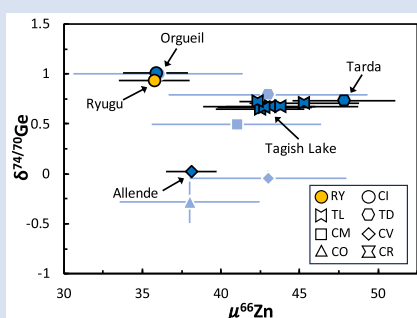


Ge, Te, and Zn isotopic link between Ryugu and CI chondrites

E. Wölfer^{1*}, J.L. Hellmann¹, C. Burkhardt¹, T. Kleine¹

Abstract



Analyses of samples returned from asteroid Ryugu have revealed chemical, mineralogical, and isotopic similarities to Ivuna-type (CI) carbonaceous chondrites. Compared to other carbonaceous chondrites, CI chondrites are characterised by heavy isotope enrichments of the moderately volatile elements, but until now no study demonstrated that this is also the case for Ryugu. Here we show that Ryugu and CI chondrites have similar elemental and mass dependent isotope systematics of the moderately volatile elements Ge, Te, and Zn, which are distinct from those of all other carbonaceous chondrites. The mass independent (nucleosynthetic) Zn isotope signatures of Ryugu are also most similar to CI chondrites, although the difference to other carbonaceous chondrites is not well resolved. Our results reinforce the notion that Ryugu and CI chondrites formed from the same precursor materials, and indicate that any processes acting on these materials before or after parent body accretion were similar. Given their similar chemical composition to the Sun, Ryugu/CI chondrites likely record the solar system's average chemical and mass dependent isotopic composition for moderately volatile elements.

Received 12 May 2025 | Accepted 15 August 2025 | Published 17 September 2025

Introduction

Japan Aerospace Exploration Agency's (JAXA) Hayabusa2 mission returned 5.4 g of sample of the Cb-type asteroid 162173 Ryugu to Earth (Tachibana *et al.*, 2022; Yada *et al.*, 2022). Initial analyses of the returned samples have revealed that Ryugu is petrologically, mineralogically, chemically, and isotopically similar to the Ivuna-type (CI) chondrites (Nakamura *et al.*, 2023; Yokoyama *et al.*, 2023a,b). These chondrites belong to the carbonaceous chondrites and with the exception of the highly volatile elements, their chemical composition closely resembles that of the solar photosphere. As such, CI chondrites are commonly taken to represent the bulk chemical composition of the solar system (*e.g.*, Palme and O'Neill, 2014). Compared to most other carbonaceous chondrites, CI chondrites are extremely rare, and owing to their friable nature, are susceptible to terrestrial alteration, which may have modified their compositions (*e.g.*, Bland *et al.*, 2006; Barrat *et al.*, 2012; Koefoed *et al.*, 2023). Thus, the returned samples from asteroid Ryugu provide the unique opportunity to examine CI chondrite-like material unaffected by terrestrial alteration.

Among the carbonaceous chondrites, CI chondrites exhibit unique nucleosynthetic isotope signatures for Fe and Ni (Hopp *et al.*, 2022; Spitzer *et al.*, 2024) and also show distinct mass dependent isotope compositions for the moderately volatile elements (MVEs; those that condense from a solar gas between ~1250 and 650 K). However, while Ryugu and Orgueil, the most commonly analysed CI chondrite, have indistinguishable mass dependent isotopic composition of the MVEs Zn (Paquet *et al.*, 2023) and K (Hu *et al.*, 2024), these compositions also overlap with those of other volatile-rich carbonaceous

chondrites and, therefore, do not provide a clear link between CI chondrites and Ryugu. Moreover, while Ryugu samples exhibit nucleosynthetic Zn isotope anomalies similar to CI chondrites, these compositions overlap with those of other carbonaceous chondrites (Paquet *et al.*, 2023). Given these ambiguities, it is important to assess whether there are other MVEs having isotopic signatures that would provide a link between CI chondrites and Ryugu, and allow distinguishing these materials from other carbonaceous chondrites. This is important for fully understanding the chemical and isotopic make-up of asteroid Ryugu, the nature of the processes determining compositional variations among CI chondrite-like materials, and, ultimately, the use of these materials to determine the bulk chemical composition of the solar system.

The two MVEs Ge and Te hold considerable promise to reveal compositional signatures that link Ryugu to CI chondrites and distinguish them from other carbonaceous chondrites. Both elements have been shown to display large and systematic mass dependent isotopic variations among the carbonaceous chondrites, where CI chondrites are characterised by the highest Ge and Te concentrations and strongest heavy isotope enrichments (Hellmann *et al.*, 2020; Wölfer *et al.*, 2025a). Given the strong genetic and chemical link between Ryugu and CI chondrites, Ryugu is expected to exhibit similarly distinct Ge and Te isotope systematics. To assess as to whether this is the case, we report Ge and Te isotope data for a single Ryugu sample together with data for several other MVE-rich carbonaceous chondrites. To facilitate direct comparison to the MVE Zn, all samples have also been analysed for their Zn isotope compositions.

1. Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany

* Corresponding author (email: wolfer@mps.mpg.de)

Samples and Methods

We analysed a 12.4 mg Ryugu sample from chamber A (A0220) together with equivalent masses of Orgueil and the ungrouped C2 chondrites Tarda and Tagish Lake. To test the reproducibility of the isotope measurements on such small sample masses, and to assess the magnitude of any potential heterogeneity at the ~12 mg level, six aggregate samples of Tagish Lake, each weighing ~12–15 mg, were also analysed. Similar to CI chondrites and Ryugu, Tagish Lake is dominated by fine grained, volatile-rich matrix with only very low abundances of chondrules, refractory inclusions, and FeNi metal (e.g., Alexander, 2019), making this sample suitable to assess the effect of any potential sample heterogeneity on the elemental and isotopic compositions of MVEs in matrix-rich carbonaceous chondrites. The Orgueil sample analysed in this study is an aliquot from a ~0.7 g powder prepared in a prior study (Schneider *et al.*, 2023). Finally, for direct comparison we also analysed aliquots of the large, homogenised MS-A powder of the CV3 chondrite Allende, which has previously been analysed for Ge and Te isotopes using the same analytical setup as in this study (Hellmann *et al.*, 2020; Wölfer *et al.*, 2025a).

The sample digestion, chemical separation and isotope measurements of Ge, Te, and Zn followed our previously established procedures (Hellmann *et al.*, 2020; Steller *et al.*, 2022; Wölfer *et al.*, 2025a,b) and are described in the [Supplementary Information](#). For Ge and Te, the instrumental mass bias was corrected using ^{70}Ge – ^{73}Ge (Wölfer *et al.*, 2025b) and ^{123}Te – ^{125}Te double spikes (Hellmann *et al.*, 2020), and the data are reported as the per mille deviations from certified standard solutions (see [Table 1](#) for definitions). The double spike measurements also provide precise Ge and Te concentrations determined by isotope dilution. No double spike was used for Zn, and the instrumental mass bias was corrected by standard sample bracketing. This has the advantage that for Zn we can also report mass independent isotope variations (*i.e.* nucleosynthetic isotope anomalies) after internal normalisation of the data. As for Ge and Te, the mass dependent Zn isotope data are reported as the per mille deviations from a certified standard solution, while the nucleosynthetic isotope anomalies are given as the ppm deviations from the standard after internal normalisation to either $^{68}\text{Zn}/^{64}\text{Zn}$ or $^{67}\text{Zn}/^{64}\text{Zn}$.

Results

The Ge, Te, and Zn concentrations and isotopic compositions of Ryugu (A0220) and the carbonaceous chondrites investigated in this study are provided in [Table 1](#). We show in the [SI \(Tables S-1 to S-3, Fig. S-1\)](#) that the new data for Orgueil, Tagish Lake, Tarda, and Allende agree well with results of prior studies, demonstrating that the combined use of two different double spikes has no effect on the isotope analyses of any of the three elements investigated, and that analysing mg-sized samples does not compromise the accuracy and precision of the isotopic data. While the six Tagish Lake subsamples have similar Ge, Te, and Zn concentrations and isotopic compositions, they show resolved $\delta^{74/70}\text{Ge}$ and $\delta^{66/64}\text{Zn}$ variations, indicating some level of compositional heterogeneities at the ~12 mg sampling scale ([Fig. S-2](#)). This heterogeneity appears to be more pronounced for Zn, where our analyses of several samples of Tagish Lake are systematically offset from some prior analyses ([Fig. S-2](#)).

Ryugu sample A0220 and Orgueil have the highest Ge, Te, and Zn concentrations and are characterised by the most elevated $\delta^{74/70}\text{Ge}$ and $\delta^{128/126}\text{Te}$ values among the carbonaceous chondrites of this and prior studies ([Figs. 1, S-3](#)). Consistent with

Paquet *et al.* (2023), we find no $\delta^{66/64}\text{Zn}$ differences among Ryugu sample A0220, Orgueil, Tagish Lake, and Tarda, despite their different Zn contents. Compared to CI chondrites, Ryugu sample A0220 is enriched in Ge, Te, and Zn by ~5–10 %, consistent with the ~10 % higher Zn concentrations found in prior studies (Paquet *et al.*, 2023; Yokoyama *et al.*, 2023a). These higher MVE concentrations can partly or wholly be accounted for by the >6 wt. % lower water content of Ryugu samples compared to CI chondrites, and ultimately might stem from the incorporation of terrestrial water into CI meteorites and/or the loss of water from Ryugu's surface during space weathering (Noguchi *et al.*, 2023; Yokoyama *et al.*, 2023a). For Ge, the $\delta^{74/70}\text{Ge}$ of sample A0220 is ~0.07 ‰ lower than for Orgueil samples analysed in this and previous studies. This difference is similar to those found among the subsamples of Tagish Lake, indicating these differences most likely reflect sample heterogeneity. This is likely also the case for Te, where sample A0220 has the same $\delta^{128/126}\text{Te}$ as Ivuna (Hellmann *et al.*, 2020), but a slightly lower $\delta^{128/126}\text{Te}$ than two analyses of Orgueil (from this study and Hellmann *et al.*, 2020).

For the nucleosynthetic Zn isotope anomalies, sample A0220, together with the other carbonaceous chondrites of this study, plots in the CC field on $\mu^{66}\text{Zn}$ – $\mu^{68}\text{Zn}$ and $\mu^{66}\text{Zn}$ – $\mu^{67}\text{Zn}$ diagrams ([Fig. 2](#)). The results for Orgueil, Tagish Lake, Tarda, and Allende agree well with those of prior studies. Ryugu sample A0220 is characterised by $\mu^{66}\text{Zn} = 36 \pm 2$, identical to the values measured for Orgueil in this study and by Steller *et al.* (2022) (the latter data have been corrected for a small –9 ppm offset measured for terrestrial samples). The only other study on Zn isotope anomalies in Ryugu only reported $\mu^{66}\text{Zn}$ values using the $^{68}\text{Zn}/^{64}\text{Zn}$ normalisation (Paquet *et al.*, 2023), which results in overall smaller anomalies than the $^{67}\text{Zn}/^{64}\text{Zn}$ normalisation. These authors found a mean $\mu^{66}\text{Zn} = 33 \pm 4$ (2 s.e.) for samples from chambers A and C, slightly higher than $\mu^{66}\text{Zn} = 27 \pm 1$ (95 % conf.) ($^{68}\text{Zn}/^{64}\text{Zn}$ normalisation) measured here.

