Hypervelocity collision and water-rock interaction in space preserved in the Chelyabinsk ordinary chondrite

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Abstract: A comprehensive geochemical study of the Chelyabinsk meteorite reveals further details regarding its history of impact-related fragmentation and melting, and later aqueous alteration, during its transit toward Earth. We support an ~30 Ma age obtained by Ar-Ar method (Beard et al., 2014) for the impact-related melting, based on Rb-Sr isotope analyses of a melt domain. An irregularly shaped olivine with a distinct O isotope composition in a melt domain appears to be a fragment of a silicate-rich impactor. Hydrogen and Li concentrations and isotopic compositions, textures of Fe oxyhydroxides, and the presence of organic materials located in fractures, are together consistent with aqueous alteration, and this alteration could have pre-dated interaction with the Earth’s atmosphere. As one model, we suggest that hypervelocity capture of the impact-related debris by a comet nucleus could have led to shock-wave-induced supercritical aqueous fluids dissolving the silicate, metallic, and organic matter, with later ice sublimation yielding a rocky rubble pile sampled by the meteorite.

Keywords: ordinary chondrite, chronology, geochemistry, impact melting, asteroid, comet

Introduction

Solar system bodies have evolved from dust to planets, and asteroids are intermediate products of this evolution, retaining much of their primitive morphology and geochemistry, and thus, providing opportunities to investigate ancient to recent interactions between solids and the solar environment. Hypervelocity collisions and impacts are the primary processes dominating the surface geology of asteroids and the diversity of materials observed on some asteroids represents an amalgamation of disparate sources. For example, Almahata Sitta, derived from near-Earth asteroid (NEA) 2008TC3, is a ureilite breccia for the most part, consisting of fragments of carbonaceous, ordinary, and enstatite chondrites. The NEA Itokawa, from which material was collected by the Hayabusa spacecraft, is a rubble pile consisting primarily of ordinary-chondrite-like materials but also rocks of different lithologies, including the decameter-sized black boulders observed on its surface.

Clearly, some asteroids are “second-generation” composite objects formed after collisional disruption of precursor bodies. To understand how and when an asteroid is re-assembled after collision, the key issues are (i) the timing of collisions in the main belt, (ii)
chemical and physical properties of the impactors, (iii) how materials with differing sources were combined to produce the body, and (iv) how the asteroid changed its orbit to become a NEA.

On February 15, 2013, a meteor airburst occurred over Chelyabinsk, in southern Ural, Russia. The immediate collection of the meteorite fragments from an icy surface argues for derivation of the fragments from a single asteroid body and for the minimized potential of overprinting by terrestrial contamination. The Chelyabinsk LL5 meteorite is rapidly becoming the best-documented NEA.5–9 The pre-atmospheric meteoroid mass was estimated at 1.2 × 10^7 kg, corresponding to a ∼19-m diameter.7,10 Chronological methods yield ages ranging from 1 Ma to 4538 Ma and appear to reflect various stages, including several impact events, in the history of the Chelyabinsk meteorite.11,12

The present physicochemical properties of the Chelyabinsk meteorite (see Fig. 1) are consequences of wide-ranging events during accretion, residency in the asteroid belt, and near-Earth orbital history. As an additional complication, such meteorites commonly experience aqueous alteration due to interaction with terrestrial surface reservoirs. In this study, we consider both terrestrial and pre-terrestrial origins for the alteration in the Chelyabinsk meteorite and we explore a model whereby the aqueous alteration evident in this meteorite could reflect interaction with cometary material during its transit toward Earth. Key evidence guiding this argument comes from mass-balance calculations using whole-rock and in situ measurements of H and Li concentrations, and Li isotope compositions, suggesting a missing reservoir of H and Li likely hosted in micro-fractures (here-

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**Fig. 1.** External and internal morphology of representative fragments containing the key textural/lithological domains outlined in this paper. Fragments contain domains with ordinary-chondrite-like texture (referred to as source, or SRC) and melt texture (referred to as melt, or MLT). The fraction of melt varies among the fragments (see the phase maps of the 14 fragments in Figs. S1 and S2). (A) Fragment of OK-10VM with a fusion crust. (B) Phase map of OK-10VM, classified as SRC in this study. See Fig. 4 for coding of the minerals to the various colors. (C) Phase map of CBK-6, which consists of melt meshwork within SRC domains. The rock is referred to as MIX. (D) Phase map of CBK-1, which is dominated by melt and classified as MLT. For this sample, only the melt domain was analyzed geochemically.
after referred to as “open space”) and along grain boundaries.

