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Formation and evolution of carbonaceous asteroid Ryugu: Direct evidence from returned samples

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Abstract: Samples of the carbonaceous asteroid Ryugu were brought to Earth by the Hayabusa2 spacecraft. We analyzed seventeen Ryugu samples measuring 1-8 mm. There are CO_2-bearing water inclusions within a pyrrhotite crystal, indicating that Ryugu's parent asteroid formed in the outer Solar System. The samples contain objects formed at high temperatures such as chondrules and Ca, Al-rich inclusions with low abundances. The samples are rich in phyllosilicates and carbonates formed by aqueous alteration at low-temperature, high-pH, and water/rock ratios < 1 by mass. Less altered fragments with olivine, pyroxene, amorphous silicates, calcite, and phosphide are identified. Numerical simulations based on mineralogical and physical properties of the samples indicate that the Ryugu parent body formed at ~ 2 million years after the birth of the solar system.

Main Text

The carbonaceous asteroid (162173) Ryugu is a rubble pile formed by reaccumulation of material ejected from a parent asteroid by a large impact (*1*). Remote sensing observations have shown that Ryugu is related to hydrous carbonaceous chondrite meteorites (*2*). However, there are some differences with those meteorites, suggesting later heating and partial dehydration of Ryugu (*2*, *3*). Reflectance spectra are nearly uniform across Ryugu's surface, indicating minimal compositional diversity at its surface (*2*, *3*), except for some boulders (*3*, *4, 5*).

We expect samples of Ryugu to retain a record of the formation and early evolution of the parent body and Ryugu itself. We analyzed samples collected by the Hayabusa2 spacecraft *(6)*, seeking to determine i) when and where in the solar nebula Ryugu's parent asteroid formed, ii) the initial mineralogy and water ice content, iii) how these original materials evolved through water-rock reactions, iv) how the asteroid was heated by the decay of short-lived radionuclides, and v) how the material was ejected from the parent body by an impact and re-accumulated to form Ryugu.

We analyzed seventeen Ryugu particles ranging from 1 to 8 mm in size (Fig. 1A shows the largest particle, C0002, and Fig. S1 shows all particles), consisting of seven particles from chamber A, collected at the first touchdown site (TD1), and ten particles from chamber C, collected at the second touchdown site (TD2) (*6*). We refer to these mm-sized particles as coarse samples. Finer-grained powder samples (<1 mm in size: Fig. S2) obtained from TD1 and TD2 were also used for reflectance spectroscopy.

Reflectance spectra

Visible (Vis), near-infrared (NIR), and mid-infrared (MIR) [wavelength range (0.4 - 18 μm)] reflectance spectra were measured from many of the coarse Ryugu samples packed together (seven particles from TD1 and seven particles from TD2: Fig. S1), from the powder samples, and from samples of meteorites Orgueil and Tagish Lake, without exposure to air in entire analysis procedures ((*7*) and Fig. S2). MIR and far-infrared (FIR, 17-100 μm) reflectance spectra were also measured in air for sample A0026 and samples of the meteorites Orgueil, Alais, Tagish Lake, and Murchison.

All analyzed Ryugu samples exhibit similar Vis-NIR spectra (Fig. 2A). They have ~2.0-2.5% reflectance (at 550 nm) with a slightly red slope of ~0.1-0.3% μm^{-1} (0.48 to 0.86 μm) and ~0.2-0.3% μm^{-1} (2.0 to 2.5 μm). There are no strong absorption features blueward of 2.7 μm (Fig. 2A). No 0.7 μm absorption, due to Fe^{3+}-rich phyllosilicates (*8*), was detected. The Ryugu samples have an absorption band (~20% in depth) centered at ~2.71 μm (Fig. 2B), which is due to O-H stretching vibrations in Mg-rich phyllosilicates (*9*, *10*). A weaker absorption band at ~3.1 μm is possibly due to ammoniated salts or other nitrogen-bearing compounds (*11*). Absorptions at ~3.4–3.5 μm are due to aliphatic organics and carbonates, and those at ~3.8–3.95 μm are due to carbonates. In the MIR-FIR, the Christiansen feature, the reflectance minimum characteristic of the chemical composition, is present at ~9.1 μm. Reststrahlen bands, the reflectance peaks associated with Si-O stretching and bending modes, appear as strong peaks at ~9.8 μm, with a shoulder at ~10.75 μm, and as a doublet at ~22.3 μm (Fig. 2C).

