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SPACE SCIENCES

Ryugu's nucleosynthetic heritage from the outskirts of the Solar System

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Little is known about the origin of the spectral diversity of asteroids and what it says about conditions in the proto-planetary disk. Here we show that samples returned from Cb-type asteroid Ryugu have Fe isotopic anomalies indistinguishable from Ivuna-type (CI) chondrites, which are distinct from all other carbonaceous chondrites. Iron isotopes, therefore, demonstrate that Ryugu and CI chondrites formed in a reservoir that was different from the source regions of other carbonaceous asteroids. Growth and migration of the giant planets destabilized nearby planetesimals and ejected some inwards to be implanted into the Main Belt. In this framework, most carbonaceous chondrites may have originated from regions around the birthplaces of Jupiter and Saturn, while the distinct isotopic composition of CI chondrites and Ryugu may reflect their formation further away in the disk, owing their presence in the inner Solar System to excitation by Uranus and Neptune.

INTRODUCTION

Main Belt asteroids show great compositional diversity (1), ranging from metallic objects that are remnants of differentiated planetesimals (2) to carbon-rich objects with comet-like dust-ejection activity (3). The original formation locations of these diverse objects are unknown. Meteorites are remnants of planetesimals and protoplanets that formed at various heliocentric distances within the first few million years after the birth of the Solar System. They, therefore, provide invaluable insights into the early evolution of the Solar System and the building blocks of the terrestrial planets. Most meteorites are fragments of Main Belt asteroids, but direct asteroid-meteorite links are scarce (1). Establishing such links is important as it provides clues on the relationship and formation locations of meteorite parent bodies, asteroids, and other small bodies in the Solar System. Cb-type asteroid (162173) Ryugu is a near-Earth object (NEO) that most likely originated from the inner Main Belt (4). Chemical and mineralogical analyses of Ryugu samples returned to Earth by JAXA's Hayabusa2 mission (5) show that they share chemical and mineralogical characteristics with Ivuna-type carbonaceous (CI) chondrites (6). The latter is the only group of meteorites containing

most non-volatile elements in proportions nearly equal to those measured in the solar photosphere (7). The physical and chemical similarities of Ryugu and CI chondrites are, however, not diagnostic of a shared heritage because the low-temperature conditions required to explain their solar-like chemical compositions could have been widespread in the outer Solar System disk.

To better constrain Ryugu's nucleosynthetic heritage, we measured the Fe isotopic compositions of four Ryugu samples collected during the first and second touchdown (5), 11 different carbonaceous chondrites from five different groups (CI, CM, CV, CO, CR), and two ungrouped chondrites. Materials formed in the Solar System display variations in the isotopic compositions of some elements that stem from the heterogeneous distribution and processing of highly anomalous presolar materials in the protosolar nebula (8–11). Such anomalies cannot easily be modified by physicochemical processes on planetary bodies and, therefore, provide lasting isotopic fingerprints of the regions where planetary bodies formed (12–14). For several elements, meteorites display a dichotomy in their isotopic anomalies between non-carbonaceous (NC) and carbonaceous (CC) meteorite groups (13). The origin of this dichotomy could have

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involved the physical separation between inner and outer Solar System reservoirs by Jupiter (13, 15, 16) and planetesimal formation at distinct locations in an evolving protoplanetary disk (17–21). Although isotopic analyses of Ti and Cr show that Ryugu's building blocks formed in the CC reservoir and support a possible kinship between Ryugu and CI chondrites (6), an unambiguous genetic link to a specific carbonaceous chondrite group could not be established because the Ti and Cr isotopic anomalies of Ryugu overlap with several carbonaceous chondrites and achondrites (Fig. 1A). Carbonaceous chondrites also display mass-independent variations in O isotopes that correlate with Ti and Cr isotopic anomalies (13). Ryugu and CI chondrites have similar O isotopic anomalies and represent an end-member composition for the CC cluster in O–Cr and O–Ti spaces (Fig. 1B,C) (6). Those results support the view that CI chondrites and Ryugu formed within the CC reservoir, but because of correlations

between O, Cr, and Ti anomalies (Fig. 1), there is significant redundancy in evidence presented thus far and further work is needed to better understand the isotopic architecture of the outer Solar System.

The Fe isotopic composition of CI chondrites (22) is clearly distinct from all other carbonaceous meteorites (22–24), where all CC meteorites except CI chondrites show significant excesses in ^{54}Fe . Iron isotopes, therefore, provide a diagnostic tool to evaluate if Ryugu has the same distinct nucleosynthetic heritage as CI chondrites.

RESULTS

Ryugu samples and all carbonaceous chondrites display limited mass-dependent isotopic variation relative to the terrestrial standard IRMM-524a (Table S1), meaning that all isotopic anomalies reported here are real and not artifacts from the internal normalization

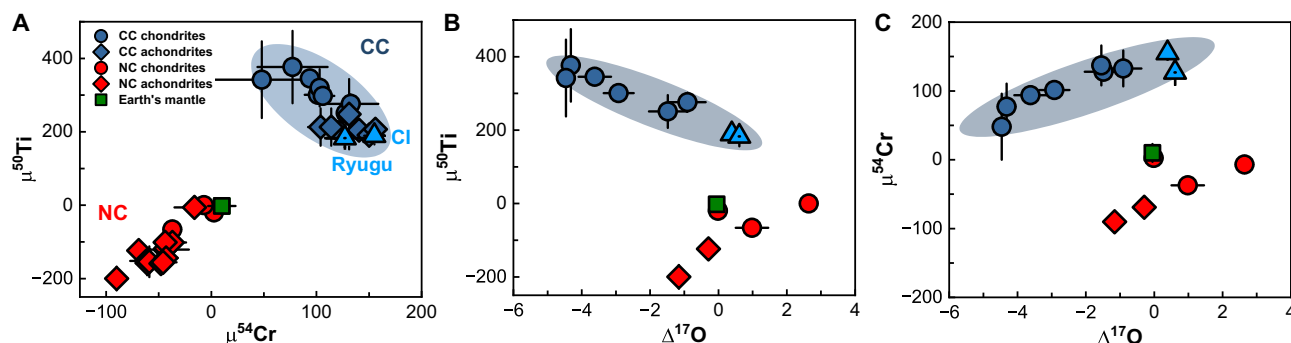


Fig. 1. Previously published isotopic anomalies of Ti, Cr, and O in Ryugu and other Solar System materials. Plots of $\mu^{50}\text{Ti}$ vs. $\mu^{54}\text{Cr}$ (A), $\mu^{50}\text{Ti}$ vs. $\Delta^{17}\text{O}$ (B), and $\mu^{54}\text{Cr}$ vs. $\Delta^{17}\text{O}$ (C). In these diagrams, Ryugu and CI represent an endmember to the CC array. Data for Ryugu are from Yokoyama et al. (6). The average Ti and Cr isotopic compositions of non-carbonaceous (NC) and carbonaceous (CC) meteorite groups and Earth's mantle are from the data compilation of Burkhardt et al. (64) and O isotopic data from the compilation of Dauphas (65). Uncertainties for individual groups are the 95% confidence interval of the mean. If not visible, error bars are smaller than symbols.

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scheme used to correct natural and instrumental isotopic fractionation (14). Mass-independent Fe isotopic analyses confirm that most carbonaceous chondrites display variable excesses of $\sim +15$ to $\sim +40$ in $\mu^{54}\text{Fe}$ but no resolvable variations in $\mu^{58}\text{Fe}$ (see Table 1 for a definition of the μ -notation) (Table 1; Fig. 2). By contrast, all three CI chondrites analyzed in this study are clearly distinct from other carbonaceous chondrites, defining an average $\mu^{54}\text{Fe} = +3 \pm 2$, consistent with previous measurements (Fig. 2; Fig. S1) (22). The four Ryugu samples (A0106 and A0106-A0107 collected during the first touchdown from the surface; C0107 and C0108 collected during the second touchdown and possibly sampling material from the sub-surface) define an average $\mu^{54}\text{Fe}$ value of $+1 \pm 4$, which is indistinguishable from the composition of CI chondrites but distinct from all other carbonaceous chondrites (Fig. 2). The $\mu^{54}\text{Fe}$ difference of Ryugu and CI chondrites compared to all other carbonaceous chondrites cannot be due to prolonged exposure to cosmic rays in space because (i) CI chondrites have low cosmic ray exposure ages (25) and (ii) cosmogenic effects would induce a positive shift in $\mu^{54}\text{Fe}$ that would correlate with a negative shift in $\mu^{58}\text{Fe}$ (24, 26), which is not observed (Table 1; Fig. S2). Thus, the distinct $\mu^{54}\text{Fe}$ values of CI chondrites and Ryugu represent the nucleosynthetic heritage of their formation reservoir in the protosolar nebula. Examination of $\mu^{54}\text{Fe}$ - $\mu^{50}\text{Ti}$ (Fig. 3) and $\mu^{54}\text{Fe}$ - $\mu^{54}\text{Cr}$ (Fig. S3) isotopic anomalies show that Ryugu and CI chondrites form a compositional cluster that is distinct from the NC and CC fields defined by other meteorites. Thus, whereas the isotopic anomalies of Ti, Cr, and O in CI chondrites (10, 11, 27–31) and Ryugu (6) tie them to the CC reservoir, the Fe isotopic data reveal that CI chondrites and Ryugu formed in a reservoir that is rarely sampled by meteorites.