The Supplementary material contains more details regarding some elements of this work, including information regarding the analytical methods employed (https://doi.org/10.2183/pjab.95.013).

Materials and methods

All analyses were undertaken at the Pheasant Memorial Laboratory for Geochemistry and Cosmochemistry (PML), Institute for Planetary Materials, Okayama University at Misasa following procedures demonstrated by refs. 3 and 13. During our study of the Chelyabinsk meteorite, we (i) estimated elemental distribution of the meteorite using whole-rock and in situ microprobe techniques such as ICP-MS, XRF, EPMA, and SIMS with modal abundances based on X-ray phase mapping, (ii) evaluated an age of the melt using TIMS, and (iii) performed whole-rock and in situ isotope analyses, including measurements of O- and Li-isotope composition by ICP-MS, IRMS, and SIMS. In this study, we in particular, focused on the catastrophic impact that produced the melt, morphology, and mineralogy of objects in the open space reflecting the physicochemical environment on the asteroid after the impact.

Polished thin-sections were prepared from 14 fragments of the meteorite and some of the remaining material was crushed into smaller pieces in a Si₃N₄ ceramic mortar for other textural and chemical studies. In almost every case, the cut surface created by the diamond saw, and the fusion crusts (related to entry into Earth’s atmosphere), were avoided during this crushing.

Lists and brief descriptions of the samples investigated are shown in Table S1. The types of results obtained for individual samples, are provided in Table S2. The analytical methods employed are described in section S1. The aliquots used for different types of analyses are summarized in Table S3. The quantities of samples consumed for each analysis are shown in Table S3. The range of total quantity consumed for individual whole-rock analyses is 2.56–1587.94 mg.

Samples treated in this study show a variety of textures. In hand specimens, material other than the dark-colored fusion crust (Fig. 1A) consists of varying proportions of silicate melt domains and a matrix regarded as the melt sources. Eight fragments lack melt and contain only the source material (Fig. S1) and another six fragments contain melt but in differing textural occurrences and abundances (Fig. S2). Some fragments contain small fractions of melt occurring as distinct veinlets. As the amount of melt increases, it forms denser networks of veins interstitial to host material, in some cases producing a meshwork, and we refer to these occurrences as mixtures. With further increase in melt fraction, the melt vein networks coalesce into melt pools, which dominate the rock. We refer to these three textural/lithological occurrences as source (SRC), mixture (MIX), and melt (MLT) and, for our textural and geochemical analyses, we selected the largest fragments representing each lithology (see the examples in Figs. 1B, C, D).

All datasets presented in this manuscript are included on our institutional depository DREAM (https://dream.misasa.okayama-u.ac.jp/),14) which is open to the public.

Results and discussion

Processes in the main belt before collision.

Based on the textures (Figs. 1, S1, S2, and S3), mineralogy (Fig. S4), and geochemistry (see sections S1 and S2 and Tables S1–S22) of the Chelyabinsk meteorite, it is possible to infer some of its history prior to collision, specifically the physical and chemical environment during metamorphism on the parent body. Three broad classes of material were recognized in hand specimens: chondrite material, dark silicate melt, and mixtures of the two, as inferred above. Importantly, fusion crusts cross-cut and cover micro-fractures that occur throughout SRC domains (Fig. S5), and less commonly in MLT domains, demonstrating that much of the fracturing occurred before entry of the meteorite into the Earth’s atmosphere.