Visible spectra of the touchdown sites were obtained by the Optical Navigation Camera Telescope (ONC-T) (*3*) on the Hayabusa2 spacecraft at spatial resolution of 0.3-0.5 m $pixel^{-1}$, before and after the sample collection. The location of TD1 showed higher reflectance than TD2 (Fig. 2D). We find similar results: the coarse and powder Ryugu samples from TD1 both exhibit higher reflectance than those from TD2 (Fig. 2A). The surface reflectance decreased after the touchdowns because the spacecraft thrusters removed powder from the surface of Ryugu during ascent (Fig. 2D) (*12*). Visible spectra of the coarse and powder Ryugu samples have similar reflectance values to the ONC-T spectra of the landing sites *(7)*, and to the global average (Fig.2A), indicating that the samples are representative of the global spectral properties of Ryugu. Reflectance ratios of ONC-T to the powder samples at 0.55μm is ~0.9 for both TD1 and TD2 (Fig. 2D).

Spectra of the Ryugu samples are generally consistent with Ryugu average spectra measured with Hayabusa2's ONC-T (*3*) and Near Infrared Spectrometer (NIRS3) (*2*) instruments. There are some differences between the NIRS3 and laboratory spectra (Fig.2A), even after converting both to the same wavelength resolution (Fig. 2B). The NIRS3 spectra have lower reflectance R relative to sample (R NIRS3 R sample^{-1} = 0.7 at 2.0 μm) and a shallower 2.7 μm absorption depth *Depth* (*Depth* NIRS3 *Depth* sample^{-1} = ~0.5 at 2.7μm), consistent with (*13*). This could be due to differences in particle size distribution and porosity between the laboratory samples and Ryugu's surface, or the much larger field of view of NIRS3 (see also (*13*)).

Ryugu and the laboratory samples have similar reflectance to asteroid Bennu (*14*) in the visible wavelength but opposite spectral slopes (Fig. 2A). The 2.7 μm feature (Fig. 2B) and the bands in the MIR-FIR spectrum (Fig. 2C) of Bennu (*15*) also differ from Ryugu.

The Ryugu samples are much darker and have a flatter spectral slope than the meteorites Orgueil and Tagish Lake (Fig. 2A). Orgueil is classified as a CI1 meteorite, meaning an aqueously altered (modified by reactions with water) Ivuna-type carbonaceous chondrite, while Tagish Lake is a C2, a carbonaceous chondrite that was less altered so retains anhydrous minerals. The position of the OH absorption band in the Ryugu sample spectra is consistent with that in Orgueil, Tagish Lake, and the ungrouped C1 chondrite Flensburg in which sub-millimeter size anhydrous aggregates made of silicate and glass, chondrules, are totally replaced by phyllosilicates (*16*). The same feature appears at longer wavelengths in the Murchison CM2, carbonaceous chondrite meteorites of Mighei type, and asteroid Bennu (Fig. 2B; (*2*, *14*)). The position of this band is known to correlate with Mg/Fe ratio in phyllosilicates, so we infer that Ryugu, Orgueil, Tagish Lake, and Flensburg contain Mg-rich phyllosilicates, while Murchison and Bennu contain Fe-rich phyllosilicates (*9*, *10*).

3D structure and density

All our coarse Ryugu samples, except one sample A0058, were characterized using synchrotron X-ray computed tomography (SR-CT (*7*)), with a resolution of 0.85 micron/voxel (Table S1). Most of the samples had an irregular shape, but some exhibited one or two broad flat surfaces. Particles with flat surfaces were also observed during the sample collection process (*6*). The particle interiors have cracks; most are irregular, but some particles (e.g., C0055) contain parallel cracks with spacings of tens to hundreds of microns (Fig. S3).