Discussion

A genetic link between asteroid Ryugu and CI chondrites has been established in numerous studies, based on for instance nucleosynthetic isotope anomalies in the non-volatile elements Cr, Ti, Fe, and Ni (Hopp *et al.*, 2022; Yokoyama *et al.*, 2023a, 2023b; Spitzer *et al.*, 2024). Among the MVEs, Zn also shows nucleosynthetic isotope anomalies, but until now no isotopic variations among the carbonaceous chondrites have been identified (Savage *et al.*, 2022; Steller *et al.*, 2022; Martins *et al.*, 2023). However, the data of this study suggest that CI chondrites and Ryugu may have distinct nucleosynthetic Zn isotope signatures compared to other carbonaceous chondrites. We find identical $\mu^{66}\text{Zn}$ values for two separate analyses of Orgueil ($\mu^{66}\text{Zn} = 36 \pm 5$ in Steller *et al.*, 2022, and 36 ± 2 in this study) and Ryugu sample A0220 ($\mu^{66}\text{Zn} = 36 \pm 2$). By contrast, for the next most volatile-rich carbonaceous chondrites, Tagish Lake and Tarda, we find more elevated $\mu^{66}\text{Zn}$ values of 43 ± 2 and 48 ± 3 , respectively ([Table 1](#)). This suggests that CI chondrites/Ryugu may be characterised by slightly lower $\mu^{66}\text{Zn}$ values than other volatile-rich carbonaceous chondrites. This difference is barely resolved, however, and there are other non-CI carbonaceous chondrites overlapping with the $\mu^{66}\text{Zn}$ values of CI chondrites and Ryugu ([Fig. 2](#)). As such, additional high precision Zn isotope data are needed for firmly establishing a nucleosynthetic Zn isotope difference between CI and other carbonaceous chondrites.

More robust evidence for an MVE-based link between Ryugu and CI chondrites comes from the elemental and mass dependent isotopic compositions reported here. Compositional

Table 1 Germanium, Te, and Zn concentration and isotopic data for Ryugu (A0220) and carbonaceous chondrites.

Sample	Weight (mg)	Ge (μg/g) (±2σ)	n (Ge)	$\delta^{74/70}\text{Ge}$ (±95 % CI)	Te (ng/g) (±2σ)	n (Te)	$\delta^{128/126}\text{Te}$ (±2 s.d.)	Zn (μg/g)	n (Zn)	$\delta^{66/64}\text{Zn}$ (±2 s.d.)	$\mu^{66}\text{Zn}$ (±95 % CI)	$\mu^{68}\text{Zn}$ (±95 % CI)	$\mu^{66}\text{Zn}$ (±95 % CI)	$\mu^{68}\text{Zn}$ (±95 % CI)
											$^{67}\text{Zn}/^{64}\text{Zn}$ int. norm.		$^{68}\text{Zn}/^{64}\text{Zn}$ int. norm.	
Ryugu (A0220)	12.4	37.2 ± 0.2	12	0.93 ± 0.03	2372 ± 8	3	0.13 ± 0.03	348	14	0.51 ± 0.12	36 ± 2	16 ± 4	27 ± 1	−12 ± 3
Orgueil (CI)	12.7	33.9 ± 0.2	12	1.01 ± 0.03	2269 ± 7	3	0.15 ± 0.02	318	10	0.51 ± 0.08	36 ± 2	16 ± 6	28 ± 2	−12 ± 4
Orgueil (CI) ^a	7.9							298	16	0.53 ± 0.11	36 ± 5	14 ± 9	28 ± 3	−10 ± 7
Tagish Lake (C2 ung.)	11.5	25.6 ± 0.3	9	0.67 ± 0.03	1729 ± 6	3	0.13 ± 0.03	196	8	0.51 ± 0.08	43 ± 3	21 ± 5	33 ± 2	−16 ± 3
Tagish Lake (C2 ung.)	11.6	25.2 ± 0.3	9	0.65 ± 0.03	1764 ± 6	3	0.12 ± 0.03	202	8	0.63 ± 0.05	42 ± 3	18 ± 4	33 ± 1	−13 ± 3
Tagish Lake (C2 ung.)	12.5	25.1 ± 0.3	9	0.66 ± 0.04	1556 ± 5	4	0.12 ± 0.06	188	8	0.52 ± 0.04	43 ± 3	19 ± 6	34 ± 3	−14 ± 5
Tagish Lake (C2 ung.)	11.7	25.5 ± 0.3	9	0.67 ± 0.02	1647 ± 5	3	0.10 ± 0.01	187	8	0.57 ± 0.06	44 ± 5	20 ± 9	34 ± 2	−15 ± 7
Tagish Lake (C2 ung.)	14.8	26.2 ± 0.3	9	0.71 ± 0.03	1756 ± 6	4	0.12 ± 0.05	197	8	0.53 ± 0.09	45 ± 3	20 ± 4	35 ± 3	−15 ± 3
Tagish Lake (C2 ung.)	13.3	25.5 ± 0.3	9	0.72 ± 0.02	1691 ± 6	4	0.11 ± 0.03	188	6	0.48 ± 0.03	42 ± 1	17 ± 6	33 ± 2	−13 ± 5
Mean (2 s.d., n = 6)		25.5 ± 0.8		0.68 ± 0.06	1690 ± 157		0.12 ± 0.02	193		0.54 ± 0.10	43 ± 2	19 ± 3	33 ± 2	−14 ± 3
Wt. mean (IsoplotR)		25.4 ± 0.1		0.69 ± 0.02	1679 ± 67		0.11 ± 0.01	193		0.53 ± 0.02	42 ± 1	19 ± 2	33 ± 1	−15 ± 2
Tarda (C2 ung.)	16.3	24.4 ± 0.2	4	0.73 ± 0.03	1622 ± 5	3	0.07 ± 0.07	194	9	0.54 ± 0.05	48 ± 3	25 ± 5	35 ± 2	−19 ± 4
Tarda (C2 ung.) ^a	13.0							205	15	0.46 ± 0.06	43 ± 6	21 ± 7	31 ± 6	−16 ± 6
J. Winselwan (CM) ^a	17.9							183	20	0.41 ± 0.08	41 ± 5	19 ± 11	31 ± 2	−14 ± 8
Allende (CV)	102.9	17.2 ± 0.2	6	0.02 ± 0.03	954 ± 3	4	0.02 ± 0.02	111	25	0.31 ± 0.07	38 ± 2	15 ± 2	31 ± 1	−11 ± 2
Allende (CV) ^a	74.3							108	68	0.27 ± 0.08	43 ± 3	19 ± 6	32 ± 1	−15 ± 4
Vigarano (CV) ^a	30.2							104	15	0.17 ± 0.05	43 ± 4	15 ± 8	35 ± 2	−11 ± 6
Kainsaz (CO) ^a	28.7							94	18	0.38 ± 0.05	38 ± 4	17 ± 7	30 ± 3	−12 ± 5