The SRC domains identified in this study appear to have genetic links with equilibrated ordinary chondrites, as described in previous studies,8,9) having elemental characteristics (see section S2.1) and O isotope compositions in the ranges for LL (Fig. 2A and ref. 15). A radius of several tens of km would have been required for the parent body to raise temperatures sufficiently to generate the observed isotopic and chemical equilibration that likely occurred within ~10 My of accretion.8,9) The isotopic and elemental distributions we present in this paper represent the first (i) thermal metamorphism, the record of which is exhibited in samples such as that shown in Fig. 1B, then (ii) melting related to catastrophic impact with a silicate body (see Figs. 1C, D), supported by occurrences of high-P phases such as wadsleyite and ringwoodite.
Figs. S6A, B) in shock veins (widths of tens of µm) and maskelynite in SRC domains (Fig. S6C). These two events were followed by (iii) aqueous alteration largely represented by mineral phases in open space. We propose melting and subsequent aqueous alteration as the two major key processes affecting the asteroid after initial equilibration in, and fragmentation from, the LL parent body.

Chelyabinsk meteorite silicate δ18O shows a range of 4‰, whereas δ7Li varies by nearly 60‰ (see Fig. 2). Because the relative mass differences of 18O and 16O, and 7Li and 6Li are comparable (13% and 17%, respectively), the responses of these two isotope ratios to the same kinetic process should be quite similar. The tightened array of O isotope compositions (Fig. 2A) likely reflects metamorphic homogenization. Because, in silicates, Li diffuses more rapidly than O, Li isotopes would similarly be expected to homogenize during this metamorphism. The observed δLi variation (Fig. 2B) is far greater than that expected from high-T equilibration and is instead likely to have resulted from later, lower-T processes. We suggest that, during late-stage low-T aqueous alteration, Li was re-located in silicates, presumably by diffusion, and into phases crystallized along grain boundaries and in impact-related fractures (open space), leading to the large variation in δ7Li.

Although Li concentrations and isotope compositions in constituent phases show large variations (0.02 to 10 µg·g$^{-1}$ and 10 to 30‰, respectively), the whole-rock compositions of SRC, MIX, and MLT are more uniform, with mean concentration of 1.8 ± 0.1 µg·g$^{-1}$ (1σ) and mean δ7Li of 4.6 ± 0.3‰ (1σ; see Fig. 2B). The concentrations and δ7Li of glass in MLT are 2.7 ± 0.7 µg·g$^{-1}$ (1σ) and 4.5 ± 2.3‰ (1σ), respectively, similar to those of whole rocks. Note that the mean [Li] is slightly higher because of the presence of relict olivine with low [Li] (see Fig. 2B). These observations indicate that the glass inherited the whole-rock δ7Li of the SRC domains.

Timing of the collision and the nature of the projectile. We obtained a Rb-Sr pseudo-isochron age of 29 ± 54 (2σ) Ma for one MLT region by analyzing the whole rocks and pseudo-mineral separates elutriated from fractions of the MLT region (see sections S1.6 and S3.2). These fractions are presumed to be in near-equilibrium isotopically based on their textures and major element concentrations (see section S3.2 and Figs. S7–S9). This age is
very similar to, but with a larger uncertainty than, the youngest $^{40}$Ar/$^{39}$Ar age of 28.6 ± 3.3 Ma obtained in an earlier study\(^\text{11}\) for a mixture of source with subordinate melt presumably similar to the MIX lithology defined in our study. The similarity of the pseudo-isochron age from the current study and the $^{40}$Ar/$^{39}$Ar age of ref. 11 can be explained by the lower closure temperature of the K-Ar system. Taking into account the uncertainty and the consistency of our date with a model line of 100 Ma, we can infer that the catastrophic collision took place at <100 Ma. Based on this reasoning, we conclude that the major collision with another asteroid occurred within 100 Ma, possibly at ~30 Ma. This is far younger than the age of 461 ± 11 Ma estimated by Rb-Sr dating for melt in a H chondrite\(^\text{19}\) and an $^{40}$Ar/$^{39}$Ar age of ~470 Ma for breakup of L and LL bodies, together interpreted as reflecting the timing of breakup of the Flora family.\(^\text{19}\)