DISCUSSION

Recent models tie the distinct isotopic characteristics of meteorites to planetesimal formation at different locations and/or at different time in an isotopically heterogeneous protoplanetary disk (9, 15, 17, 18, 20, 21). The main driver of the isotopic heterogeneity could be a change in the composition of infalling material during collapse of the parental molecular cloud core of the Solar System (14, 32, 33), or alternatively, unmixing of presolar carriers by disk processes (9, 10, 19). Irrespective of the origin of the heterogeneity, it requires the existence of large-scale isotopic heterogeneities throughout the disk. Interestingly, the Fe isotopic compositions of CI chondrites and Ryugu are similar to Earth's mantle and NC meteorites, while isotopic anomalies in other elements are similar to CC meteorites and significantly different compared to inner Solar System material (Fig. 1; Fig. 3). This suggests that CI chondrites and Ryugu derive from an isotopic reservoir that has a distinctive nucleosynthetic heritage from NC and CC meteorites. While the Fe isotopic characteristics of CI chondrites could be explained by an inner Solar System origin, the isotopic anomalies of Ti, Cr, and Mo clearly tie CI chondrites to the CC reservoir and the outer Solar System (10–12, 16, 27). More importantly, the unfractionated chemical compositions and volatile element-rich nature of CI chondrites and Ryugu support the view that they formed beyond the snow line, mostly from material that experienced minimal thermal processing. The heavy hydrogen and nitrogen isotopic compositions of Ryugu are also consistent with an outer Solar System origin (34). The findings that CI chondrites and Ryugu share the same nucleosynthetic heritage (Fig. 3) and have close mineralogical, chemical, and isotopic

characteristics (6, 34), therefore, suggest that these objects formed contemporaneously and were co-located in the same outer Solar System reservoir. It is even possible, although not required by the data, that CI chondrites and the NEO Ryugu originally derived from the same precursor object, which was fragmented by collision during its residence in the inner Main Belt (4, 35).

The distinct isotopic heritage of CI chondrites and Ryugu is unlikely to reflect a temporal change in the isotopic composition of the CC reservoir because (i) CI chondrites and Ryugu are distinct from other carbonaceous chondrites and intermediate compositions are missing (Fig. 2), and (ii) CI chondrites have similar inferred accretion ages as other carbonaceous chondrites (~ 2.5 to 4 Myr after condensation of refractory inclusions) (36). Thus, the distinctive isotopic heritage of CI chondrites and Ryugu is most likely caused by spatial separation of their source region from the CC reservoir, or as discussed below, bias in the implantation of planetesimals from distinct heliocentric distances into the Main Belt.

Cb-type asteroids like Ryugu represent ~ 10 – 20% of all C-type asteroids (37, 38), suggesting that a substantial portion of Main Belt asteroids formed in the same outer Solar System reservoir where CI chondrites and Ryugu formed. Planetesimals from a large range of heliocentric distances could have been implanted into the inner Solar System during the growth and migration of the giant planets within the protoplanetary disk, before dissipation of nebular gas (39). Planetesimals from the outer Solar System could have also been implanted during subsequent instabilities in the orbits of Uranus and Neptune after dissipation of nebular gas (40–43), but the efficiency of this process is low and early implantation of C-type asteroids in the Main Belt while nebular gas was still present is more likely. The planetesimals scattered by the growth and migration of the giant planets were originally on highly eccentric orbits but they experienced a strong headwind from nebular gas that circularized their orbits, leading to their trapping in the Main Belt. Simulations of the growth and migration of the giant planets show that most outer Solar System planetesimals implanted in the Main Belt originated from the formation region of the gas giant planets Jupiter and Saturn (e.g., ~ 4 – 12 AU), but some could have come from further away in the formation region of ice giant planets Uranus and Neptune (e.g., 13 – 25 AU) (39). The dynamical process of orbital excitation and circularization introduces strong biases in the original orbital radius of the planetesimals that are eventually implanted in the Main Belt (Fig. S4). In that context, most CC meteorites could have come from the birth region of Jupiter and Saturn, while the distinctive Fe isotopic heritage (Fig. 3) and primitive chemical characteristics of CI chondrites and Ryugu (6) could be explained if they were implanted into the Main Belt from a reservoir that was located further outside, possibly in the vicinity of the birthplaces of Uranus and Neptune (Fig. 4; Fig. S4). If correct, CI chondrites and Ryugu would possibly share a common heritage with Oort cloud comets (44, 45).

A common source region for the parent bodies of CI chondrites/Ryugu and Oort cloud comets would need to be reconciled with their present-day distinct chemical and physical characteristics (6, 34, 46). Deuterium/hydrogen (D/H) ratios of water in carbonaceous chondrites (47) and Ryugu (34) are lower than those of Oort cloud comets and overlap partially with Jupiter-family comets (48). Simulations of ice transport in the nebula predict a spatially and temporally complex evolution of water D/H ratio in the nebula (49). Furthermore, the water D/H ratio of active comets and asteroids might have been modified by water sublimation (50, 51) and water-rock

Table 1. Iron isotopic compositions of Ryugu samples and carbonaceous chondrites. Calculated mass-independent ($\mu^{54}\text{Fe}$, $\mu^{58}\text{Fe}$) and mass-dependent ($\delta^{56}\text{Fe}$) Fe isotopic compositions in Ryugu samples, carbonaceous chondrites, and geostandards. Uncertainties of individual samples are 95% confidence intervals of the mean of N standard-sample-standard bracketing analyses. Uncertainties on group averages are the 95% confidence intervals of the mean. The isotopic anomalies are calculated by internal normalization to $^{57}\text{Fe}/^{56}\text{Fe} = 0.023095$ and expressed in μ -notation (22, 24) defined as the parts-per-million deviation of the internally normalized $^{5x}\text{Fe}/^{56}\text{Fe}$ ratio in the sample relative to bracketing measurements of IRMM-524a. The mass-dependent Fe isotopic variations are calculated by sample-standard bracketing and given as δ -notation defined parts-per-thousand deviation of the $^{56}\text{Fe}/^{54}\text{Fe}$ ratio of the sample relative to the IRMM-524a standard solution.