The mass of each coarse sample particle was measured under dry conditions in a glove box and the density was calculated from the sample volume determined using SR-CT (Table S1). The bulk density (mass/total volume, including cracks and pores) ranged from 1.7 to 1.9 g/cm^3 with an average of 1.79±0.08 g/cm^3 (Table S1), which is higher than estimated from earlier measurements in the curation facility (1.3 g/cm^3 (*17*)) which did not consider the full 3D structure. These densities are higher than the measured average density of Ryugu (1.2 g/cm^3: (*1*)), indicating that the asteroid has high internal macro-porosity. The average bulk densities of CI (Ivuna-type) and CM (Mighei-type) chondrite meteorites are 2.12 and 2.21g/cm^3, respectively (*18*), while the ungrouped C1 chondrite Flensburg has density 1.98 g/cm^3 (*16*). Considering mineralogical similarities to CI chondrites, the lower density of Ryugu samples indicates a porosity higher than for CI chondrites.

Mechanical, thermal, electrical, and magnetic properties

The Ryugu samples A0026 (TD1) and C0002 (TD2, our largest particle) were measured (*7*) to determine mechanical, thermal, electrical, and magnetic properties (Tables 1) to compare with carbonaceous chondrites (Table S2) and for use in numerical simulations.

The resulting physical properties of the Ryugu samples are not identical to any known meteorite. Most properties are similar to hydrous CI and CM chondrites, but differ from anhydrous CV (Vigarano-type) and CO (Ornans-type) chondrites (Tables 1 and S2). The mechanical properties show that Ryugu samples are weaker in strength, especially Young's modulus and Poisson's ratio, than hydrous carbonaceous chondrites (Table S2) and have a larger volume change upon deformation (such as compression or impact). The thermal expansivity of the Ryugu samples differs from the nonlinear temperature-dependent results measured for some carbonaceous chondrites (*19*), but is linear in the temperature range of 220-370 K (Fig. S4).

The thermal properties (Table 1) could be responsible for the low thermal inertia of Ryugu (*20*, *21*). The thermal diffusivity (Table 1) and the bulk density of sample C0002 (Table S1) were used to calculate the thermal conductivity of 0.5 $Wm^{-1}K^{-1}$ and thermal inertia of 890 J m^{-2} $s^{-0.5}$ K^{-1} (hereafter thermal inertia units, TIU) at a temperature of 298 K. The thermal inertia of the sample is higher than the mean of the asteroid surface observed by Hayabusa2 [225 ± 45 TIU (*22*)], and measured in situ at the Mobile Asteroid Surface Scout (MASCOT) landing site [295 ± 18 TIU (*21*)]. Remote sensing is sensitive to a thermal skin depth of ~10 mm, whereas the thickness of the sample measured in the laboratory is <1 mm, so a thermal shielding effect could arise on intermediate scales (e.g. cracks of several millimeters length).

Thin sections of magnetite framboids (aggregates of equidimensional microcrystals of magnetite) with diameters of 300-1100 nm were observed using electron holography at a spatial resolution of 14 nm (*7*). These magnetite inclusions have vortex magnetic structures and magnetic flux leakage out of the particles (Figs. 3A-C and S5). The externally leaking magnetic flux was detected as remanent magnetization in macroscopic measurements. Mössbauer spectra showed that half of the iron in these samples is in magnetite, and the magnetic hysteresis parameter values (Table 1) similar to those of carbonaceous chondrites containing the submicron-sized equidimensional magnetite framboids (*23*, *24*). Therefore, the magnetite framboids dominate the natural remanent magnetization (NRM) of asteroid Ryugu. Two Ryugu particles from different sampling sites (A0026 from TD1 and C0002 from TD2) record magnetic fields of 31–260 μT and 18-704 μT (Fig. S6), respectively, suggesting that the source magnetic field was homogeneous in Ryugu's parent planetesimal size.

Elemental abundances

We used muon X-ray emission spectroscopy to measure the abundances of major chemical elements in the ten coarse Ryugu samples, including the largest sample C0002 (126.6 mg in total) (*7*, *25*, *26*). Because the muon beam is > 3cm in diameter, we analyzed all ten samples together to obtain a mean bulk elemental abundance. Pellets of the meteorites Murray (CM2; 306.5 mg) and Orgueil (CI1; 195 mg) were measured for comparison.