We discovered an irregularly shaped ~100 µm olivine grain in a MLT domain having O isotope compositions distinct from those of other whole-rock and olivine samples from the meteorite. Its heavy O isotope composition (Figs. 2A and 3) is unlike that of most known solar system materials and most resembles the isotopically heaviest olivine-pyroxene mixtures in chondrules in the Rumuruti (R) chondrites.\(^\text{20}\) The major elemental composition of the olivine grain is homogeneous, with $\delta^{17}$O\textsuperscript{20} overlapping that of other olivine in the Chelyabinsk meteorite (including in melt domains; for all, $\delta^{17}$O\textsuperscript{20}=8.5–74.5) and overlapping with the compositions of olivine in equilibrated and unequilibrated R chondrites ($\delta^{17}$O\textsuperscript{20}=83 and 90, respectively; see Table S21).
The angular shape of this olivine (Fig. 3B) implies that it is a fragment produced during shattering, and because of its location in a MLT domain, we infer that it is a fragment of the projectile that caused the melting. We observed no significant variation in the O isotope compositions in the grain as a function of distance from its rim (Fig. 3C), suggesting little diffusive exchange of the object with the surrounding melt. That the olivine is exotic is also supported by the observation that its $\Delta^{17}O$ differs significantly from the uniform whole-rock $\Delta^{17}O$ of domains, with and without melt, with a mean and variation ($2\sigma$) of $+1.22\%o$ and $+0.05\%o$, respectively. The difference in $\Delta^{17}O$ between the projectile and its host is $\sim 2\%o$, considerably larger than the variation among the whole-rock samples, and the contribution of the exotic component delivered by the collision can thus be estimated as being $< 0.75 \text{ wt}\%$. The presumed impact-related introduction of the exogenous olivine projectile demonstrates that the Chelyabinsk material resided at or near the surface of the larger parent-body. This is also supported by the occurrence of bubbles in sulfide spheres in a MLT domain, indicating formation of the spheres at relatively low pressure (see section S2.1). The inferred melting age of $\sim 30 \text{ Ma}$ for the Chelyabinsk meteorite is similar to the cosmic-ray exposure (CRE) ages for R chondrites (the latter, $15$ to $25 \text{ Ma}$). The CRE age for Chelyabinsk is significantly younger than that of R chondrites, only $1$ to $2 \text{ Ma}$.\(^5,9\)

**Aqueous alteration processes preserved in open space.** Figure 4A shows the CI-normalized concentrations of 54 elements in SRC, MIX, and MLT, and rare earth elements (REEs) in constituent phases similarly normalized. These normalized patterns are near identical among the SRC, MIX, and MLT domains, with significant depletions in H, C, Cl, and Cs compared to the reference values for LL5s. The REE pattern for glass is similar to that of the whole rock, but with $1.3\times$ enrichment resulting from the presence in the whole rock of relict phases such as low-REE olivine (Fig. 3A).

We estimated whole-rock element concentrations in SRC and MLT domains based on modal abundances and analyses of the individual mineral phases (Tables S4 and S5) and compared these estimated concentrations with the measured whole-rock concentrations (Figs. 4B, C). Estimated whole-rock H concentrations are low by $\sim 60\%$ in SRC and $\sim 40\%$ in MLT, relative to measured whole-rock concentrations, differences far larger than analytical errors. Similarly, estimated whole-rock Li concentration is appreciably lower than that measured, particularly for SRC domains.

Hydrogen concentrations [H] in unequilibrated LL3 chondrites range from $300$ to $2000 \mu g \cdot g^{-1}$, whereas those of high-grade LL5 and LL6 chondrites (including the Chelyabinsk meteorite) are lower, ranging from $34$ to $419 \mu g \cdot g^{-1}$.\(^1,21,22\) This difference is consistent with the expectation that for an LL parent body, [H] related to early-stage low-$T$ aqueous alteration would be lowered during later metamorphism.\(^23\) A collision event, and related heating, would have even further reduced the [H] of the Chelyabinsk LL5 body. Hydrogen transport out of the system from silicates during collision is demonstrated by the low estimated whole-rock [H] based on compositions and modal abundances of the mineral phases (from $40$ to $20 \mu g \cdot g^{-1}$ for SRC\(^{exa}\) and MLT\(^{exa}\), respectively; see Figs. 4B and S10). It appears that, after collision, the body re-acquired H during formation of an additional reservoir, resulting in the measured whole-rock [H] of $100$ and $34 \mu g \cdot g^{-1}$ for SRC\(^{mes}\) and MLT\(^{mes}\), respectively. Seeking the missing reservoir for H (and Li), we examined for minor phases present in cracks and grain boundaries (open space; see Figs. S11A, B) that could have resulted from the major impact that induced the melting or from later processes.