Sample	<i>N</i>	$\mu^{54}\text{Fe}$	$\mu^{58}\text{Fe}$	$\delta^{56}\text{Fe}$
<i>Ryugu</i>				
A0106	30	-2 ± 5	14 ± 14	-0.01 ± 0.02
A0106-A0107	30	2 ± 5	10 ± 10	-0.01 ± 0.02
C0107	25	4 ± 4	15 ± 17	-0.02 ± 0.02
C0108	25	2 ± 5	11 ± 7	0.01 ± 0.02
Average Ryugu		1 ± 4	13 ± 4	-0.01 ± 0.02
<i>CI chondrites</i>				
Orgueil-1	30	2 ± 5	12 ± 8	-0.02 ± 0.02
Orgueil-2	30	3 ± 5	2 ± 11	0.01 ± 0.02
Orgueil-3	14	4 ± 9	3 ± 12	0.00 ± 0.02
Orgueil-4	30	3 ± 5	12 ± 8	0.06 ± 0.02
Ivuna	30	1 ± 4	16 ± 11	0.00 ± 0.02
Alais	28	6 ± 6	17 ± 12	-0.02 ± 0.02
Average CI		3 ± 2	10 ± 6	0.00 ± 0.02
<i>CM chondrites</i>				
Murchison-1	14	23 ± 5	6 ± 7	0.00 ± 0.02
Murchison-2	15	18 ± 6	2 ± 9	0.01 ± 0.02
Mighei	14	27 ± 8	7 ± 9	-0.01 ± 0.02
Average CM		24 ± 7	6 ± 11	0.00 ± 0.02
<i>CV chondrites</i>				
Allende-1	15	29 ± 4	2 ± 9	-0.02 ± 0.02
Allende-2	15	32 ± 6	2 ± 9	-0.05 ± 0.02
Allende-3	15	21 ± 7	3 ± 12	0.08 ± 0.02
Vigarano	15	29 ± 5	-7 ± 13	0.02 ± 0.02
Average CV		28 ± 6	0 ± 6	0.01 ± 0.08
<i>CO chondrites</i>				
Ornans	15	21 ± 5	0 ± 8	-0.03 ± 0.02
Lance	15	18 ± 5	1 ± 10	0.01 ± 0.02
<i>CR chondrites</i>				
Acfer 139	14	38 ± 8	9 ± 11	-0.11 ± 0.02
GRA 06100	15	39 ± 5	9 ± 6	0.00 ± 0.02
<i>Ungrouped chondrites</i>				
Tagish Lake-1	15	18 ± 7	2 ± 14	-0.03 ± 0.02
Tagish Lake-2	15	15 ± 6	2 ± 22	0.05 ± 0.02
Tarda	30	24 ± 8	3 ± 12	-0.01 ± 0.02
<i>Geostandards</i>				
BHVO-2-1	15	1 ± 7	-9 ± 8	0.09 ± 0.02
BHVO-2-2	15	1 ± 7	-1 ± 11	0.06 ± 0.02
AGV-2	30	2 ± 4	1 ± 6	0.08 ± 0.02
Average Geostandards		1 ± 1	-3 ± 14	0.09 ± 0.06

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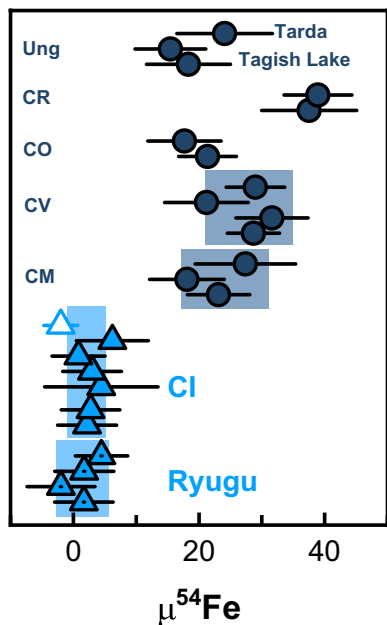


Fig. 2. Fe isotopic anomalies of returned samples from Cb-type asteroid (162173) Ryugu and carbonaceous chondrites (Table 1). Ryugu samples and CI chondrites have identical $\mu^{54}\text{Fe}$ values, which is distinct from all other carbonaceous chondrite groups (CM, CV, CO, CR, Ung = ungrouped). The Open triangle is the CI chondrite average from Schiller et al. (22).

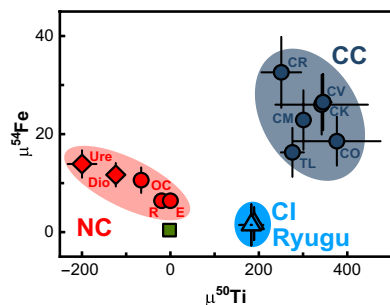


Fig. 3. Isotopic anomalies of Fe and Ti in Solar System materials. Ryugu samples and CI chondrites have identical $\mu^{54}\text{Fe}$ and $\mu^{50}\text{Ti}$ values that are distinct from other meteorites. Red circles correspond to non-carbonaceous (NC) chondrite groups (E = enstatite; R = rumuruti; OC = ordinary chondrites), red diamonds to NC achondrites (Ure = ureilites; Dio = diogenites), and blue circles to carbonaceous (CC) chondrite groups (TL = Tagish Lake). The green square is Earth's mantle. The average composition of Ryugu and Ivuna-type carbonaceous chondrites (CI) are shown as triangles. Average compositions of meteorite groups and Earth's mantle are calculated using data from this study (Table 1) and the data compilation of Burkhardt et al. (64) (Table S1). If not visible, error bars are smaller than symbols.

reactions (52) during their lifetimes. Therefore, the present-day water D/H ratio of ice in comets and rock-bound water in carbonaceous chondrites provide little insights into formation locations. CI chondrites and Ryugu show evidence for extensive aqueous alteration as late as ~5 Myr after the birth of the Solar System (6, 53, 54). Water responsible for this aqueous alteration would have presumably been accreted as ice, with melting caused by decay of ^{26}Al . Such melting could have been hampered in ice-rich comets if much of radioactive heat from ^{26}Al was consumed by ice sublimation rather than melting (55). While most dust grains captured in the coma of comet

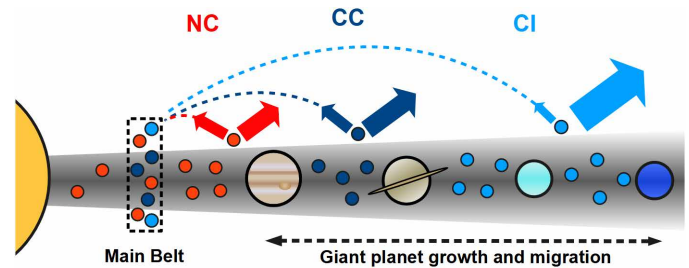


Fig. 4. Schematic of the possible source region of Cb-type asteroids and CI chondrites. Planetesimals formed in different regions of the protoplanetary disk. Volatile-poor planetesimals (red circles) formed in the inner region, while volatile-rich planetesimals (blue circles) formed beyond Jupiter's orbit. The growth and migration of the gas and ice giant planets implanted some of the planetesimals into the Main Belt (small arrows), while the majority of planetesimals were transported outwards or ejected from the disk (large arrows) (39). A plausible explanation for the different Fe nucleosynthetic heritage and primitive chemical composition of CI chondrites and Ryugu is that they were implanted in the Main Belt by excitation from Uranus and Neptune (filled bright blue circles), while other CCs formed in more internal regions near Jupiter and Saturn (filled dark blue circles) (Fig. S4). The icy planetesimals that were formed around Uranus and Neptune and were ejected outwards went to populate the Oort cloud (44, 45). CI chondrites and Ryugu may thus share some parentage with long-period comets. Such a scenario could explain the trichotomy between NC, CC, and CI for nucleosynthetic anomalies (Fig. 3).

81P/Wild2 were anhydrous (46), Berger et al. (56) found evidence for low-temperature aqueous activity in 81P/Wild2 under conditions akin to those inferred for CI chondrites. The Deep Impact mission also found signatures of carbonates, phyllosilicates, sulfides, water gas, and ice in the ejecta of comet 9P/Tempel, which is consistent with extensive aqueous alteration (57). While these observations support the presence of aqueous activity on extant comets, a comparison between icy planetesimals that were scattered inwards and outwards by the growth and migration of the giant planets is difficult because they would have experienced very different thermal histories. Indeed, the planetesimals scattered inwards would have been put on eccentric orbits with low perihelion, well inside the snow line, where ice could have been sublimated and the more volatile compounds could have been lost. For a ~100 km planetesimal, the timescale for damping eccentricity through gas interaction is on the order of several tens of thousands of years, which is in the order of the expected lifetime of short-period comets (58). Thus, the rock/ice ratio of ice-rich planetesimals formed around Uranus and Neptune may have increased substantially by the time these planetesimals were implanted in the Main Belt. Such processing could also have affected other characteristics of the icy planetesimals, notably their inventories of organics, mineralogical compositions, and physical properties. Further transformations would have taken place due to collisions during residence in the Main Belt (35, 59). Consequently, although the Ryugu asteroid and Oort cloud comets may have been born in the same region of the protoplanetary disk, they would have rapidly diverged in their chemical evolution after being scattered inwards and outwards by the ice giant planets.

In our model, Cb-type asteroids formed in a reservoir that was located at the outskirts of the planetary accretion region and were possibly implanted into the Main Belt due to excitation by Uranus and Neptune (Fig. 4). The outer extent of this isotopic reservoir is unknown. The main source region of Kuiper Belt objects (KBOs) was likely the trans-Neptunian disk (>20–25 AU) (60). These KBOs are out of

reach for sample return missions but possible trans-Neptunian objects 203 Pompeja and 269 Justitia were recently found in the Main Belt (61). Measuring the Fe and Ti isotopic compositions of these objects would provide important new insights into the isotopic architecture of the early Solar System and help evaluate the extent of the CI reservoir.

