Okazaki R. *et al.* (2022) *Science submitted.*