Exposure Conditions of Samples Collected on Ryugu's Two Touchdown Sites Determined by Cosmogenic Nuclides

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Hayabusa2 arrived at the C-type asteroid 162173 Ryugu in Jun. 2018, and successfully collected surface samples from two sampling sites, returning ~5.4 g of samples to Earth on Dec. 6, 2020. Surface samples stored in Chamber A were collected by the 1st touchdown (TD) on Ryugu's surface on Feb. 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 Apr. 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 Jul. 11, 2019 [2].

Our studies are based on the measurement of those nuclides produced in asteroidal surface materials by cosmic rays - both solar and galactic cosmic rays. 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. They are also key to understanding the history of Ryugu's surface and 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 touchdown 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 3 particles from Chamber C (C0106-09, -10, and -11) for measurements of cosmogenic radionuclides and noble gases. Each sample is several hundred µm in size.

We transferred the individual grains to acid cleaned sapphire containers, with ~2 mm diameter hole, using a vacuum tweezer at the JAXA curation facility. The five samples were hand carried to the Space Sciences Laboratory (SSL), University of California, Berkeley. 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. 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 (Table 1). Beryllium and Al 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 ($t_{1/2} = 1.36 \times 10^6$ yr) AMS analysis was performed at PRIME lab, Purdue University [3] and result was shown in Table 1. Analyses of ^{26}Al (7.05×10^5 yr) and ^{36}Cl (3.01×10^5 yr) as well as noble gases will be done in the near future.

Table 1. Chemical compositions and cosmogenic nuclide ^{10}Be concentration in Hayabusa2 samples and Nogoya CM2 chondrite.

Sample	Mass (mg)	Mg (%)	Ti (ppm)	Mn (ppm)	Fe (%)	Co (ppm)	Ni (%)	^{10}Be (dpm/kg)
Hayabusa2 A0105-19	0.2429	8.18	470	-	17.6	590	1.00	12.76 ± 0.37
Hayabusa2 A0105-20	0.2061	8.41	720	(2010)	18.0	460	1.03	12.75 ± 0.29
Hayabusa2 C0106-09	0.1228	6.05	690	(2090)	19.5	580	1.36	7.10 ± 0.30
Hayabusa2 C0106-10	0.1543	7.97	490	-	21.0	440	1.43	7.48 ± 0.26
Hayabusa2 C0106-11	0.1898	8.45	450	-	21.5	430	1.29	7.21 ± 0.43
Nogoya CM2	0.4594	9.96	480	1800	20.0	580	1.18	2.09 ± 0.13
Nogoya CM2	0.3437	9.61	480	1680	19.9	540	1.17	2.12 ± 0.09
Nogoya CM2	0.2049	11.27	410	1710	19.8	380	1.20	2.00 ± 0.13

Mn concentrations in parentheses are large uncertainty.

Although the chemical compositions of all 5 Hayabusa2 particles are very similar, the concentrations of Fe and Ni of the 3 Chamber C samples are ~10 % higher than that of Chamber A samples. Our measurements of the 5 Hayabusa2 samples indicate that the chemical composition of Ryugu is closer to those of CI or CM carbonaceous chondrites, rather than CV or CO.

To validate our procedures we measured the ^{10}Be concentrations in 3 individual grains from Nogoya. The concentrations from the Nogoya grains are nearly identical and in good agreement with our previous measurement of 2.22 ± 0.10 dpm/kg. The measurements reported here used ~3 orders of magnitude less sample mass than the measurements made years ago, have essentially the same uncertainties. For Ryugu, we were able to obtain high quality ^{10}Be measurements using ~100 μg sample.

