RADIOGENIC, NUCLEOSYNTHETIC, AND STABLE ISOTOPE VARIATIONS IN STRONTIUM IN SAMPLES RETURNED BY HAYABUSA2 OF Cb-TYPE ASTEROID RYUGU.

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Introduction: In December of 2020, JAXA's Hayabusa2 mission returned a total of 5.4 g of samples from the Cb-type near-Earth asteroid Ryugu [1,2]. Petrologic, geochemical, and isotopic analyses conducted thus far indicate that these returned Ryugu samples are most closely related to carbonaceous chondrites of the CI (Ivuna-like) group [3-8].

The refractory lithophile element strontium has four stable isotopes, ^{84}Sr (0.56%), ^{86}Sr (9.86%), ^{87}Sr (7.00%) and ^{88}Sr (82.58%) produced by distinct nucleosynthetic processes. While ^{84}Sr is a *p*-nuclide, ^{86}Sr and ^{87}Sr are produced by the *s*-process (~60% by the main *s*-process and the rest by the weak *s*-process); ~70% of ^{88}Sr is produced by the main *s*-process and the rest by the *r*-process. Anomalies in these isotopes can be used to trace the delivery of materials from distinct nucleosynthetic sources to the solar protoplanetary disk, and to identify potential genetic relationships between Solar System materials (e.g., [9,10]). Moreover, ^{87}Sr is produced by the decay of the long-lived radioactive isotope ^{87}Rb; the Rb-Sr isotope system has been applied widely as a chronometer and geochemical tracer in not just terrestrial but also meteoritic studies (e.g., [11-13]). Finally, investigation of mass-dependent variations in the stable Sr isotopes can provide insights into nebular and parent body processes (e.g., [14-16]).

Samples and Methods: In this study, we determined the Sr isotope compositions of the carbonaceous chondrites Allende (CV3), Murchison (CM2), Orgueil (CI), Tarda (C2-ung), and Tagish Lake (C2-ung), and three Ryugu samples, A0106 and A0106-A0107 from Chamber A (surface samples from first touchdown) and C0108 from Chamber C (surface and subsurface samples from second touchdown).

Sample processing and elemental separation chemistry were conducted at Tokyo Institute of Technology using methods described by [4]. A ~8% aliquot of each Ryugu sample solution was removed for determining elemental abundances using a X-series 2 Thermo Fisher Scientific quadrupole ICP-MS at Tokyo Tech; another ~2% aliquot was saved for precise determination of Rb and Sr abundances by the isotope dilution method. An approximately 80% aliquot of the sample solution was processed for multi-elemental isotopic analyses after multi-step chemical separation procedures [4]; the overall Sr recovery from these procedures was >90%.

Sr isotope analyses with TIMS. The Sr isotopic compositions of the Ryugu samples (~50 ng of A0106, and ~120 ng each of A0106-A0107 and C0108) and the carbonaceous chondrites (50-140 ng) were measured with a Triton-Plus TIMS at Tokyo Tech using methods described in [17]; errors are reported similarly to [17]. The $^{87}Sr/^{86}Sr$ ratios reported here are re-normalized to a NIST SRM987 value of 0.71025. The mass-independent variations in the $^{84}Sr/^{86}Sr$ ratio are reported as $\mu^{84}Sr$ notation (relative deviation from the SRM987 standard in parts per 10^6).

Sr isotope analyses with MC-ICPMS. The Sr isotopic composition of another ~100 ng aliquot of purified Sr from the A0106-A0107 Ryugu sample was analyzed with the Thermo Neptune XT in dry plasma mode (using an ARIDUS III desolvating nebulizer) at the Isotope Cosmochemistry and Geochronology Laboratory (ICGL) at Arizona State University. The mass spectrometry method for these analyses was described recently in [18]; errors were calculated similarly to [17]. Analyses of the A0106-A0107 Ryugu sample and bracketing standard (NIST SRM987) were conducted with a Sr concentration of 75 ppb. The $^{87}Sr/^{86}Sr$ ratios are reported relative to a SRM987 value of 0.71025. Mass-independent variations in the $^{84}Sr/^{86}Sr$ ratio are reported as $\mu^{84}Sr$ notation. Mass-dependent variations in the $^{88}Sr/^{86}Sr$ ratio are reported as $\delta^{88}Sr$ notation (relative deviation from the SRM987 standard in parts per 10^3).

Results and Discussion: *Rb-Sr isotope systematics.* The $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios of the carbonaceous chondrites measured here via TIMS generally fall within the range of values reported previously for the carbonaceous chondrites ([10,13,17] and references therein); some variability among analyses of the same samples in this and other studies may be the result of heterogeneities at sampling scales.