We detect carbon, nitrogen, oxygen, sodium, magnesium, silicon, sulfur, iron, and nickel (Fig. 4A). The Ryugu and Orgueil spectra are very similar, indicating similar major elemental abundances. However, the Ryugu samples contain less oxygen than Orgueil.

We calculated elemental mass ratios M/Si (M=C, N, O, Na, Mg, S, and Fe) from the muon X-ray data (*7*). M/Si has previously been measured for the Murray meteorite (Table 3), so it was used as a standard. We determined Ryugu mass ratios of C/Si=0.338±0.008, N/Si=0.019±0.009, O/Si=3.152±0.099, Na/Si=0.039±0.006, Mg/Si=0.890±0.021, S/Si=0.510±0.019, and Fe/Si=1.620±0.040. These elemental ratios are consistent with CI chondrites (*27*) and the Sun *(28*), except O/Si is 25% lower in Ryugu than CIs (Table S3 and Fig. S7). These abundances nevertheless classify Ryugu as a CI chondrite, consistent with other lines of evidence *(29)*.

CI chondrites contain 45 wt% oxygen (*27*); Ryugu is depleted in oxygen by 11.3 wt%, given its similar Si concentration to CI chondrites (*29*). The Ryugu samples were prepared and analyzed in low oxygen conditions (< 0.1 %) and in dry atmosphere (dew points < -50 °C), so the indigenous oxygen abundance of Ryugu samples was determined. The lower water content and sulfate abundance of Ryugu samples than CI chondrites (*29*) are probably the cause of the low oxygen abundance.

Nitrogen-bearing molecules, such as NH_3, CN, and N_2, have low freezing points and could only have been incorporated into asteroids in the outer Solar System (*30*). The N/C ratio can therefore be used to infer the distance from the Sun of Ryugu's parent body during its formation. We measured an average N/C atomic ratio of 0.047±0.022 from the ten coarse samples. This is higher than primitive anhydrous chondrites (N/C = 0.001 to 0.02), consistent with hydrated chondrites such CM and CI (N/C = 0.02 to 0.06), and lower than ultra-carbonaceous micrometeorites of probable cometary origin (N/C = 0.06 to 0.2) (*30*). We conclude that Ryugu's parent body formed at heliocentric distances similar to hydrated carbonaceous chondrites.

Mineralogy and mineral chemistry

The SR-CT image of C0002 (Fig. 1B) shows that it consists almost entirely of fine-grained matrix material. No distinct objects formed at high temperatures (>1000 °C) in the early solar nebula such as chondrules (formed by melting of precursor silicate-rich dust) or Ca, Al-rich inclusions (CAIs: formed by condensation from hot nebular gas and were the earliest indigenous solid in the solar system) over 100 µm diameter were found from all coarse samples, but there are smaller examples (discussed below).

We produced 31 polished sections cut from 11 samples (Table S4) including 2 plates from the largest sample C0002. Observations with field-emission electron microscopes show that most of the coarse samples are breccias consisting of fragments ranging in size from ~10 to ~500 microns. Elemental abundance maps of Na and Mg show compositional differences between fragments (Fig. S8), usually with sharp boundaries. Most of the fragments consist primarily of fine-grained matrix material, with similar (though not identical) mineralogy and mineral chemistry, which we refer to as Ryugu's major lithology. CI1 chondrites have similar properties, with Orgueil being the most brecciated, with the Ryugu samples having similar brecciation to Orgueil *(31, 32)*.

The major lithology of Ryugu (Fig. 1C) consists of minerals formed by aqueous alteration: the dominant phase is a phyllosilicate-rich matrix that contains minerals including abundant iron sulfides (pyrrhotite and pentlandite), carbonates (breunnerite and dolomite), magnetite, and hydroxyapatite. The phyllosilicates consist of the minerals saponite and serpentine. Chlorite was only detected in a limited area in C0076. Mg-Na phosphate occurs in some places and appears to have shrunk in volume since its formation, probably due to degassing of volatile species, such as water (Fig. S9). Dolomite is the most abundant carbonate mineral; breunnerite is less abundant but occurs as larger crystals, with one in C0002 measuring 940µm × 450µm × 262 µm (Movie S1). Ca carbonate is rare. Pyrrhotite crystals with a pseudohexagonal shape (1-100 µm) are abundant and sometimes include pentlandite. Nano- to submicron-size pyrrhotite and pentlandite crystals occur ubiquitously in the phyllosilicate matrix (Fig. S10). Magnetite is present in diverse morphologies (Fig. S11), which is typical of CI1 chondrites (*31*). The carbonates often contain small (< 10 µm) crystals of magnetite and pyrrhotite. Small (< 10 µm) olivine and low-Ca pyroxene crystals are present but rare; they are completely absent from some of the coarse samples.