Carbonaceous materials in the open space were identified by Raman mapping using the G and D bands (1360 and 1580 cm$^{-1}$) and a C-H stretching feature at 2940 cm$^{-1}$, demonstrating the presence of graphitic material and hydrocarbon compounds (Fig. S12). The Raman spectroscopy, together with whole-rock C concentrations ([C] = $0.04 \text{ wt}\%$ in SRC), supports the existence of organic matter in open space regions.

Iron oxyhydroxide occurs in the vicinity of Fe-Ni metal, in cracks in SRC domains (Figs. 5A, B), and occasionally in cracks in MLT domains (Fig. 5C), with the cracks reflecting cooling-related contraction. One Fe oxyhydroxide aggregate (Fig. 5B) shows a colloform banded-texture region and varies widely in its Fe/Ni ratio (Figs. S11D, E, F). The textures of these aggregates, and the occurrence of C in the open space domains (Fig. S12), suggest that the mineralization resulted from the interaction of metal with C-bearing aqueous fluids. These colloform aggregates have [H] of $2000$ to $6400 \mu g \cdot g^{-1}$ (see section S2.6, Tables S8 and S9, and Fig. S10) and, based on TEM observations and Raman spectrometry, it appears they are composed of anhydrous Fe-oxides such as magnetite or maghemite, associated with Fe.
oxyhydroxides such as ferrihydrite or the more rarely observed feroxyhyte. Raman spectra of Fe oxyhydroxide (see Fig. S13) show bands corresponding to some combination of ferrihydrite, maghemite, and feroxyhyte.\textsuperscript{24,25} The large range in $[H]$ of the aggregates likely reflects varying mixtures of anhydrous and hydrous Fe-oxide. Iron oxyhydroxide can contain 1.2 wt% H, according to its ideal chemical formula [Fe$^{3+}$O(OH)]. Therefore, the presence of this Fe oxyhydroxide can explain the deficit in H ($\Delta = \ldots$)

Fig. 4. Element concentrations and distribution. (A) Elemental concentrations in SRC, MIX, and MLT, normalized to CI, and in constituent phases similarly normalized (for the latter, see the inset). For plotting purposes, concentrations of H, C, and Pb are multiplied by 100, 10, and 10, respectively. (B, C) Element concentrations in phases in the SRC and MLT are presented on a linear scale. Uncertainties are estimated as 1 standard deviation (1$\sigma$) for the average concentration in each phase. As for most of the elements examined, whole-rock element concentrations calculated from concentrations and modal abundances of individual phases ($SRC^{calc}$, $MLT^{calc}$) are consistent with those measured for the same whole-rocks ($SRC^{meas}$, $MLT^{meas}$). Analyses of Fe oxyhydroxides suggest that they are composed mainly of feroxyhyte, likely the major reservoir for H and Li.
60 µg·g⁻¹), based on comparison of the measured and calculated H concentrations and taking into account its modal abundance of ~1%. We believe that partial dissolution and hydration of the Fe-Ni metal by fluid, then evaporation of the resulting solution, led to the precipitation of this Fe-oxyhydroxide.

