Cosmogenic Radionuclide Records of Hayabusa Aggregate and Particle Samples

Kunihiko Nishiizumi[1], Marc W. Caffee[2], Keisuke Nagao[3], Kees C. Welten[1], Jozef Masarik[4]
[1]Space Sciences Laboratory, Univ. of California, Berkeley, CA 94720-7450, USA., [2]Dept. of Physics & Astronomy, Purdue Univ., West Lafayette, IN 47907-2036, USA., [3]Div. of Polar Earth-System Sci., KOPRI, Incheon 21990, Korea, [4]Faculty of Math. & Physics, Comenius Univ., SK-842 15, Bratislava, Slovakia

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 material to Earth on December 6, 2020. The 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]. The samples in Chamber C were collected proximal to the north side of this artificial crater by the 2nd TD on July 11, 2019 and possibly contain ejecta from the crater [2]. Distance between TD1 and TD2 is ~820 m.

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. 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 particles from Chamber A and Chamber C for measurements of cosmogenic radionuclides and noble gases as a part of initial analysis of Ryugu. We have measured cosmogenic ^{10}Be ($t_{1/2}$ = 1.36 x 10^6 yr), ^{26}Al (7.05 x 10^5 yr), ^{36}Cl (3.01 x 10^5 yr), and stable noble gases in those samples [3-5]. Based on noble gas analysis of ~2 dozen Ryugu samples, we found that cosmic ray exposure (CRE) ages of Chamber A (surface) samples, A0105, range from 2.9 to 7.5 Myr and Chamber C (sub-surface) samples, C0106, range from 1.6 to 5.8 Myr based on ^{21}Ne concentrations [3, 6]. We also found that four C0106 particles were exposed at depth of ~50, 110, 130, and 145 g/cm^2 respectively and had different CRE ages based on cosmogenic nuclide measurements [3, 5].

To further study of the exposure condition of Ryugu surface materials, we obtained one grain, A0130, from Chamber A and 3 grains, C0012, 0162, and 0182 from Chamber C. In addition, we obtained two aggregate samples, A0221 and C0212, in order to determine average exposure ages and depths for both Chamber A and C samples. As shown above, each grain had different exposure histories (age and depth). This is similar to what we found for exposure histories of individual grains of lunar core samples. While cosmogenic radionuclides of lunar bulk soils show smooth depth profiles, the measured radionuclide concentrations of individual rock fragments at the same depth show deviations from the smooth depth profiles [7].

Each sample was gently crushed by a mortar and pestle made from sapphire and then divided into two fractions, one fraction for cosmogenic radionuclides (this work) and one for noble gases measurements [8]. 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 and dissolved with HF and HNO_3 mixture in the presence of Be and Cl carriers. After Cl was separated as AgCl for ^{36}Cl measurements, a small analysis aliquot was taken for chemical analysis by ICP-OES. Beryllium, Al, and Mn were separated by ion chromatography, using anion and cation ion exchange columns, and Be and Al were purified for AMS measurements. To serve as a baseline comparison, a few grains of the Orgueil CI chondrite were analyzed using the same protocols. Beryllium-10 and ^{26}Al AMS analyses were performed at PRIME Lab, Purdue University [9]. Measured isotopic ratios were normalized by AMS standards [10, 11] and converted to radionuclide concentrations (dpm/kg).

Chemical compositions in Ryugu samples measured by ICP-OES are shown in Table 1. Since sample sizes are slightly larger than previous Ryugu initial analysis, data show less scatter. Bulk chemical compositions of samples from TD1 and TD2 determined using ICP-MS [12] are also shown in the table. Our analysis of A0221 and C0212 are in good agreement with analysis of TD1 and TD2 samples determined by [12]. Noticeably, both our two samples and published analysis of TD1 and TD2 samples [12] were obtained from aggregate samples and not individual grains. Although [12] concluded that are no systematic differences in chemical composition between the samples from TD1 and TD2 sites, our limited measurements indicate that Ca is slightly higher and Fe is lower in TD1 samples than that of TD2.

Table 1. Chemical compositions in Ryugu samples and Orgueil CI chondrite.