The Ge and Te concentrations were determined by isotope dilution and the Zn concentrations were determined by quadrupole ICP-MS, the latter of which have an uncertainty of ~5 %. The isotope data of individual samples are reported as the mean of pooled measurements and are expressed as in the common δ notation as $\delta^{74}\text{Ge}$ [‰] = $[(^{74}\text{Ge}/^{70}\text{Ge})_{\text{sample}}/(^{74}\text{Ge}/^{70}\text{Ge})_{\text{SRM3210a}} - 1] \times 10^3$, $\delta^{128}\text{Te}$ [‰] = $[(^{128}\text{Te}/^{126}\text{Te})_{\text{sample}}/(^{128}\text{Te}/^{126}\text{Te})_{\text{SRM3156}} - 1] \times 10^3$, $\delta^{66}\text{Zn}$ [‰] = $[(^{66}\text{Zn}/^{64}\text{Zn})_{\text{sample}}/(^{66}\text{Zn}/^{64}\text{Zn})_{\text{JMC.Lyon}} - 1] \times 10^3$, and $\mu^{66}\text{Zn} = [(^{66}\text{Zn}/^{64}\text{Zn})_{\text{sample}}/(^{66}\text{Zn}/^{64}\text{Zn})_{\text{SRM683}} - 1] \times 10^6$, respectively. n: number of isotope analyses.

^a Mass independent Zn isotope data previously published in [Steller et al. \(2022\)](#).