Ferrihydrite was not observed, despite being a major component of Orgueil (*33*, *34*). Nor was magnesium sulfate. Calcium sulfate (gypsum; $CaSO_4(H_2O)_2$) was detected only as very small grains around larger crystals of calcite (Fig. S12) and probably formed after sample recovery on Earth, by reactions of calcite with sulfuric acid produced by oxidation of small pyrrhotite crystals within the Ryugu samples *(35, 36)*. Small crystals of sodium sulfate grew on the surface of polished sections of Ryugu samples (Fig. S13), which is apparently of terrestrial origin. We infer that sulfates are likely absent on Ryugu, implying that sulfates in CI1 chondrites are terrestrial contamination (*37*). Additional minor minerals include chromite, Mn-rich ilmenite, spinel, ZnS, cubanite, and daubréelite. Carbonaceous material occurs as globules and diffuse objects in matrix.

Phyllosilicates in the major lithology have Mg# (defined as atomic ratio of Mg/(Mg+Fe)× 100) mostly in the range of 75-90, similar to Orgueil, but Ryugu phyllosilicates have more magnesium-rich varieties than in Orgueil, because parts of Ryugu data are plotted in the Mg#>85 area (Fig. 4B). The compositions of the carbonates are very similar to CI1 chondrites (Fig. 4C). Breunnerite and dolomite contain 1-10 and 2-5 wt % MnO, respectively. Hydroxyapatite contains a small amount of fluorine (< 1 wt%), typical of chondrites (*38*). We performed high-energy synchrotron X-ray fluorescence (XRF) tomographic analysis (*39*), finding enrichment of rare-earth elements (REEs) in hydroxyapatite, with mutually-consistent levels of each REE (Fig. S14). This is unlike apatite grains in ordinary chondrites (*40*) and Orgueil (*32*), which have higher levels of Eu and Gd, respectively, than other REEs. Ordinary chondrites and CK (Karoonda-type carbonaceous chondrites) have REE abundances that decrease from light to heavy atomics masses (*40*), unlike Ryugu. The magnetite does not contain detectable trace elements, while ilmenite contains various concentrations of MnO up to 10 wt%, both typical of CIs (*34*, *41*). Pyrrhotite contains Ni up to 2 wt%. The Ni/Fe atomic ratio of pentlandite ranges from 1 to 1.2 in most cases. Representative compositions are listed in Table S5.

Relative mineral abundances were estimated from two element maps of C0002 (~9.0 and ~8.6 mm^2 area) composed primarily of the major lithology. The abundances (Table S6) are broadly consistent with those of Orgueil (*31*, *32*, *42*).

We performed X-ray diffraction (XRD) analysis of a whole sample of C0002 (Fig. S15), finding a large, broad peak at approximately 10 Å and a distinct peak at 7.45 Å, which we identify as due to saponite and serpentine, respectively. The 10 Å peak indicates a low abundance of interlayer H_2O in saponite, as previously inferred using other techniques (*29*). To characterize the phyllosilicates, we applied ethylene glycol to 10 small particles separated from several coarse samples *(7)* and observed peak shifts in the XRD patterns, indicating expansion of interlayer spacings due to addition of glycol (Fig. S16). We identify reflections at 16.8, 13.3 and 7.28 Å as due to saponite-serpentine mixed-layer minerals based on the first two reflections and pure serpentine from the last reflection *(7)*. The saponite-rich mixed-layer mineral is the most abundant followed by serpentine, but the relative abundances differ between samples. Similar results have previously been obtained for Orgueil (*43*).