MATERIALS AND METHODS

Samples, preparation, and chemical purification

The Hayabusa2 spacecraft returned a total of ~5 g of material from Cb-type (162173) asteroid Ryugu. Surface samples were collected in Chamber A (~3 g) during the first touchdown and subsurface samples in Chamber C (~2 g) during the second touchdown (5, 62). Two subsamples from Chamber A (A0106, A0106-A0107) and two from Chamber C (C0107, C0108) were digested for isotopic analysis (Table 1). Sample masses were 14.2, 23.88, 14.20, 12.90, and 22.24 mg, respectively. For samples A0106 and C0107 soluble organic matter was separated prior to digestion by acids. Sample A0108 was analyzed by XRF before digestion. Approximately 20–25 mg of six carbonaceous chondrite powders (Table 1: Orgueil-4, Alais, Murchison-2, Allende-3, Tagish Lake-2, and Tarda) were digested and processed together with the Hayabusa2 samples. Sample digestion for these samples was conducted at Tokyo Tech. Powder aliquots were digested using mixtures of HF-HNO₃-HCl-H₂O₂ on hot plate and under ultrasonic agitation. Approximately 80% of the solutions was taken for sequential separation of several elements for isotopic analysis. We measured 20 additional carbonaceous chondrite samples and three terrestrial geostandards (Table 1) to provide some context for interpreting Ryugu's results. Some samples were digested for this study while others are elution cuts from previous studies focused on elements other than Fe. The masses digested, original masses homogenized, and details on the processing history for each sample are summarized in Table S2. The first step in the chemical processing of Fe in the four Ryugu samples and six accompanying carbonaceous chondrites was conducted at Tokyo Tech and involved: (i) separation of major elements, including Fe, from Zn, Pb, and highly siderophile elements using anion exchange chromatography (AG-1X8), (ii) Separation of Fe and U from remaining major elements using AG-1X8, and (iii) Separation of U from Fe using Eichrom UTEVA resin. A 20% aliquot of the Fe solution was then purified from remaining traces of Cr, Ni, Co, and Cu at the University of Chicago using an established protocol (24). Approximately 0.5–1 mg of Fe was loaded in 0.25 ml 10 M HCl onto 10.5 cm long PFA columns (0.62 cm inner diameter) filled with 3 ml pre-cleaned AG1-X8 (200–400 mesh) anion resin. Matrix elements were eluted in 5 ml 10 M HCl. Other possible contaminants (*e.g.*, Cu, Cr) were eluted from the resin using 30 ml 4 M HCl. Iron was eluted using 9 ml 0.4 M HCl. The samples not previously processed at Tokyo Institute of Technology were purified using the same procedure, but the elution was repeated using new resin. The overall Fe yield is >99% and the procedural blank is negligible (~70 ng) compared to the amount of Fe purified for each sample (0.5–1 mg Fe). Interfering elements Cr (⁵⁴Cr on ⁵⁴Fe) and Ni (⁵⁸Ni on ⁵⁸Fe) were present at low enough levels (Cr/Fe ≤ 9 × 10⁻⁶ and Ni/Fe ≤ 2 × 10⁻⁵) to not affect the accuracy of the analyses (24).

Iron isotopic measurements

High precision Fe isotopic compositions were measured following the protocol used for analysis of Fe isotopic anomalies in iron

meteorites (24). Measurements were conducted with a Thermo Scientific Neptune multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS) at the Origins Laboratory of the University of Chicago. Measurements were made on the flat-topped peak shoulder in medium-resolution (MR) mode (63). Ion beams of ⁵⁴Fe⁺, ⁵⁶Fe⁺, ⁵⁷Fe⁺, and ⁵⁸Fe⁺ were analyzed statically on Faraday collectors. All isotopes were measured using 10¹¹ Ω amplifiers, except for high abundance ⁵⁶Fe⁺, which was measured using a 10¹⁰ Ω amplifier. Isobaric interferences from ⁵⁴Cr⁺ and ⁵⁸Ni⁺ were determined simultaneously by monitoring ⁵³Cr⁺ and ⁶⁰Ni⁺ using 10¹² Ω amplifiers. The purified Fe solutions (10 μg/g in 0.3 M HNO₃) were introduced into the MC-ICP-MS using an ESI PFA nebulizer with an uptake rate of ~100 μl/min combined with a cyclonic glass spray chamber. Iron isotopic composition was measured at a typical ⁵⁶Fe⁺ ion signal intensity of 1.3 nA on a 10¹⁰ Ω amplifier. Each measurement consisted of 50 cycles of 8.369 s each. Sample analyses were bracketed by measurements of IRMM-524a in a standard-sample-standard scheme. On peak zero intensities from a blank solution measured at the start of each sequence were subtracted from measurements. A washout time of 210 s was used between each analysis. The Fe concentrations of the samples and standards were matched to within ≤2 %, which is required for accurate and precise Fe isotopic analysis (24).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <https://science.org/doi/10.1126/sciadv.add8141>

REFERENCES AND NOTES

1. F. E. DeMeo, B. J. Burt, M. Marsset, D. Polishook, T. H. Burbine, B. Carry, R. P. Binzel, P. Vernazza, V. Reddy, M. Tang, C. A. Thomas, A. S. Rivkin, N. A. Moskovitz, S. M. Slivan, S. J. Bus, Connecting asteroids and meteorites with visible and near-infrared spectroscopy. *Icarus* **380**, 114971 (2022).
2. L. T. Elkins-Tanton, E. Asphaug, J. F. Bell, C. J. Bierson, B. G. Bills, W. F. Bottke, S. W. Courville, S. D. Dobb, I. Jun, D. J. Lawrence, S. Marchi, T. J. McCoy, J. M. G. Merayo, B. Oran, J. G. O'Rourke, R. S. Park, P. N. Peplowski, T. H. Prettyman, C. A. Raymond, B. P. Weiss, M. A. Wicczorek, M. T. Zuber, Distinguishing the origin of asteroid (16) Psyche. *Space Sci. Rev.* **218**, 17 (2022).
3. D. S. Lauretta, C. W. Hergenrother, S. R. Chesley, J. M. Leonard, J. Y. Pelgrift, C. D. Adam, M. Al Asad, P. G. Antreasian, R. L. Ballouz, K. J. Becker, C. A. Bennett, B. J. Bos, W. F. Bottke, M. Brozović, H. Campins, H. C. Connolly, M. G. Daly, A. B. Davis, J. de León, D. N. DellaGiustina, C. Y. Drouet d'Aubigny, J. P. Dworkin, J. P. Emery, D. Farnocchia, D. P. Glavin, D. R. Golish, C. M. Hartzell, R. A. Jacobson, E. R. Jawin, P. Jenniskens, J. N. Kidd, E. J. Lessac-Chenen, J. Y. Li, G. Libourel, J. Licandro, A. J. Liounis, C. K. Maleszewski, C. Manzoni, B. May, L. K. McCarthy, J. W. McMahon, P. Michel, J. L. Molaro, M. C. Moreau, D. S. Nelson, W. M. Owen, B. Rizk, H. L. Roper, B. Rozitis, E. M. Sahr, D. J. Scheeres, J. A. Seabrook, S. H. Selznick, Y. Takahashi, F. Thuillet, P. Tricarico, D. Vokrouhlický, C. W. V. Wolner, Episodes of particle ejection from the surface of the active asteroid (101955) Bennu. *Science* **366**, eaay3544 (2019).
4. H. Campins, J. de León, A. Morbidelli, J. Licandro, J. Gayon-Markt, M. Delbo, P. Michel, The origin of asteroid 162173 (1999 JU3). *Astron. J.* **146**, 26 (2013).
5. S. Tachibana, H. Sawada, R. Okazaki, Y. Takano, K. Sakamoto, Y. N. Miura, C. Okamoto, H. Yano, S. Yamanoouchi, P. Michel, Y. Zhang, S. Schwartz, F. Thuillet, H. Yurimoto, T. Nakamura, T. Noguchi, H. Yabuta, H. Naraoka, A. Tsuchiyama, N. Imae, K. Kurosawa, A. M. Nakamura, K. Ogawa, S. Sugita, T. Morota, R. Honda, S. Kameda, E. Tatsumi, Y. Cho, K. Yoshioka, Y. Yokota, M. Hayakawa, M. Matsuoka, N. Sakatani, M. Yamada, T. Kouyama, H. Suzuki, C. Honda, T. Yoshimitsu, T. Kubota, H. Demura, T. Yada, M. Nishimura, K. Yogata, A. Nakato, M. Yoshitake, A. I. Suzuki, S. Furuya, K. Hatakeda, A. Miyazaki, K. Kumagai, T. Okada, M. Abe, T. Usui, T. R. Ireland, M. Fujimoto, T. Yamada, M. Arakawa, H. C. Connolly Jr., A. Fujii, S. Hasegawa, N. Hirata, C. Hirose, S. Hosoda, Y. Iijima, H. Ikeda, M. Ishiguro, Y. Ishihara, T. Iwata, S. Kikuchi, K. Kitazato, D. S. Lauretta, G. Libourel, B. Marty, K. Matsumoto, T. Michikami, Y. Mimasu, A. Miura, O. Mori, K. Nakamura-Messenger, N. Namiki, A. N. Nguyen, L. R. Nittler, H. Noda, R. Noguchi, N. Ogawa, G. Ono, M. Ozaki, H. Senshu, T. Shimada, Y. Shimaki, K. Shirai, S. Soldini, T. Takahashi, Y. Takei, H. Takeuchi, R. Tsukizaki, K. Wada, Y. Yamamoto, K. Yoshikawa, K. Yumoto, M. E. Zolensky, S. Nakazawa, F. Terui, S. Tanaka, T. Saiki, M. Yoshikawa, S. Watanabe, Y. Tsuda, Pebbles