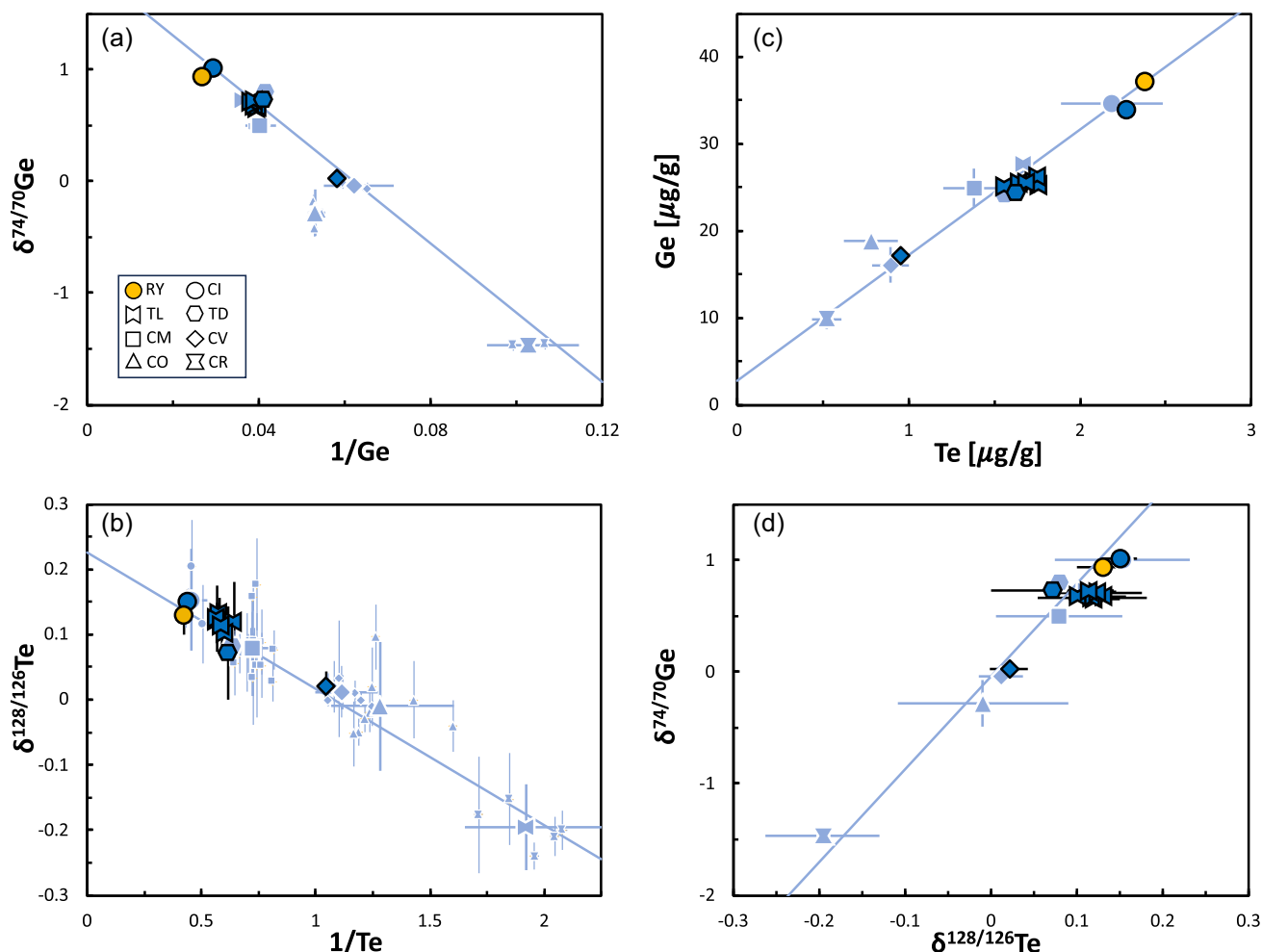


Figure 1 Diagrams of (a) Ge concentration vs. $\delta^{74/70}\text{Ge}$, (b) Te concentration vs. $\delta^{128/126}\text{Te}$, (c) Te vs. Ge concentrations, and (d) $\delta^{128/126}\text{Te}$ vs. $\delta^{74/70}\text{Ge}$ for carbonaceous chondrites (data from this study in dark blue; literature data in light blue [small symbols represent individual samples; large symbols represent group averages]). Ryugu sample A0220 is plotted as orange circle. Literature data for Ge is from Wölfer *et al.* (2025a); data for Te is from Hellmann *et al.* (2020, 2023) and Morton *et al.* (2024). The data of Morton *et al.* (2024) are re-normalised to $\delta^{128/126}\text{Te}$ and the SRM standard used by Hellmann *et al.* (2020, 2023). Linear regressions calculated using IsoplotR based on group averages.

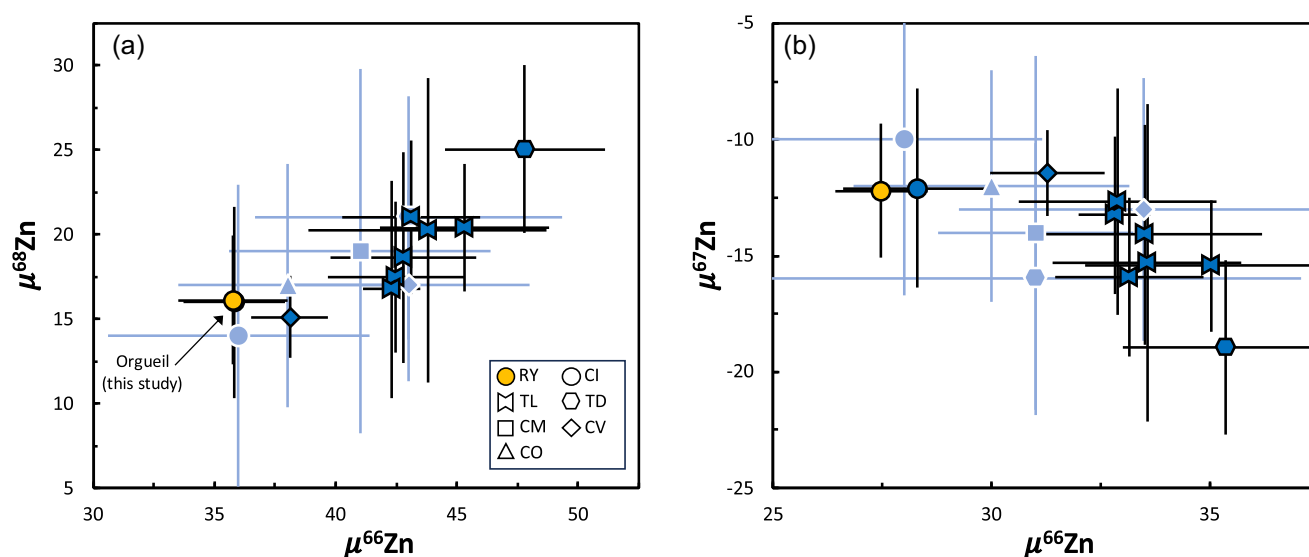


Figure 2 (a) $\mu^{66}\text{Zn}$ vs. $\mu^{68}\text{Zn}$ and (b) $\mu^{66}\text{Zn}$ vs. $\mu^{67}\text{Zn}$ diagrams for carbonaceous chondrites. Symbols as in Figure 1. Ryugu sample A0220 plots within the CC field and, together with CI chondrites, is characterised by slightly smaller μ^{Zn} values compared to Tarda and Tagish Lake. Literature data from Steller *et al.* (2022).