In contrast to the situation for H, Li abundance in the aggregates is 1–2 µg·g⁻¹, similar to that in the olivine. Thus, another reservoir is required to explain the enrichments in measured [Li] in SRC relative to [Li] calculated from mineral modes and measured compositions (Figs. 2B and 4B). Iron oxyhydroxide also occurs as small domical features (1–2 µm in diameter) on an olivine grain surface exposed to open space (Figs. 5D, E, F). These micro-domes occur as Li-enriched spots observed during ion-microprobe rastering of 100 × 100 µm² areas on 20 fragments (see Fig. S14A) in SRC domains. Twenty micro-domes observed in one of the rastered areas (Figs. S14B, C, D) have flat tops with heights of ~0.8 µm and surface area of ~1.5 µm² (Figs. S14E, F, G), shapes and dimensions indicating formation in a very narrow space. Bulk [Li] of the rastered area is ~20 µg·g⁻¹, far higher than that of the olivine substrate with <2 µg·g⁻¹. Because the modal abundance of the micro-domes is estimated at 0.2%, the [Li] of the micro-domes is estimated as being as high as 1 wt%.

A TEM electron-diffraction-pattern (Figs. S14H, I) demonstrates that the micro-domes are composed of ferroxyhyte [δ-Fe³⁺O(OH)]₄. Based on observations in all 20 of the surveyed areas, the modal abundance of the micro-domes in SRC is estimated at 0.01%. Thus the contribution of Li from the micro-domes to whole-rock SRC is 1 µg·g⁻¹, which is sufficient to explain the difference between the measured and calculated Li concentrations (1.9 and 1.0 µg·g⁻¹, respectively; Δ = 0.9 µg·g⁻¹).

Greater addition of H could have occurred in SRC than in MLT during interaction with fluids because of the higher porosity of SRC domains relative to MLT, represented by the abundant cracks (Figs. S3A, B and Figs. S3C, D for SRC and MLT, respectively). This higher porosity could have resulted in larger degrees of uptake of H into hydrous phases. Whole-rock δ²H determined in this study, ranging from ~151 to ~88‰ (Tables S6 and S18), is similar to that of other equilibrated ordinary chondrites and largely reflects the H in open space.
As a similar argument against appreciable incorporation of a terrestrial surface component, the “missing” Li reservoir we infer by mass-balance would have had [Li] = 88 µg·g⁻¹ and δ⁷Li = -9.1‰ (see Fig. 2B), whereas values for lake water are typically strongly positive (+~30‰). Equilibrium Li isotope fractionations between fluid and various low-temperature alteration phases (e.g., clays, gibbsite, zeolite) are in the range of −14 to 0‰, with the minerals having lower δ⁷Li. The incorporation of Li from lake water with δ⁷Li near +30‰ would likely have led to values for minerals considerably higher (>+15‰) than those observed for the Chelyabinsk meteorite (again, with the latter having values near −9‰), even with this significant mineral-fluid fractionation.

Pillinger et al. concluded that the very low concentrations and isotope compositions of C and N, and noble gas isotopic compositions, in the Chelyabinsk meteorite indicate little contamination by exchange with terrestrial reservoirs and largely reflect “indigenous” (i.e., non-terrestrial) compositions. Righter et al. also suggested that their samples of the Chelyabinsk meteorite were fresh and unweathered, based on Mössbauer spectroscopy and petrographic analysis. The same authors also reported aliphatic hydrocarbons, n-alkanes, which could be the organic materials in open space observed in our study. They interpreted these compounds as being of a terrestrial source, although they presented similar results of these studies are thus consistent with our conclusion that the Chelyabinsk meteorite experienced aqueous alteration within open space after impact-related destruction, but before entry into Earth’s atmosphere. As possible further evidence, the relatively large amount (15%) of N released at low temperatures (200 °C) in stepped-heating analyses of samples of Chelyabinsk meteorite yielded high δ¹⁵N values, near +30‰ (relative to Earth atmosphere at 0‰). It is difficult to produce such a value from interaction with atmospheric or biological N reservoirs on Earth (together, mostly ranging from −5 to +10‰). Furthermore, the presence of this isotopically heavy N is consistent with the release of a component of non-terrestrial N, loosely bound in phases, stabilized during aqueous alteration with a high δ¹⁵N similar to that of organic matter in primitive meteorites and cometary matter (see ref. 35).