The surface of Ryugu is bombarded by cosmic ray in a 2π exposure geometry, similar to surface of the Moon. On the Moon, the production profile of cosmogenic ^{10}Be from the surface to a depth of over 400 g/cm^2 is well established by measurements of ^{10}Be concentrations in the Apollo 15 drill core and 15008/7 core, shown in Fig. 1 [4, 5]. The ^{10}Be concentrations in A0105-19 and -20 are equivalent to the saturation value measured at the surface of the Moon. The simplest scenario is that both A0105-19 and -20 were collected from a depth of 0-30 g/cm^2 on Ryugu. Both samples have been continuously exposed to cosmic ray at a similar depth for more than several Myr. A more precise depth can be obtained by measurement of ^{26}Al, which has a different production profile than ^{10}Be, and is also produced by solar cosmic ray at shallow depth (≤ several g/cm^2). Since the ^{10}Be activity is saturated, the total exposure age must be obtained by measurements of longer half-life (3.7 x 10^6 yr) ^{53}Mn and cosmogenic noble gases. Beryllium-10 concentrations in three Chamber C samples are lower than that of the Chamber A samples but nearly the same as each other. The sampling location of the 2nd TD is close to the "ejecta ray 3" described by [1]. Assuming that the Chamber C samples were shielded during their exposure to cosmic rays and then were incorporated into the ejecta deposits from the artificial crater by SCI impact, we can calculate the depth at which they were exposed. All three Chamber C samples were ejected from a depth of 150 – 180 g/cm^2 from Ryugu (see Fig. 1). This depth corresponds to 1.3 – 1.5 m, assuming the regolith density is the same as Ryugu's bulk density of 1.2 g/cm^3 [6]. Since the depth of the crater floor from the initial surfaces was determined 1.7 m by a digital elevation map (DEM) [1], three Chamber C samples were ejected from near bottom of the crater. Alternatively, if we assume these were not ejecta, but were resident on the surface, the lower ^{10}Be activities would indicate that these grains have shorter exposure ages, ~ 1 Myr. Based on their location near the artificial crater ejecta ray, we consider this scenario unlikely. Aluminum-26 and ^{36}Cl measurements of these samples will further constrain ejection depth and condition.

For our work, we obtained 5 similar sized, ~0.5 – 1 mm, grains. We don't know whether the sizes we observe now are representative of the grain's original sizes on Ryugu's surface; it is possible that they were broken during the collection process or during sample handling. We are certain though that independent of their original size on Ryugu, the three Chamber C grains were exposed to cosmic rays at the same depth. These grains had ample ^{10}Be for measurement, ^{10}Be measurements are possible in smaller grain sizes. A logical next step would be the measurement of ^{10}Be in grains of different sizes to investigate whether any possible association of grain size and ejection depth.

Based on saturated ^{10}Be in surface samples and from ejecta samples we conclude that the surface of Ryugu has been exposed to cosmic rays for more than several Myr and that the upper 1 - 2 m of regolith have been relatively undisturbed for more than several Myr. Our observation shows that the surface of Ryugu is more stable than the surface of Itokawa and the estimation by geomorphological indicators [7]. Additional cosmogenic nuclide measurements, especially stable noble gases, will allow a detailed understanding of the surface evolution of Ryugu.

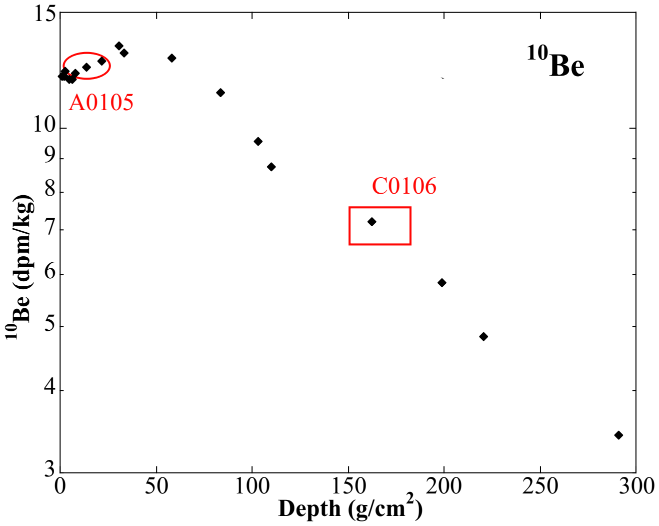

Figure 1. The depth profile of ^{10}Be production on the Moon. Black diamonds indicate ^{10}Be concentration vs. depth on the Moon measured in undisturbed Apollo 15 drill core and 15008/7 core [4, 5]. Observed ^{10}Be concentrations in Hayabusa2 samples are plot at estimate depths on Ryugu and marked red circle (A0105) and square (C0106).

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