Sample	Mg (%)	Al (%)	K (ppm)	Ca (%)	Ti (ppm)	Mn (ppm)	Fe (%)	Co (ppm)	Ni (%)
A0130	9.32	0.94	720	1.45	520	1990	18.39	540	1.13
A0221	10.84	0.90	520	1.69	530	3040	19.76	560	1.20
C0012	10.54	0.91	600	1.09	460	2020	21.15	600	1.31
C0012	10.74	0.91	580	1.18	490	2340	20.11	560	1.21
C0162	10.81	0.90	570	1.08	570	2120	20.75	560	1.26
C0182	9.36	0.84	400	0.95	510	1510	18.63	520	1.13
C0212	10.77	0.98	550	1.18	510	2370	20.53	590	1.26
Ryugu (TD1)*	10.69	0.86	520	1.63	480	3000	19.49	550	1.18
Ryugu (TD2)*	10.42	0.90	600	1.37	470	2490	20.22	590	1.22
Orgueil CI	7.37	0.64	440	0.60	340	1380	14.23	400	1.18
Orgueil CI#	9.63	0.60	530	0.76	-	1680	17.76	540	1.04

*[12], #Previous measurement (unpublishd 2003)

Cosmogenic nuclide ^{10}Be and ^{26}Al concentrations in Ryugu samples are shown in Table 2 along with that of Orgueil CI chondrite. Using the MCNP Code System [13], we calculated the GCR production rates of ^{10}Be and ^{26}Al by spallation reactions for a body having a 2π geometry with Ryugu's chemical composition [12]. Based on the comparison of the observed radionuclide concentrations with model calculated ^{10}Be and ^{26}Al production rate depth profiles, assuming the radionuclide concentrations in Ryugu are saturated, we obtained the first order estimation of exposure depth of each sample and shown in Table 2. Based on those depths we calculated ^{21}Ne production rates and calculated ^{21}Ne CRE ages in each sample [8]. The calculated exposure depths and CRE ages of each grain obtained by TD2 scatter, in similar fashion as previous works [3, 5]. The preliminary estimation of average exposure depth of aggregate sample A0221 is somewhat deeper than those of each grain obtained from TD1. The depth range of aggregate sample C0212 collected by TD2 is estimated to be 110 - 140 g/cm^2 based on ^{10}Be concentration. The ^{26}Al concentration of C0212 indicates much shallow depth of 10 – 90 g/cm^2. One possible explanation is that C0212 contains a small amount of surface material that contains high SCR produced ^{26}Al. The measurement of thermal neutron-capture produced ^{41}Ca ($t_{1/2}$ = 1.0 x 10^5 yr) – in progress - is critical to further constrain the exposure depth of each sample.

Table 2. Cosmogenic nuclide ^{10}Be and ^{26}Al concentrations in Ryugu samples and Orgueil CI chondrite.

Sample	Mass (mg)	^{10}Be (dpm/kg)	^{26}Al (dpm/kg)	Depth (g/cm^2)
A0130	0.676	9.94 ± 0.29	29.2 ± 1.3	10 - 70
A0221	10.718	11.23 ± 0.10	27.4 ± 0.6	70 - 100
C0012	4.200	7.50 ± 0.10	24.3 ± 0.8	90 - 140
C0012	7.274	7.43 ± 0.15	23.3 ± 0.8	110 - 150
C0162	1.531	7.58 ± 0.21	24.6 ± 1.0	95 - 145
C0182	0.983	6.28 ± 0.15	25.3 ± 1.3	85 - 135
C0212	8.406	9.06 ± 0.09	29.3 ± 0.6	110 -140
Orgueil CI	6.000	14.91 ± 0.31	35.9 ± 1.2	-
Orgueil CI#	52.60	21.19 ± 0.36	40.4 ± 0.8	-

#Previous measurement (unpublished 2003)

Acknowledgments: We thank Hayabusa2 project team and Hayabusa2 curation members. Orgueil was obtained from MNHN-Paris. 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] Nagao K. et al. (2022) Meteor. Planet. Sci. 57, A337 #6320. [4] Nishiizumi K. et al. (2022) Lunar Planet. Sci. LIII, #1777. [5] Nishiizumi K. et al. (2022) Hayabusa Symposium 2022. S21-08. [6] Okazaki R. et al. (2022) Science. 379, eabo0431. [7] Nishiizumi K. et al. (1985) Lunar Planet. Sci. XVI, 620-621. [8] Nagao K. et al. (2023) Hayabusa Symposium 2023 (this meeting). [9] Sharma P. et al. (2000) Nucl. Instrum. Methods Phys. Res. B 172, 112-123. [10] Nishiizumi K. (2004) Nucl. Instrum. Methods Phys. Res. B223-224, 388-392. [11] Nishiizumi K. et al. (2007) Nucl. Instrum. Methods Phys. Res. B258, 403-413. [12] Yokoyama T. et al. (2022) Science. 379, eabn7850. [13] Masarik J. and Reedy R. C. (1994) Geochim. Cosmochim. Acta. 58, 5307-5317.