**Discussion on the possible interaction between an asteroid-fragment and a comet-nucleus during transit to Earth.** Here, we address how the Chelyabinsk asteroid changed its orbit to be a near-Earth asteroid, and how the materials with apparent differing sources were assembled. We explore a model in which aqueous alteration in ordinary chondrites could, in some cases, reflect interaction between comets and asteroids during transit toward a near-Earth orbit.

After thermal metamorphism, the ancient LL parent-body remained largely unchanged for most of the age of the solar system. Very recently, at ~30 Ma, the part of the parent-body now represented by the 19-m-sized Chelyabinsk meteorite was impacted by a silicate-rich body, leading to the generation of silicate melt. Near-Earth asteroids have dynamic lifespans of only a few million years. Thus, this collision likely occurred in the main asteroid belt. The difference between the cosmic ray exposure (CRE) age and the age of the major collision is significant. We describe a scenario in which the exotic olivine arrives at the surface of the larger silicate-rich body, prior to the exposure of the current Chelyabinsk meteorite, surface to cosmic rays at 1–2 Ma. The CRE “clock” would be expected to record an age similar to that of the melting, because the presence of the exogenous olivine projectile demonstrates that the melting occurred during disaggregation of the Chelyabinsk material residing near the surface of the larger parent-body. Particles from the rubble pile asteroid Itokawa similarly show a CRE age of 8 Ma considerably younger than the peak-CRE age of 15 Ma common for LL chondrites. It is possible that until 1–2 Ma, the 19-m body represented by the Chelyabinsk meteorite was shielded from cosmic ray bombardment because of its position inside, and not at the surface of, a larger body immediately after the catastrophic collision.

Two key remaining uncertainties are how the impacted Chelyabinsk boulder acquired the H₂O responsible for the aqueous alteration demonstrated in our study and how a small body was shielded from cosmic rays for this long period of time (seemingly more than 20 million years). Based on the several
lines of evidence presented above, we propose that fragments of an asteroid in the main belt could have been accreted with, and interacted with, an icy cometary nucleus.

A collision between an asteroid and a comet would have resulted in a transient high-$P$-$T$ condition that transformed solid ice into liquid water that permeated cracks on the asteroid. The liquid would have cooled down since the peak $T$ of the asteroids rocky material is lower than that of the liquid. After passage of a rarefaction wave, the pressure is unloaded and the shocked cometary water ice expands adiabatically and $P$-$T$ changes toward (C) $P$-$T$ condition where liquid transforms into vapor. Two $P$-$T$ paths for the impact velocities of 3.5 and 5.0 km/s are shown. We assume the initial temperature of the comet to be 150 K. The phase diagram is compiled from refs. 46 and 47, where Ih, Il, Iii, . . . , and XI are polymorphs of ice.

The supercritical fluid would permeate into cracks to a greater degree because of its low viscosity ($\mu \sim 10^{-5}$ Pa s) similar to that of vapor. The typical velocity of this permeating fluid, $U$, was estimated for plane Hagen-Poiseuille flow ($U = h^2/12\mu \ dP/dx$), where $h$ is the crack width, and $dP/dx$ is the pressure gradient. Approximating $dP/dx$ to be $\sim P/x$, where $x$ is a permeating depth, we obtained $x \sim (Ph^2t/6\mu)^{1/2}$, where $t$ is the duration of permeation assuming $dx/dt = U$. Calculation with $P = 10$ GPa and $h = 10 \mu$m yields a permeation depth of $x \sim 10$ m when the high $P$-$T$ state is maintained for 0.01 s, a timescale similar to that of a shock-wave-passing through an object with a diameter of a few-tens of meters. This suggests that the 10-m-sized asteroid would be flooded with