variations among the carbonaceous chondrites are thought to reflect mixing among the chondrite's constituent components, namely volatile-poor, isotopically light chondrules and volatile-rich, isotopically heavy, CI chondrite-like matrix (e.g., Alexander, 2019; Hellmann *et al.*, 2020). Variations in the abundance of these two components result in correlations among the concentrations and mass dependent isotopic compositions of the MVEs, including Ge (Wölfer *et al.*, 2025a), Te (Hellmann *et al.*, 2020), Zn (e.g., Pringle *et al.*, 2017), Rb (e.g., Nie *et al.*, 2021), K (e.g., Koefoed *et al.*, 2023), and Cd (Morton *et al.*, 2024). Our results are consistent with these correlations and demonstrate that Ryugu and Orgueil together are characterised by distinctly higher MVE abundances and heavier isotopic compositions compared to other carbonaceous chondrites (Fig. 1). However, given the small mass analysed for each sample, it is important to assess how much of the observed variability may reflect sample heterogeneities rather than true compositional variations among the chondrite groups. For instance, different Ryugu subsamples exhibit variable Cr, Ti, and Ni nucleosynthetic isotope signatures (Yokoyama *et al.*, 2023a, 2023b; Spitzer *et al.*, 2024), which at least in part have been attributed to the redistribution of isotopically anomalous phases during aqueous alteration in the parent body (Yokoyama *et al.*, 2023b). The pronounced Mo isotope anomalies observed for a Ryugu sample has been explained in a similar manner (Nakanishi *et al.*, 2023). These observations suggest that small scale heterogeneities may also exist for mass dependent isotope compositions. For instance, mass dependent Zn isotope variations have been observed among the components of chondrites (Luck *et al.*, 2005; Pringle *et al.*, 2017), and so over- or under-sampling of certain components having distinct isotopic compositions may have occurred.

Our results for six ~12–15 mg subsamples of Tagish Lake show that the effects of sample heterogeneity are different for Ge, Te, and Zn. While the $\delta^{128/126}\text{Te}$ values are quite homogeneous, $\delta^{74/70}\text{Ge}$ and $\delta^{66/64}\text{Zn}$ values vary by ~0.07 ‰ and ~0.16 ‰, respectively. For Zn this difference covers almost half of the entire $\delta^{66/64}\text{Zn}$ variations observed among carbonaceous chondrites. By contrast, for Ge, these variations amount to only ~3 % of the overall $\delta^{74/70}\text{Ge}$ variability among the carbonaceous chondrites (Wölfer *et al.*, 2025a), and the difference between CI chondrites and Tagish Lake itself is about four times larger than the heterogeneity observed among the CI chondrite and Ryugu samples. These observations suggest that the disparate levels of isotopic heterogeneity among the Tagish Lake subsamples are neither controlled by volatility (because Te and Zn have similar condensation temperatures) nor by heterogeneous sampling of chondrule and matrix fractions (because in this case similar relative variations would be expected for all three elements). Instead, they more likely reflect differences in the mobility of these elements during parent body alteration, and in the magnitude of isotope fractionation among the MVE's host minerals. Regardless of their exact cause, the larger intra-sample $\delta^{66/64}\text{Zn}$ variability combined with the overall smaller range of $\delta^{66/64}\text{Zn}$ values among carbonaceous chondrites makes Zn less suitable for linking Ryugu samples to a specific carbonaceous chondrite group than Ge and Te. Moreover, the larger overall isotope fractionation of Ge compared to Te makes mass dependent Ge isotope variations particularly powerful to identify genetic relations of MVEs among carbonaceous chondrite-like materials, especially for the small sample sizes typically available from sample return missions.

The Ge and Te results of this study demonstrate that compared to other carbonaceous chondrites, Ryugu and CI chondrites are characterised by elemental and heavy isotope enrichments in the MVEs. The same conclusion was reached

previously based on Zn isotopes (Paquet *et al.*, 2023), but we emphasise that only for Ge and Te are the isotopic compositions of Ryugu and CI chondrites distinct from those of other volatile-rich carbonaceous chondrites.

Identical nucleosynthetic isotope signatures of Ryugu and CI chondrites have revealed that both formed from the same mix of presolar and nebular materials, but these signatures provide little information on any physicochemical processes acting on these materials before and after parent body accretion. The mass dependent isotopic compositions of MVEs are a more sensitive tracer of such processes, and so the MVE-based link between Ryugu and CI chondrites indicates that any physicochemical processes acting on these materials were also similar. Given the strong chemical similarities between Ryugu/CI chondrites and the solar photosphere, this in turn implies that these samples are good proxies for the average chemical and mass dependent isotopic compositions of the MVEs for most of the solar protoplanetary disk and, hence, the bulk solar system. Importantly, as is evident for instance from the distinct O isotope composition of the Sun (McKeegan *et al.*, 2011) for mass independent isotope anomalies, the isotopic composition of the solar system may be markedly different from that of CI chondrites, which likely was established by mixing of isotopically distinct materials during the formation and dynamical evolution of the protoplanetary disk (e.g., Nanne *et al.*, 2019).

Acknowledgements

The Ryugu samples used in this paper were distributed through The Announcement of Opportunity for Hayabusa2 samples. These samples were referred to the Ryugu Sample Database at <https://www.darts.isas.jaxa.jp/curation/hayabusa2/>. We gratefully acknowledge Rayssa Martins and Kun Wang for their constructive comments and Helen Williams for her editorial handling. This work was funded by the European Research Council Advanced Grant HolyEarth (grant no. 101019380).