The $^{87}Sr/^{86}Sr$ ratios of the Ryugu samples measured via TIMS are as follows: 0.7286796±30, 0.7351541±35, and 0.7423592±35 for A0106, A0106-A0107, and C0108, respectively. The $^{87}Sr/^{86}Sr$ ratio of the A0106-A0107 Ryugu sample measured via MC-ICPMS is 0.7351562±55, which agrees well with that determined here via TIMS. The corresponding $^{87}Rb/^{86}Sr$ ratios for these samples are 0.3778, 0.5645, and 0.6681, respectively. The range of $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios in these Ryugu samples suggests significant heterogeneity

at the size scale of these samples (i.e., 20-25 mg). Given that the Ryugu samples appear to lack components such as chondrules and calcium-aluminum-rich inclusions (CAIs), but contain significant carbonates [3] (some of which have relatively high Sr abundances [19]), it is possible this heterogeneity in ^{87}Rb-^{87}Sr isotope systematics is the result of heterogeneity in the distribution of this phase. This is further supported by the correlation of Rb/Sr ratios with Fe/Mn and Mn/Cr ratios [20].

On the ^{87}Rb-^{87}Sr isochron diagram, ordinary chondrites, enstatite chondrites, and carbonaceous chondrites scatter along a ~4.6 Ga isochron ([13] and references therein). The Rb-Sr data for the Ryugu samples also scatter along this line, with isotopic and elemental ratios most similar to CI and CM chondrites.

Nucleosynthetic anomalies. The μ^{84}Sr anomalies measured via TIMS for the carbonaceous chondrites range from 0±30 (Orgueil) to 77±30 (Murchison). All measured values agree with previously reported ones [10,17]. The μ^{84}Sr values for the Ryugu samples are as follows: 13±28, 90±30, and 30±30 for A0106, A0106-A0107, and C0108, respectively. While the μ^{84}Sr anomalies in the two Ryugu samples from the two touchdown locations (A0106-A0107 and C0108) are just barely within agreement, those in the two samples from the same location (A0106 and A0106-A0107) are resolvably distinct. The μ^{84}Sr value measured via MC-ICPMS for A0106-A0107 has a large uncertainty (100±120), but agrees with values determined via TIMS.

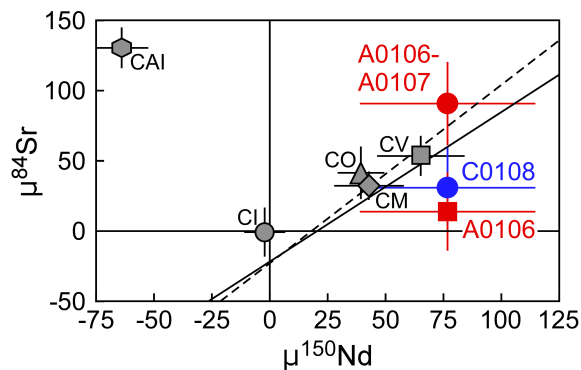*Figure 1. μ^{84}Sr vs. μ^{150}Nd in "CAI-subtracted" carbonaceous chondrites [10] and the 3 Ryugu samples analyzed here (μ^{84}Sr values are from this study; μ^{150}Nd values are from [21]); s-process mixing trends (solid and dashed lines) are from [10].*

A recent study reports an average μ^{150}Nd value for the A0106, A0106-A0107, C0107, and C0108 Ryugu samples of 77±38 [21]. Assuming this value for the Ryugu samples analyzed here, it is evident that two of these (A0106-A0107 and C0108) fall along the same s-process mixing trend defined by "CAI-subtracted" carbonaceous chondrites (Fig. 1), while one (A0106) falls below this trend. This suggests that the apparent

heterogeneity in Ryugu samples may be due to the heterogeneous distribution of components with distinct isotopic compositions (possibly the secondary carbonates). This additionally indicates that these Ryugu samples are apparently depleted in *s*-process nuclides, as was also suggested based on their Mo isotope systematics [22].

Stable Sr isotope composition. The δ^{88}Sr value determined via MC-ICPMS for A0106-A0107 is 0.19±0.09. This value is similar to those for CI, CM2, and CV3 chondrites, but is somewhat lighter than those for CO3 chondrites [23].

Conclusions: The Sr isotope systematics of Ryugu samples generally indicate similarity to the carbonaceous chondrites. The data are most consistent with a genetic relationship between Ryugu and CI or CM chondrites. The variations among Ryugu samples in Rb/Sr systematics and mass-independent Sr isotope anomalies are likely related to heterogeneous distribution of secondary carbonates at their sampling scale.

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