Although the bulk mineralogy of Ryugu samples is similar to Orgueil, we found above that the Ryugu samples are much darker. Possible explanations are the presence of bright Mg-sulfate epsomite in Orgueil *(37)*, and a lower Fe^{3+} abundance in phyllosilicates in the Ryugu samples (Fe^{3+}/Fe_{total} is 0.4 for Ryugu and 0.9 for Orgueil). Mg-rich smectite becomes brighter as Fe^{3+}/Fe_{total} increases from 0.40 to 0.97 (*44*). The oxidation of phyllosilicates and the formation of epsomite can occur on Earth due to weathering, which we infer is the likely origin of the brightness of Orgueil. Ryugu samples also contain a high abundance of opaque, nano-size pyrrhotite, (Fig. S10) which acts as a darkening agent; Orgueil lacks these *(34)*, possibly also due to oxidation on Earth (*45*).

The mineralogy, mineral chemistry, and relative mineral abundances of the major lithology indicate that Ryugu (or its parent body) experienced pervasive aqueous alteration. Except for the lack of sulfate and ferrihydrite, the petrological and mineralogical properties of Ryugu are consistent with the five CI chondrites (*31*, *32, 34, 46–48)*; we therefore classify the Ryugu samples as CI chondrites.

Less altered fragments

While most Ryugu fragments have experienced extensive aqueous alteration, some fragments in samples of C0002, C0033, C0023, C0025, C0040, C0046, C0076, and C0103 show a considerably lesser degrees of alteration. Electron-microprobe analysis *(7)* indicates that these fragments contain higher abundances of olivine and pyroxene (Table S6). Electron diffraction (Fig. S17) shows that they also contain calcite or aragonite (not dolomite or breunnerite) and phosphides (schreibersite $(Fe, Ni)_3P$ and allabogdanite $(Fe, Ni)_2P$) not hydroxyapatite. These are characteristic features of a less-altered lithology. These less-altered fragments are enriched in Na, with Na/Si ratios ~2 times that of the Sun (Table S7).

We identified five less altered fragments in one of the thin sections of C0002. The Mg map of C0002 (fragment 1 in Fig. S8B) indicates a high abundance of olivine and low-Ca pyroxene, which are rich in Mg relative to surrounding phyllosilicates, and spinel grains with sizes < 30 µm (Fig. S18 and Table S6). Most olivine in the Ryugu samples occurs in these less altered fragments; it has Mg# > 97 (corresponding to FeO < 3 wt% in Fig. 4D), similar to olivine in CI chondrites (*49–51*). A similar, but more altered, fragment has previously been reported in Orgueil [(*52*), their clast 1].

We identified the two fragments that exhibit the least alteration among our samples: labelled fragments 4 and 5 in Fig. S8B. The fragments are small (Fig. S19: 130 µm x 50 µm and 200 µm x 90 µm for fragment 4 and 5, respectively) and embedded within the major lithology. They have a very porous texture, dominated by submicron particles of olivine, pyroxene, and other smaller silicate phases with numerous iron sulfide inclusions (Fig. 3D and E). They also contain micron-sized regions of Ca carbonate, pyrrhotite, Al spinel, magnetite spherules, small quantities of phosphides, MgNa phosphate, pentlandite, Cr spinel, and tochilinite, a hydrous sulfide that is abundant in CM2 chondrites (*53*) (Fig. S20). These mineral assemblages are similar to fragment 1, but the abundance of olivine and pyroxene is much higher (12.8 and 14.1 vol % for olivine in fragments 4 and 5, respectively; see Table S6). Most of the olivine and pyroxene is enriched in Mg, but examples of Fe-rich olivine (Mg#<44) are also present. Several small areas in fragment 4 contain Na-rich phyllosilicate, indicating that aqueous alteration fluids were enriched in sodium. The high abundance of anhydrous silicates leads us to classify the least altered fragments as CI2 (a CI chondrite that was altered but still retains anhydrous minerals), rather than CI1 (in which almost all anhydrous silicates are replaced by phyllosilicates).

We observed the least-altered fragments using transmission electron microscopy (TEM *(7)*), finding that the least-altered fragments also contain numerous partially rounded, mostly 100-500 nm, amorphous silicate objects that contain abundant Fe sulfides (mainly < 50nm pyrrhotite and minor pentlandite) (Fig. 3F and S21A). These objects are similar in texture and composition (Fig. S21A and B) to glass with embedded metal and sulfides (GEMS) that occur in anhydrous chondritic interplanetary dust particles (IDPs) of probable cometary origin (*54*). The silicates are mostly amorphous or very poorly crystalline material (the latter possibly phyllosilicates) with lattice spacings close to 2.6 and 1.5 Å (Fig. S21A). This is similar to fine-grained fibrous material reported in the GEMS-like objects in the Paris CM chondrite (*55, 56*).