Editor: Helen Williams

Additional Information

Supplementary Information accompanies this letter at <https://www.geochemicalperspectivesletters.org/article2537>.



© 2025 The Authors. This work is distributed under the Creative Commons Attribution 4.0 License, which permits unrestricted use,

distribution, and reproduction in any medium, provided the original author and source are credited. Additional information is available at <http://www.geochemicalperspectivesletters.org/copyright-and-permissions>.

Cite this letter as: Wölfer, E., Hellmann, J.L., Burkhardt, C., Kleine, T. (2025) Ge, Te, and Zn isotopic link between Ryugu and CI chondrites. *Geochem. Persp. Let.* 37, 1–6. <https://doi.org/10.7185/geochemlet.2537>

References

- ALEXANDER, C.M.O'D. (2019) Quantitative models for the elemental and isotopic fractionations in chondrites: The carbonaceous chondrites. *Geochimica et Cosmochimica Acta* 254, 277–309. <https://doi.org/10.1016/j.gca.2019.02.008>
- BARRAT, J.-A., ZANDA, B., MOYNIER, F., BOLLINGER, C., LIORZOU, C., BAYON, G. (2012) Geochemistry of CI chondrites: Major and trace elements, and Cu and Zn Isotopes. *Geochimica et Cosmochimica Acta* 83, 79–92. <https://doi.org/10.1016/j.gca.2011.12.011>