- and sand on asteroid (162173) Ryugu: In situ observation and particles returned to Earth. *Science* **375**, 1011–1016 (2022).
6. T. Yokoyama, K. Nagashima, I. Nakai, E. D. Young, Y. Abe, J. Aléon, C. M. O'D. Alexander, S. Amari, Y. Amelin, K.-I. Bajor, M. Bizzarro, A. Bouvier, R. W. Carlson, M. Chaussidon, B.-G. Choi, N. Dauphas, A. M. Davis, T. di Rocco, W. Fujiya, R. Fukai, I. Gautam, M. K. Haba, Y. Hibiya, H. Hidaka, H. Homma, P. Hoppe, G. R. Huss, K. Ichida, T. Iizuka, T. R. Ireland, A. Ishikawa, M. Ito, S. Itoh, N. Kawasaki, N. T. Kita, K. Kitajima, T. Kleine, S. Komatani, A. N. Krot, M.-C. Liu, Y. Masuda, K. D. McKeegan, M. Morita, K. Motomura, F. Moynier, A. Nguyen, L. Nittler, M. Onose, A. Pack, C. Park, L. Piani, L. Qin, S. S. Russell, N. Sakamoto, M. Schönbachler, L. Tafla, H. Tang, K. Terada, Y. Terada, T. Usui, S. Wada, M. Wadhwa, R. J. Walker, K. Yamashita, Q.-Z. Yin, S. Yoneda, H. Yui, A.-C. Zhang, H. C. Connolly, H. Sawada, H. Senshu, Y. Shimaki, K. Shirai, S. Sugita, Y. Takei, H. Takeuchi, S. Tanaka, E. Tatsumi, F. Terui, Y. Tsuda, R. Tsukizaki, K. Wada, S.-i. Watanabe, M. Yamada, T. Yamada, Y. Yamamoto, H. Yano, Y. Yokota, K. Yoshihara, M. Yoshikawa, K. Yoshikawa, S. Furuya, K. Hatakeda, T. Hayashi, Y. Hitomi, K. Kumagai, A. Miyazaki, A. Nakato, M. Nishimura, H. Soejima, A. Suzuki, T. Yada, D. Yamamoto, K. Yogata, M. Yoshitake, S. Tachibana, H. Yurimoto, The first returned samples from a C-type asteroid show kinship to the chemically most primitive meteorites. *Science first release*, 1–8 (2022).
 7. K. Lodders, Relative atomic solar system abundances, mass fractions, and atomic masses of the elements and their isotopes, composition of the solar photosphere, and compositions of the major chondritic meteorite groups. *Space Sci. Rev.* **217**, 44 (2021).
 8. N. Dauphas, B. Marty, L. Reisberg, Molybdenum evidence for inherited planetary scale isotope heterogeneity of the protosolar nebula. *Astrophys. J.* **565**, 640–644 (2002).
 9. M. Ek, A. C. Hunt, M. Lugaro, M. Schönbachler, The origin of s-process isotope heterogeneity in the solar protoplanetary disk. *Nat. Astron.* **4**, 273–281 (2020).
 10. A. Trinquier, T. Elliott, D. Ulfbeck, C. Coath, A. N. Krot, M. Bizzarro, Origin of nucleosynthetic isotope heterogeneity in the solar protoplanetary disk. *Science* **324**, 374–376 (2009).
 11. A. Trinquier, J.-L. Birck, C. J. Allègre, Widespread ^{54}Cr heterogeneity in the inner Solar System. *Astrophys. J.* **655**, 1179–1185 (2007).
 12. C. Burkhardt, T. Kleine, F. Oberli, A. Pack, B. Bourdon, R. Wieler, Molybdenum isotope anomalies in meteorites: Constraints on solar nebula evolution and origin of the Earth. *Earth Planet. Sci. Lett.* **312**, 390–400 (2011).
 13. P. H. Warren, Stable-isotopic anomalies and the accretionary assemblage of the Earth and Mars: A subordinate role for carbonaceous chondrites. *Earth Planet. Sci. Lett.* **311**, 93–100 (2011).
 14. N. Dauphas, E. A. Schauble, Mass fractionation laws, mass-independent effects, and isotopic anomalies. *Annu. Rev. Earth Planet. Sci.* **44**, 709–783 (2016).
 15. T. S. Kruijer, C. Burkhardt, G. Budde, T. Kleine, Age of Jupiter inferred from the distinct genetics and formation times of meteorites. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 6712–6716 (2017).
 16. G. Budde, C. Burkhardt, G. A. Brennecka, M. Fischer-Gödde, T. S. Kruijer, T. Kleine, Molybdenum isotopic evidence for the origin of chondrules and a distinct genetic heritage of carbonaceous and non-carbonaceous meteorites. *Earth Planet. Sci. Lett.* **454**, 293–303 (2016).
 17. T. Lichtenberg, J. Drazkowska, M. Schönbachler, G. J. Golabek, T. O. Hands, Bifurcation of planetary building blocks during Solar System formation. *Science* **371**, 365–370 (2021).
 18. A. Morbidelli, K. Baillié, K. Batygin, S. Charnoz, T. Guillot, D. C. Rubie, T. Kleine, Contemporary formation of early Solar System planetesimals at two distinct radial locations. *Nat. Astron.* **6**, 72–79 (2022).
 19. M. Schiller, M. Bizzarro, V. A. Fernandes, Isotopic evolution of the protoplanetary disk and the building blocks of Earth and the Moon. *Nature* **555**, 501–510 (2018).
 20. B. Liu, A. Johansen, M. Lambrechts, M. Bizzarro, T. Haugbølle, Natural separation of two primordial planetary reservoirs in an expanding solar protoplanetary disk. *Sci. Adv.* **8**, eabm3045 (2022).
 21. A. Izidoro, R. Dasgupta, S. N. Raymond, R. Deienno, B. Bitsch, A. Isella, Planetesimal rings as the cause of the Solar System's planetary architecture. *Nat. Astron.* **6**, 357–366 (2022).
 22. M. Schiller, M. Bizzarro, J. Siebert, Iron isotope evidence for very rapid accretion and differentiation of the proto-Earth. *Sci. Adv.* **6**, eaay7604 (2020).
 23. D. L. Cook, B. S. Meyer, M. Schönbachler, Iron and nickel isotopes in IID and IVB iron meteorites: Evidence for admixture of an SN II component and implications for the initial abundance of ^{60}Fe . *Astrophys. J.* **917**, 59 (2021).
 24. T. Hopp, N. Dauphas, F. Spitzer, C. Burkhardt, T. Kleine, Earth's accretion inferred from iron isotopic anomalies of supernova nuclear statistical equilibrium origin. *Earth Planet. Sci. Lett.* **577**, 117245 (2022).
 25. O. Eugster, Cosmic-ray exposure ages of meteorites and lunar rocks and their significance. *Chem. Erde* **63**, 3–30 (2003).
 26. D. L. Cook, I. Leya, M. Schönbachler, Galactic cosmic ray effects on iron and nickel isotopes in iron meteorites. *Meteorit. Planet. Sci.* **55**, 2758–2771 (2020).
 27. I. Leya, M. Schönbachler, U. Wiechert, U. Krähenbühl, A. N. Halliday, Titanium isotopes and the radial heterogeneity of the solar system. *Earth Planet. Sci. Lett.* **266**, 233–244 (2008).