However, there are differences between the least-altered Ryugu fragments and GEMS in IDPs. The GEMS-like objects we identify in Ryugu lack Fe metal, instead containing pyrrhotite, pentlandite, and tochilinite. The silicates have signs of incipient alteration to phyllosilicates (Fig. S21A). The Mg-rich silicate composition of the GEMS-like objects in Ryugu is similar to the silicates in GEMS in IDPs (Fig. S21B), but also to the phyllosilicate composition in the major lithology (Fig.4B). This indicates that the GEMS-like objects in Ryugu are at least partially altered, similar to the primitive clasts in the Paris CM chondrite (*55-57*).

Chondrules, CAIs, and porous olivine

We do not identify any normal sized chondrules (100-1000 μm) in the Ryugu samples analyzed using SR-CT. However, some smaller objects and fragments (Fig. 3G-I) have features characteristic of chondrules. Some of these (Fig. 3G and H) contain FeNi metal spheres embedded in Mg-rich olivine (Mg#>98), indicative of melting in very chemically reduced conditions, which is typical of type-I chondrules that consist mainly of olivine with Mg#>90. One object has a barred olivine texture in TEM observations (Fig. 3I) - a thin rim and many bars constituting a single crystal of Mg-rich olivine. Therefore, this object is a type-I barred olivine chondrule. No glass is present between the olivine bars, only pores, probably indicating glass was originally present but dissolved during the early stages of aqueous alteration. We also identified a small (~ 30 μm in size) chondrule that has been completely replaced by phyllosilicates (Fig. S22 and Movie S2). Similar completely altered chondrules have previously been found in the ungrouped C1 chondrite Flensburg, although they are larger (>300 μm) (*16*). The small size and low abundance of the chondrules in Ryugu are similar to those found in samples of the short-period comet 81P/Wild2 (*58*).

We also identified a few small (< 30 μm) CAIs in the Ryugu samples (Fig. 3K and L). Their sizes are smaller than CAIs in the Ivuna CI1 chondrite (~100 μm) (*59*). One of the CAIs (Fig. 3K) consists of half hibonite and half Al-rich Fe-free spinel, with a small perovskite inclusion. Another (Fig. 3L) consists solely of Al-rich Fe-free spinel, with a small hibonite and a perovskite inclusion. We interpret this as evidence that CAI material that is susceptible to aqueous alteration, such as melilite (*60*), was replaced by phyllosilicates. Several CAI-related spinel-rich aggregates, together with forsteritic olivine, were also observed (Fig. S18).

Forsterite (Mg#98-99) grains occur in the less-altered lithology, being < 30 μm in size with numerous micron-size pores. One (Fig. 3J) contains Al, Ti-bearing Ca, Mg-rich pyroxene, diopside. We analyzed 20 grains of porous forsterite by an electron microprobe, finding they all contain ~0.5 wt% MnO. Atomic ratios of Mn/Fe do not exceed 1 in most cases and thus they are not low-iron manganese-enriched (LIME) olivine (*61*). The pores suggest partial dissolution during aqueous alteration. The origin of this porous olivine is unclear; they could be condensation products, similar to amoeboid olivine aggregates (AOAs) found in carbonaceous chondrites (*62*), although the texture of the olivine crystals in Ryugu is different from AOAs (*63*).

Fluid inclusions in pyrrhotite

We performed higher-resolution (~50 nm/voxel) synchrotron nano-computed tomography (SR-nanoCT) of a large pyrrhotite crystal taken from sample C0002. This crystal showed probable fluid inclusions in the center (Fig. 5A and B), suggesting the fluids were trapped in the early stages of crystal growth. These inclusions are completely encapsuled in pyrrhotite and filled with a light-element material (Fig. S23). We performed Time-of Flight-Secondary Ion Mass Spectrometry (TOF-SIMS) depth profiling and lateral mapping (<80 nm/pixel) at a temperature of -120 °C to expose and measure, respectively, the composition of the (now frozen) fluids in five inclusions.