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**Fig. 6.** $P$-$T$ path of cometary water ice after collision overlaid on phase diagram of water. (A) The highest $P$-$T$ condition of cometary water ice and (B) that of asteroid rocky materials after collision. The cometary water ice transforms into a supercritical liquid then infiltrates cracks on the asteroid. The liquid would have cooled down since the peak $T$ of the asteroids rocky material is lower than that of the liquid. After passage of a rarefaction wave, the pressure is unloaded and the shocked cometary water ice expands adiabatically and $P$-$T$ changes toward (C) $P$-$T$ condition where liquid transforms into vapor. Two $P$-$T$ paths for the impact velocities of 3.5 and 5.0 km/s are shown. We assume the initial temperature of the comet to be 150 K. The phase diagram is compiled from refs. 46 and 47, where Ih, Il, Iii, . . . , and XI are polymorphs of ice.
supercritical liquid. The liquid would have cooled down during the infiltration, because the peak $T$ of the asteroids’ rocky material is lower than that of the fluid. The fluid would solidify into the ice VII (see path A $\rightarrow$ B on Fig. 6), and with pressure release due to propagation of the rarefaction wave, the ice VII would melt into liquid again (see path B $\rightarrow$ C). After the pressure release, the residual heat inside of the asteroid would maintain $T$ above the melting point of ice Ih. Further decompression would result in vaporization of liquid on (C) $P$-$T$ condition where liquid transforms into vapor, and the vapor would move along the cracks. By replacing $P$ with $P_{\text{vap}}$ (the vapor pressure of water in the crack) in the equation for the permeation depth, we obtain a retention time of the vapor to be $t_{\text{ret}} = 3.5$ km s$^{-1}$ and $t_{\text{vap}} = 5.0$ km s$^{-1}$. Because the residual heat inside of the asteroid is maintained for longer period, open space would be aqueously altered by liquid mixed with vapor.

The above calculation suggests that 10-µm-width cracks were filled with supercritical fluid produced from cometary ice and that the 19-nm-sized Chelyabinsk could have experienced aqueous alteration immediately after asteroid-comet interaction. This supercritical fluid has an extremely high oxidizing power and could have acted as a strong solvent for many substances$^{39,40}$ Thus, it could have conveyed carbonaceous matter and silicate and metal components from the cometary ice and reacted with the surfaces of silicates and metals located in the cracks. During the residence time of the fluid, perhaps up to several tens of hours, the fluids would have evolved chemically, experiencing enrichment in Fe. Complex fluid-metal interactions could have resulted in the colloform textures observed in the vicinities of the Fe-Ni metals. As pressure decreased, the fluid could have converted into gas, as bubbles, then escaped from the fractures. The volume of the fluid would have decreased through release of water into a gas phase, and the nucleation of feroxyhyte nanoparticles would likely have initiated in the resulting Fe-enriched fluid (see Fig. S15A). As the water evaporated, the suspended particles could have accumulated and formed the micro-domes. The domes are aggregates of nanoparticles rather than single crystals, and the strong surface tension could have prevented the conversion of the feroxyhyte to goethite,$^{41}$ which is not observed in the Chelyabinsk meteorite (see Fig. S15B). Evaporation concentrates not only Fe in the fluid, but also Li, and the feroxyhyte nanoparticles could have incorporated or adsorbed Li, resulting in the observed co-enrichments in Fe, H, Li, and O.

How long could the Chelyabinsk meteorite material have been maintained in a comet? The lifetime of a Jupiter-family comet (0.4–0.6 Ma$^{42}$) is too brief to sustain small bodies for the apparent >20 Ma between the possible impact age of ~30 Ma and the exposure age of 1–2 Ma. If the comet was of the Jupiter-family, it should have become inactive and “dormant,” after capture of the Chelyabinsk material, by formation of a non-volatile crust on its surface. The formation of this crust would have prevented further volatilization,$^{43}$ thus extending the lifetime of the comet. Another possibility is that the comet originated in the Oort cloud with a long orbital period up to 100 million years.$^{44}$ If the latter is the case, rotation of the comet could have resulted in the incorporation of the Chelyabinsk boulder into an icy nucleus for a few tens of million years. With time, after sublimation of water ice and frozen gases,$^{45}$ which protected the boulder from cosmic rays until 1–2 Ma, the Chelyabinsk body could have been buried in a rubble pile consisting of silicate boulders, captured dust, and organic matter of cometary origin.

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