 28. R. N. Clayton, T. K. Mayeda, Oxygen isotope studies of carbonaceous chondrites. *Geochim. Cosmochim. Acta* **63**, 2089–2104 (1999).
 29. A. Shukolyukov, G. W. Lugmair, Manganese–chromium isotope systematics of carbonaceous chondrites. *Earth Planet. Sci. Lett.* **250**, 200–213 (2006).
 30. L. Qin, C. M. O'D. Alexander, R. W. Carlson, M. F. Horan, T. Yokoyama, Contributors to chromium isotope variation of meteorites. *Geochim. Cosmochim. Acta* **74**, 1122–1145 (2010).
 31. J. Zhang, N. Dauphas, A. M. Davis, I. Leya, A. Fedkin, The proto-Earth as a significant source of lunar material. *Nat. Geosci.* **5**, 251–255 (2012).
 32. J. A. M. Nanne, F. Nimmo, J. N. Cuzzi, T. Kleine, Origin of the non-carbonaceous–carbonaceous meteorite dichotomy. *Earth Planet. Sci. Lett.* **511**, 44–54 (2019).
 33. C. Burkhardt, N. Dauphas, U. Hans, B. Bourdon, T. Kleine, Elemental and isotopic variability in solar system materials by mixing and processing of primordial disk reservoirs. *Geochim. Cosmochim. Acta* **261**, 145–170 (2019).
 34. M. Ito, N. Tomioka, M. Uesugi, A. Yamaguchi, N. Shirai, T. Ohigashi, M. C. Liu, R. C. Greenwood, M. Kimura, N. Imae, K. Uesugi, A. Nakato, K. Yogata, H. Yuzawa, Y. Kodama, A. Tsuchiyama, M. Yasutake, R. Findlay, I. A. Franchi, J. A. Malley, K. A. McCain, N. Matsuda, K. D. McKeegan, K. Hirahara, A. Takeuchi, S. Sekimoto, I. Sakurai, I. Okada, Y. Karouji, M. Arakawa, A. Fujii, M. Fujimoto, M. Hayakawa, N. Hirata, N. Hirata, R. Honda, C. Honda, S. Hosoda, Y. ichi Iijima, H. Ikeda, M. Ishiguro, Y. Ishihara, T. Iwata, F. Kawahara, S. Kikuchi, K. Kitazato, K. Matsumoto, M. Matsuoka, T. Michikami, Y. Mimasu, A. Miura, O. Mori, T. Morota, S. Nakazawa, N. Namiki, H. Noda, R. Noguchi, N. Ogawa, K. Ogawa, T. Okada, C. Okamoto, G. Ono, M. Ozaki, T. Saiki, N. Sakatani, H. Sawada, H. Senshu, Y. Shimaki, K. Shirai, S. Sugita, Y. Takei, H. Takeuchi, S. Tanaka, E. Tatsumi, F. Terui, R. Tsukizaki, K. Wada, M. Yamada, T. Yamada, Y. Yamamoto, H. Yano, Y. Yokota, K. Yoshihara, M. Yoshikawa, K. Yoshikawa, R. Fukai, S. Furuya, K. Hatakeda, T. Hayashi, Y. Hitomi, K. Kumagai, A. Miyazaki, M. Nishimura, H. Soejima, A. Iwamae, D. Yamamoto, M. Yoshitake, T. Yada, M. Abe, T. Usui, S.-i. Watanabe, Y. Tsuda, A pristine record of outer Solar System materials from asteroid Ryugu's returned sample. *Nat. Astron.* 10.1038/s41550-022-01745-5, (2022).
 35. W. F. Bottke, M. Brož, D. P. O'Brien, A. C. Bagatin, A. Morbidelli, S. Marchi, The collisional evolution of the main asteroid belt, in *Asteroids IV* (University of Arizona Press, 2015), pp. 701–724.
 36. N. Sugiura, W. Fujiya, Correlated accretion ages and $\epsilon^{54}\text{Cr}$ of meteorite parent bodies and the evolution of the solar nebula. *Meteorit. Planet. Sci.* **49**, 772–787 (2014).
 37. A. S. Rivkin, The fraction of hydrated C-complex asteroids in the asteroid belt from SDSS data. *Icarus* **221**, 744–752 (2012).
 38. F. E. DeMeo, R. P. Binzel, S. M. Slivan, S. J. Bus, An extension of the Bus asteroid taxonomy into the near-infrared. *Icarus* **202**, 160–180 (2009).
 39. S. N. Raymond, A. Izidoro, Origin of water in the inner Solar System: Planetesimals scattered inward during Jupiter and Saturn's rapid gas accretion. *Icarus* **297**, 134–148 (2017).
 40. H. F. Levison, W. F. Bottke, M. Gounelle, A. Morbidelli, D. Nesvorný, K. Tsiganis, Contamination of the asteroid belt by primordial trans-Neptunian objects. *Nature* **460**, 364–366 (2009).
 41. B. Liu, S. N. Raymond, S. A. Jacobson, Early Solar System instability triggered by dispersal of the gaseous disk. *Nature* **604**, 643–646 (2022).
 42. D. Vokrouhlický, W. F. Bottke, D. Nesvorný, Capture of trans-Neptunian planetesimals in the main asteroid belt. *Astron. J.* **152**, 39 (2016).
 43. R. de S. Ribeiro, A. Morbidelli, S. N. Raymond, A. Izidoro, R. Gomes, E. Vieira Neto, Dynamical evidence for an early giant planet instability. *Icarus* **339**, 113605 (2020).
 44. J. A. Fernández, W.-H. Ip, Dynamical evolution of a cometary swarm in the outer planetary region. *Icarus* **47**, 470–479 (1981).
 45. M. Duncan, T. Quinn, S. Tremaine, The formation and extent of the Solar System comet cloud. *Astron. J.* **94**, 1330–1339 (1987).
 46. D. Brownlee, P. Tsou, J. Aléon, C. M. O'D. Alexander, T. Araki, S. Bajt, G. A. Baratta, R. Bastien, P. Bland, P. Bleuet, J. Borg, J. P. Bradley, A. Brearley, F. Brenker, S. Brennan, J. C. Bridges, N. D. Browning, J. R. Brucato, E. Bullock, M. J. Burchell, H. Busemann, A. Butterworth, M. Chaussidon, A. Cheuvront, M. Chi, M. J. Cintala, B. C. Clark, S. J. Clemett, G. Cody, L. Colangeli, G. Cooper, P. Cordier, C. Daghlain, Z. Dai, Z. Djouadi, G. Dominguez, T. Duxbury, J. P. Dworkin, D. S. Ebel, T. E. Economou, S. Fakra, S. A. J. Fairey, S. Fallon, G. Ferrini, T. Ferroir, H. Fleckenstein, C. Floss, G. Flynn, I. A. Franchi, M. Fries, Z. Gainsforth, J. Gallien, M. Genge, M. K. Gilles, P. Gillet, J. Gilmour, D. P. Glavin, M. Gounelle, M. M. Grady, G. A. Graham, P. G. Grant, S. F. Green, F. Grossemly, L. Grossman, J. N. Grossman, Y. Guan, K. Hagiya, R. Harvey, P. Heck, G. F. Herzog, P. Hoppe, F. Hörz, J. Huth, I. D. Hutcheon, K. Ignatyev, H. Ishii, M. Ito, D. Jacob, C. Jacobsen, S. Jacobsen, S. Jones, D. Joswiak, A. Jurewicz, A. T. Kearsley, L. P. Keller, H. Khodja, A. D. Kilcoyne, J. Kissel, A. Krot, F. Langenhorst, A. Lanzirrotti, L. Le, L. A. Leshin, J. Leitner, L. Lemelle, H. Leroux, M.-C. Liu, K. Luening, I. Lyon, G. MacPherson, M. A. Marcus, K. Marhas, B. Marty, G. Matrajt, K. McKeegan, D. A. Papanastassiou, R. Palma, M. E. Palumbo, R. O. Pepin, D. Perkins, M. Perronnet, P. Pianetta, W. Rao, F. J. M. Rietmeijer, F. Robert, D. Rost,