- BLAND, P.A., ZOLENSKY, M.E., BENEDIX, G.K., SEPTON, M.A. (2006) Weathering of Chondritic Meteorites. In: LAURETTA, D.S., MCSWEEN, H.Y. (Eds.) *Meteorites and the Early Solar System II*. University of Arizona Press, Tucson, 853–868. <https://doi.org/10.2307/j.ctv1v7zdm45>
- HELLMANN, J.L., HOPP, T., BURKHARDT, C., KLEINE, T. (2020) Origin of volatile element depletion among carbonaceous chondrites. *Earth and Planetary Science Letters* 549, 116508. <https://doi.org/10.1016/j.epsl.2020.116508>
- HELLMANN, J.L., SCHNEIDER, J.M., WÖLFER, E., DRĄŻKOWSKA, J., JANSEN, C.A., HOPP, T., BURKHARDT, C., KLEINE, T. (2023) Origin of Isotopic Diversity among Carbonaceous Chondrites. *The Astrophysical Journal Letters* 946, L34. <https://doi.org/10.3847/2041-8213/acc102>
- HOPP, T., DAUPHAS, N., ABE, Y., ALÉON, J., ALEXANDER, C.M.O'D. *et al.* (2022) Ryugu's nucleosynthetic heritage from the outskirts of the Solar System. *Science Advances* 8, eadd8141. <https://doi.org/10.1126/sciadv.add8141>
- HU, Y., MOYNIER, F., DAI, W., PAQUET, M., YOKOYAMA, T. *et al.* (2024) Pervasive aqueous alteration in the early Solar System revealed by potassium isotopic variations in Ryugu samples and carbonaceous chondrites. *Icarus* 409, 115884. <https://doi.org/10.1016/j.icarus.2023.115884>
- KOEFOED, P., BARRAT, J.-A., PRAVDITSEVA, O., ALEXANDER, C.M.O'D., LODDERS, K., OGLORE, R., WANG, K. (2023) The potassium isotopic composition of CI chondrites and the origin of isotopic variations among primitive planetary bodies. *Geochimica et Cosmochimica Acta* 358, 49–60. <https://doi.org/10.1016/j.gca.2023.07.025>
- LUCK, J.-M., OTHMAN, D.B., ALBARÈDE, F. (2005) Zn and Cu isotopic variations in chondrites and iron meteorites: Early solar nebula reservoirs and parent-body processes. *Geochimica et Cosmochimica Acta* 69, 5351–5363. <https://doi.org/10.1016/j.gca.2005.06.018>
- MARTINS, R., KUTHNING, S., COLES, B.J., KREISSIG, K., REHKÄMPER, M. (2023) Nucleosynthetic isotope anomalies of zinc in meteorites constrain the origin of Earth's volatiles. *Science* 379, 369–372. <https://doi.org/10.1126/science.abn1021>
- MCKEEGAN, K.D., KALLIO, A.P.A., HEBER, V.S., JARZEBINSKI, G., MAO, P.H., COATH, C.D., KUNIHITO, T., WIENS, R.C., NORDHOLT, J.E., MOSES JR., R.W., REISENFELD, D.B., JUREWICZ, A.J.G., BURNETT, D.S. (2011) The Oxygen Isotopic Composition of the Sun Inferred from Captured Solar Wind. *Science* 332, 1528–1532. <https://doi.org/10.1126/science.1204636>
- MORTON, E.M., PICKARD, H., WOMBACHER, F., HUANG, Y., PALK, E., MARTINS, R., KUTHNING, S., SCHÖNBÄCHLER, M., REHKÄMPER, M. (2024) Volatile Element Depletion of Carbonaceous Chondrites—Insights from Mass-dependent Zinc, Cadmium, and Tellurium Isotope Variations. *The Astrophysical Journal* 977, 53. <https://doi.org/10.3847/1538-4357/ad87ed>
- NAKAMURA, T., MATSUMOTO, M., AMANO, K., ENOKIDO, Y., ZOLENSKY, M.E. *et al.* (2023) Formation and evolution of carbonaceous asteroid Ryugu: Direct evidence from returned samples. *Science* 379, eabn8671. <https://doi.org/10.1126/science.abn8671>
- NAKANISHI, N., YOKOYAMA, T., ISHIKAWA, A., WALKER, R.J., ABE, Y. *et al.* (2023) Nucleosynthetic s-Process Depletion in Mo from Ryugu samples returned by Hayabusa2. *Geochemical Perspectives Letters* 28, 31–36. <https://doi.org/10.7185/geochemlet.2341>
- NANNE, J.A.M., NIMMO, F., CUZZI, J.N., KLEINE, T. (2019) Origin of the non-carbonaceous–carbonaceous meteorite dichotomy. *Earth and Planetary Science Letters* 511, 44–54. <https://doi.org/10.1016/j.epsl.2019.01.027>
- NIE, N.X., CHEN, X.-Y., HOPP, T., HU, J.Y., ZHANG, Z.J., TENG, F.-Z., SHAHAR, A., DAUPHAS, N. (2021) Imprint of chondrule formation on the K and Rb isotopic compositions of carbonaceous meteorites. *Science Advances* 7, eabl3929. <https://doi.org/10.1126/sciadv.abl3929>
- NOGUCHI, T., MATSUMOTO, T., MIYAKE, A., IGAMI, Y., HARUTA, M. *et al.* (2023) A dehydrated space-weathered skin cloaking the hydrated interior of Ryugu. *Nature Astronomy* 7, 170–181. <https://doi.org/10.1038/s41550-022-01841-6>
- PALME, H., O'NEILL, H.St.C. (2014) 3.1 - Cosmochemical Estimates of Mantle Composition. In: HOLLAND, H.D., TUREKIAN, K.K. (Eds.) *Treatise on Geochemistry*. Second Edition, Elsevier, Amsterdam, 1–39. <https://doi.org/10.1016/B978-0-08-095975-7.00201-1>
- PAQUET, M., MOYNIER, F., YOKOYAMA, T., DAI, W., HU, Y. *et al.* (2023) Contribution of Ryugu-like material to Earth's volatile inventory by Cu and Zn isotopic analysis. *Nature Astronomy* 7, 182–189. <https://doi.org/10.1038/s41550-022-01846-1>
- PRINGLE, E.A., MOYNIER, F., BECK, P., PANIELLO, R., HEZEL, D.C. (2017) The origin of volatile element depletion in early solar system material: Clues from Zn isotopes in chondrules. *Earth and Planetary Science Letters* 468, 62–71. <https://doi.org/10.1016/j.epsl.2017.04.002>
- SAVAGE, P.S., MOYNIER, F., BOYET, M. (2022) Zinc isotope anomalies in primitive meteorites identify the outer solar system as an important source of Earth's volatile inventory. *Icarus* 386, 115172. <https://doi.org/10.1016/j.icarus.2022.115172>
- SCHNEIDER, J.M., BURKHARDT, C., KLEINE, T. (2023) Distribution of s-, r-, and p-process Nuclides in the Early Solar System Inferred from Sr Isotope Anomalies in Meteorites. *The Astrophysical Journal Letters* 952, L25. <https://doi.org/10.3847/2041-8213/ace187>
- SPITZER, F., KLEINE, T., BURKHARDT, C., HOPP, T., YOKOYAMA, T. *et al.* (2024) The Ni isotopic composition of Ryugu reveals a common accretion region for carbonaceous chondrites. *Science Advances* 10, eadp2426. <https://doi.org/10.1126/sciadv.adp2426>
- STELLER, T., BURKHARDT, C., YANG, C., KLEINE, T. (2022) Nucleosynthetic zinc isotope anomalies reveal a dual origin of terrestrial volatiles. *Icarus* 386, 115171. <https://doi.org/10.1016/j.icarus.2022.115171>
- TACHIBANA, S., SAWADA, H., OKAZAKI, R., TAKANO, Y., SAKAMOTO, K. *et al.* (2022) Pebbles and sand on asteroid (162173) Ryugu: In situ observation and particles returned to Earth. *Science* 375, 1011–1016. <https://doi.org/10.1126/science.abj8624>
- WÖLFER, E., BURKHARDT, C., NIMMO, F., KLEINE, T. (2025a) Origin of moderately volatile elements in Earth inferred from mass-dependent Ge isotope variations among chondrites. *Earth and Planetary Science Letters* 663, 119435. <https://doi.org/10.1016/j.epsl.2025.119435>
- WÖLFER, E., BURKHARDT, C., KLEINE, T. (2025b) Germanium stable isotope measurements by double-spike MC-ICPMS. *Journal of Analytical Atomic Spectrometry* 40, 1023–1036. <https://doi.org/10.1039/D4JA00359D>
- YADA, T., ABE, M., OKADA, T., NAKATO, A., YOGATA, K. *et al.* (2022) Preliminary analysis of the Hayabusa2 samples returned from C-type asteroid Ryugu. *Nature Astronomy* 6, 214–220. <https://doi.org/10.1038/s41550-021-01550-6>
- YOKOYAMA, T., NAGASHIMA, K., NAKAI, I., YOUNG, E.D., ABE, Y. *et al.* (2023a) Samples returned from the asteroid Ryugu are similar to Ivuna-type carbonaceous meteorites. *Science* 379, eabn7850. <https://doi.org/10.1126/science.abn7850>
- YOKOYAMA, T., WADHWA, M., IZUKA, T., RAI, V., GAUTAM, I. *et al.* (2023b) Water circulation in Ryugu asteroid affected the distribution of nucleosynthetic isotope anomalies in returned sample. *Science Advances* 9, eadi7048. <https://doi.org/10.1126/sciadv.adi7048>