- A. Rotundi, R. Ryan, S. A. Sandford, C. S. Schwandt, T. H. See, D. Schlutter, J. Sheffield-Parker, A. Simonovic, S. Simon, I. Sitnitsky, C. J. Snead, M. K. Spencer, F. J. Stadermann, A. Steele, T. Stephan, R. Stroud, J. Susini, S. R. Sutton, Y. Suzuki, M. Taheri, S. Taylor, N. Teslich, K. Tomeoka, N. Tomioka, A. Toppini, J. M. Trigo-Rodríguez, D. Troadec, A. Tsuchiyama, A. J. Tuzzolino, T. Tyliczszak, K. Uesugi, M. Velbel, J. Vellenga, E. Vicenzi, L. Vincze, J. Warren, I. Weber, M. Weisberg, A. J. Westphal, S. Wirick, D. Wooden, B. Wopenka, P. Wozniakiewicz, I. Wright, H. Yabuta, H. Yano, E. D. Young, R. N. Zare, T. Zega, K. Ziegler, L. Zimmermann, E. Zinner, M. Zolensky, Comet 81P/Wild 2 under a microscope. *Science* **314**, 1711–1716 (2006).
47. C. M. O'D. Alexander, R. Bowden, M. L. Fogel, K. T. Howard, C. D. K. Herd, L. R. Nittler, The provenances of asteroids, and their contributions to the volatile inventories of the terrestrial planets. *Science* **337**, 721–723 (2012).
48. D. R. Müller, K. Altwegg, J. J. Berthelier, M. Combi, J. de Keyser, S. A. Fuselier, N. Hänni, B. Pestoni, M. Rubin, I. R. H. G. Schroeder, S. F. Wampfler, High D/H ratios in water and alkanes in comet 67P/Churyumov-Gerasimenko measured with the Rosetta/ROSINA DFMS. *Astron. Astrophys.* **662**, A69 (2022).
49. L. Yang, F. J. Ciesla, C. M. O'D. Alexander, The D/H ratio of water in the solar nebula during its formation and evolution. *Icarus* **226**, 256–267 (2013).
50. D. C. Lis, D. Bockelée-Morvan, R. Güsten, N. Biver, J. Stutzki, Y. Delorme, C. Durán, H. Wiesemeyer, Y. Okada, Terrestrial deuterium-to-hydrogen ratio in water in hyperactive comets. *Astron. Astrophys.* **625**, L5 (2019).
51. R. H. Brown, D. S. Lauretta, B. Schmidt, J. Moores, Experimental and theoretical simulations of ice sublimation with implications for the chemical, isotopic, and physical evolution of icy objects, in *Planetary and Space Science* (2012), vol. 60, pp. 166–180.
52. C. M. O. D. Alexander, S. D. Newsome, M. L. Fogel, L. R. Nittler, H. Busemann, G. D. Cody, Deuterium enrichments in chondritic macromolecular material—Implications for the origin and evolution of organics, water and asteroids. *Geochim. Cosmochim. Acta* **74**, 4417–4437 (2010).
53. A. J. Brearley, The action of water, in *Meteorites and the Early Solar System*, D. S. Lauretta, H. Y. McSweeney, Eds. (University of Arizona Press, IL, 2006), pp. 587–624.
54. E. Nakamura, K. Kobayashi, R. Tanaka, T. Kunihiro, H. Kitagawa, C. Potiszi, T. Ota, C. Sakaguchi, M. Yamanaka, D. M. Ratnayake, H. Tripathi, R. Kumar, M. L. Avramescu, H. Tsuchida, Y. Yachi, H. Miura, M. Abe, R. Fukai, S. Furuya, K. Hatakeda, T. Hayashi, Y. Hitomi, K. Kumagai, A. Miyazaki, A. Nakato, M. Nishimura, T. Okada, H. Soejima, S. Sugita, A. Suzuki, T. Usui, T. Yada, D. Yamamoto, K. Yogata, M. Yoshitake, M. Arakawa, A. Fujii, M. Hayakawa, N. Hirata, R. Honda, C. Honda, S. Hosoda, Y. I. Iijima, H. Ikeda, M. Ishiguro, Y. Ishihara, T. Iwata, K. Kawahara, S. Kikuchi, K. Kitazato, K. Matsumoto, M. Matsuoka, T. Michikami, Y. Mimasu, A. Miura, T. Morota, S. Nakazawa, N. Namiki, H. Noda, R. Noguchi, N. Ogawa, K. Ogawa, C. Okamoto, G. Ono, M. Ozaki, T. Saiki, N. Sakatani, H. Sawada, H. Senshu, Y. Shimaki, K. Shirai, Y. Takei, H. Takeuchi, S. Tanaka, E. Tatsumi, F. Terui, R. Tsukizaki, K. Wada, M. Yamada, T. Yamada, Y. Yamamoto, H. Yano, Y. Yokota, K. Yoshikawa, M. Yoshikawa, K. Yoshikawa, M. Fujimoto, S.-i. Watanabe, Y. Tsuda, On the origin and evolution of the asteroid Ryugu: A comprehensive geochemical perspective. *Proc. Jpn. Acad. Ser. B Phys. Biol. Sci.* **98**, 227–282 (2022).
55. M. Gounelle, A. Morbidelli, P. A. Bland, E. D. Young, M. Sephton, Meteorites from the outer solar system? in *The Solar System Beyond Neptune*, M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, A. Morbidelli, Eds. (Univ Arizona Press, 2008), pp. 525–541.
56. E. L. Berger, T. J. Zega, L. P. Keller, D. S. Lauretta, Evidence for aqueous activity on comet 81P/Wild 2 from sulfide mineral assemblages in Stardust samples and CI chondrites. *Geochim. Cosmochim. Acta* **75**, 3501–3513 (2011).
57. C. M. Lisse, J. Vancleve, A. C. Adams, M. F. A'hearn, Y. R. Fernández, T. L. Farnham, L. Armus, C. J. Grillmair, J. Ingalls, M. J. S. Belton, O. Groussin, L. A. McFadden, K. J. Meech, P. H. Schultz, B. C. Clark, L. M. Feaga, J. M. Sunshine, Spitzer spectral observations of the deep impact ejecta. *Science* **313**, 635–640 (2006).
58. I. Ferrin, C. Gil, The aging of comets Halley and Encke. *Astron. Astrophys.* **194**, 288–296 (1988).
59. T. Okada, T. Fukuhara, S. Tanaka, M. Taguchi, T. Arai, H. Senshu, N. Sakatani, Y. Shimaki, H. Demura, Y. Ogawa, K. Suko, T. Sekiguchi, T. Kouyama, J. Takita, T. Matsunaga, T. Imamura, T. Wada, S. Hasegawa, J. Helbert, T. G. Müller, A. Hagermann, J. Biele, M. Grott, M. Hamm, M. Delbo, N. Hirata, N. Hirata, Y. Yamamoto, S. Sugita, N. Namiki, K. Kitazato, M. Arakawa, S. Tachibana, H. Ikeda, M. Ishiguro, K. Wada, C. Honda, R. Honda, Y. Ishihara, K. Matsumoto, M. Matsuoka, T. Michikami, A. Miura, T. Morota, H. Noda, R. Noguchi, K. Ogawa, K. Shirai, E. Tatsumi, H. Yabuta, Y. Yokota, M. Yamada, M. Abe, M. Hayakawa, T. Iwata, M. Ozaki, H. Yano, S. Hosoda, O. Mori, H. Sawada, T. Shimada, H. Takeuchi, R. Tsukizaki, A. Fujii, C. Hirose, S. Kikuchi, Y. Mimasu, N. Ogawa, G. Ono, T. Takahashi, Y. Takei, T. Yamaguchi, K. Yoshikawa, F. Terui, T. Saiki, S. Nakazawa, M. Yoshikawa, S. Watanabe, Y. Tsuda, Highly porous nature of a primitive asteroid revealed by thermal imaging. *Nature* **579**, 518–522 (2020).
60. D. Nesvorný, Dynamical evolution of the Early Solar System. *Annu. Rev. Astron. Astrophys.* **56**, 137–174 (2018).
61. S. Hasegawa, M. Marsset, F. E. DeMeo, S. J. Bus, J. Geem, M. Ishiguro, M. Im, D. Kuroda, P. Vernazza, Discovery of two TNO-like bodies in the asteroid belt. *Astrophys. J. Lett.* **916**, L6 (2021).
62. T. Yada, M. Abe, T. Okada, A. Nakato, K. Yogata, A. Miyazaki, K. Hatakeda, K. Kumagai, M. Nishimura, Y. Hitomi, H. Soejima, M. Yoshitake, A. Iwamae, S. Furuya, M. Uesugi, Y. Karouji, T. Usui, T. Hayashi, D. Yamamoto, R. Fukai, S. Sugita, Y. Cho, K. Yumoto, Y. Yabe, J. P. Bibring, C. Pilorget, V. Hamm, R. Brunetto, L. Riu, L. Louri, D. Loizeau, G. Lequertier, A. Moussi-Soffys, S. Tachibana, H. Sawada, R. Okazaki, Y. Takano, K. Sakamoto, Y. N. Miura, H. Yano, T. R. Ireland, T. Yamada, M. Fujimoto, K. Kitazato, N. Namiki, M. Arakawa, N. Hirata, H. Yurimoto, T. Nakamura, T. Noguchi, H. Yabuta, H. Naraoka, M. Ito, E. Nakamura, K. Uesugi, K. Kobayashi, T. Michikami, H. Kikuchi, N. Hirata, Y. Ishihara, K. Matsumoto, H. Noda, R. Noguchi, Y. Shimaki, K. Shirai, K. Ogawa, K. Wada, H. Senshu, Y. Yamamoto, T. Morota, R. Honda, C. Honda, Y. Yokota, M. Matsuoka, N. Sakatani, E. Tatsumi, A. Miura, M. Yamada, A. Fujii, C. Hirose, S. Hosoda, H. Ikeda, T. Iwata, S. Kikuchi, Y. Mimasu, O. Mori, N. Ogawa, G. Ono, T. Shimada, S. Soldini, T. Takahashi, Y. Takei, H. Takeuchi, R. Tsukizaki, K. Yoshikawa, F. Terui, S. Nakazawa, S. Tanaka, T. Saiki, M. Yoshikawa, S.-i. Watanabe, Y. Tsuda, Preliminary analysis of the Hayabusa2 samples returned from C-type asteroid Ryugu. *Nat. Sci.* **6**, 214–220 (2022).
63. S. Weyer, J. B. Schwieters, High precision Fe isotope measurements with high mass resolution MC-ICPMS. *Int. J. Mass Spectrom.* **226**, 355–368 (2003).
64. C. Burkhardt, F. Spitzer, A. Morbidelli, G. Budde, J. H. Render, T. S. Kruijer, T. Kleine, Terrestrial planet formation from lost inner solar system material. *Sci. Adv.* **7**, abj7601 (2021).
65. N. Dauphas, The isotopic nature of the Earth's accreting material through time. *Nature* **541**, 521–524 (2017).
66. C. Burkhardt, N. Dauphas, H. Tang, M. Fischer-Gödde, L. Qin, J. H. Chen, S. S. Rout, A. Pack, P. R. Heck, D. A. Papanastassiou, In search of the Earth-forming reservoir: Mineralogical, chemical, and isotopic characterizations of the ungrouped achondrite NWA 5363/NWA 5400 and selected chondrites. *Meteorit. Planet. Sci.* **52**, 807–826 (2017).
67. M. E. Sanborn, J. Wimpenny, C. D. Williams, A. Yamakawa, Y. Amelin, A. J. Irving, Q.-Z. Yin, Carbonaceous achondrites Northwest Africa 6704/6693: Milestones for early Solar System chronology and genealogy. *Geochim. Cosmochim. Acta* **245**, 577–596 (2019).
68. S. Gerber, C. Burkhardt, G. Budde, K. Metzler, T. Kleine, Mixing and transport of dust in the early solar nebula as inferred from titanium isotope variations among chondrules. *Astrophys. J.* **841**, L17 (2017).
69. Z. A. Torrano, D. L. Schrader, J. Davidson, R. C. Greenwood, D. R. Dunlap, M. Wadhwa, The relationship between CM and CO chondrites: Insights from combined analyses of titanium, chromium, and oxygen isotopes in CM, CO, and ungrouped chondrites. *Geochim. Cosmochim. Acta* **301**, 70–90 (2021).
70. C. D. Williams, M. E. Sanborn, C. Defouilloy, Q.-Z. Yin, N. T. Kita, D. S. Ebel, A. Yamakawa, K. Yamashita, Chondrules reveal large-scale outward transport of inner Solar System materials in the protoplanetary disk. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 23426–23435 (2020).
71. A. Anand, J. Pape, M. Wille, K. Mezger, B. Hofmann, Early differentiation of magmatic iron meteorite parent bodies from Mn–Cr chronometry. *Geochim. Perspect. Lett.* **20**, 6–10 (2021).
72. C. S. Dey, Q.-Z. Yin, M. Zolensky, Exploring the planetary genealogy of Tarda—A unique new carbonaceous chondrite, (52nd Lunar and Planetary Science Conference, 2021), p. 2548.
73. B. Mougél, F. Moynier, C. Göpel, Chromium isotopic homogeneity between the Moon, the Earth, and enstatite chondrites. *Earth Planet. Sci. Lett.* **481**, 1–8 (2018).
74. C. Göpel, J. L. Birc, A. Galy, J. A. Barrat, B. Zanda, Mn–Cr systematics in primitive meteorites: Insights from mineral separation and partial dissolution. *Geochim. Cosmochim. Acta* **156**, 1–24 (2015).
75. K. K. Larsen, A. Trinquier, C. Paton, M. Schiller, D. Wielandt, M. A. Ivanova, J. N. Connelly, Å. Nordlund, A. N. Krot, M. Bizzarro, Evidence for magnesium isotope heterogeneity in the solar protoplanetary disk. *Astrophys. J. Lett.* **735**, L37 (2011).
76. E. M. M. E. van Kooten, D. Wielandt, M. Schiller, K. Nagashima, A. Thomen, K. K. Larsen, M. B. Olsen, Å. Nordlund, A. N. Krot, M. Bizzarro, Isotopic evidence for primordial molecular cloud material in metal-rich carbonaceous chondrites. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 2011–2016 (2016).
77. K. Zhu, F. Moynier, M. Schiller, D. Wielandt, K. K. Larsen, E. M. M. E. van Kooten, J.-A. Barrat, M. Bizzarro, Chromium isotopic constraints on the origin of the ureilite parent body. *Astrophys. J.* **888**, 126 (2020).
78. M. Petit, J. L. Birc, T. H. Luu, M. Gounelle, The chromium isotopic composition of the ungrouped carbonaceous chondrite Tagish lake. *Astrophys. J.* **736**, 23 (2011).
79. K. Zhu, J. Liu, F. Moynier, L. Qin, C. M. O'D. Alexander, Y. He, Chromium isotopic evidence for an early formation of chondrules from the ornans CO chondrite. *Astrophys. J.* **873**, 82 (2019).
80. L. Qin, D. Rumble, C. M. O'D. Alexander, R. W. Carlson, P. Jenniskens, M. H. Shaddad, The chromium isotopic composition of Almahata Sitta. *Meteorit. Planet. Sci.* **45**, 1771–1777 (2010).
81. M. Schiller, E. van Kooten, J. C. Holst, M. B. Olsen, M. Bizzarro, Precise measurement of chromium isotopes by MC-ICPMS. *J. Anal. At. Spectrom.* **29**, 1406–1416 (2014).
82. K. Zhu, F. Moynier, M. Schiller, C. M. O'D. Alexander, J. A. Barrat, A. Bischoff, M. Bizzarro, Mass-independent and mass-dependent Cr isotopic composition of the Rumuruti (R)

- chondrites: Implications for their origin and planet formation. *Geochim. Cosmochim. Acta* **293**, 598–609 (2021).
83. J. M. Schneider, C. Burkhardt, Y. Marrocchi, G. A. Brenneke, T. Kleine, Early evolution of the solar accretion disk inferred from Cr-Ti-O isotopes in individual chondrules. *Earth Planet. Sci. Lett.* **551**, 116585 (2020).
84. E. van Kooten, L. Cavalcante, D. Wielandt, M. Bizzarro, The role of Bells in the continuous accretion between the CM and CR chondrite reservoirs. *Meteorit. Planet. Sci.* **55**, 575–590 (2020).
85. A. Yamakawa, K. Yamashita, A. Makishima, E. Nakamura, Chromium isotope systematics of achondrites: Chronology and isotopic heterogeneity of the inner solar system bodies. *Astrophys. J.* **720**, 150–154 (2010).
86. D. L. Cook, B. S. Meyer, M. Schönbachler, Iron and nickel isotopes in IID and IVB iron meteorites: Evidence for admixture of an SN II component and implications for the initial abundance of ^{60}Fe . *Astrophys. J.* **917**, 59 (2021).

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Ryugu's nucleosynthetic heritage from the outskirts of the Solar System

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