The TOF-SIMS measurements show that the trapped fluids were solutions containing H_2O, CO_2, sulfur species, and nitrogen- and chlorine-bearing organic compounds. These were identified by their representative secondary ion species including O^-, OH^-, CO^-, C_2^-, C_2H^-, Cl^-, S^-, and CN^- (Fig. 5C). The detection of CO^-, C_2^-, C_2H^- and C_3^- suggests a complex molecular structure of organic molecules dissolved in the aqueous solution. Electron microscope observations of the largest inclusion show no phyllosilicates or other OH^- bearing phases that could have contributed to the signal (Fig. 5D). The presence of CO_2-bearing water in a crystal of pyrrhotite indicates that the Ryugu parent body formed beyond the snow lines, boundaries between gas and ice, of H_2O and CO_2 in the early Solar System, i.e. > 3-4 astronomical units (au) from the Sun (*64*).

Flat surfaces and CuS tabular coral-shaped object

We identified some features of the Ryugu samples that have not been observed in meteorites. These include very flat surfaces of coarse samples (Fig. 6A). We cut five slices (each 10 × 10 × 0.1 μm) from the flat surface of A0067 to perform depth profiles. TEM observations show a 2 μm thick saponite-rich layer with high Mg#~90 running along the flat surface (Fig. 6B). The saponite layer is superposed on an irregular surface of the major lithology, indicating that it formed later. All five slices show similar features, which we infer are present across the whole flat surface. The formation of the saponite layer requires fluids were present. Pyrrhotite crystals on the flat surface are aligned with their pseudohexagonal facets parallel to the saponite layer (Fig. S24), implying a compressive force during formation. One possible explanation is ice lensing, formation and growth of subsurface ice crystals (*65*, *66*), as occurs in permafrost soils. At the final stage of aqueous alteration, fluids could have been segregated in thin cracks as they froze. Ice in the cracks would then have grown to form ice lenses. The pressure exerted by the expanding ice lens would have squeezed the adjacent regolith, compacting and aligning phyllosilicates, especially expandable clays such as saponite (*66*).

We also identified table coral-shaped growths of a CuS phase on the flat surface of A0067 (Fig. 6C). A thin section was made by cutting the CuS object perpendicular to the flat surface, then observed with TEM. The CuS has a morphology which resembles a table coral, with a root, several branches, and many disk-shape crystals on top (Fig. 6D). Electron diffraction suggests that the CuS phase is probably digenite (Cu_9S_5), which is of hydrothermal origin (*67*). We cannot determine the formation mechanism, but it might have grown from a solution that filled a crack exposed on the flat surface.

Shock effects

Most of our samples show no features indicating strong deformation or shock melting, indicating the collected material generally did not experience any intense shock. However, C0055 shows evidence of uniaxial compression and sets of parallel fractures perpendicular to the compaction axis (Fig. S3). Such features are common in shocked hydrous carbonaceous chondrites (*68*) and appear in experiments that shocked the Murchison CM2 chondrite to a pressure of 20 GPa (*69*). Therefore, C0055 experienced a shock while the other 16 samples seem to free of shock effects.

Aqueous alteration conditions

The low abundance of Mg-chlorite suggests that aqueous alteration occurred at low temperature, below the ~ 100 °C (*70*) required to stabilize Mg-chlorite . All 10 pyrrhotite crystals observed by X-ray and electron diffraction show the monoclinic 4C structure, one of crystal structures of pyrrhotite having three unequal crystal axes with one oblique intersection, and indicates they formed below 254 °C (*71*). The Ryugu pentlandite and pyrrhotite compositions are most consistent with 25°C (Fig. S25) [(*67*), see also (*72*, *73*)], suggesting low-temperature formation. The site occupancy by Fe and Ni in pentlandite and its lattice constants are a function of temperature (*74*). We measured the pentlandite lattice constant of 10.0643±0.0009 Å using XRD analysis of a single pentlandite crystal, 5 µm in size, which was separated from sample C0040, following established methods (*75*). This lattice spacing, and the chemical composition, indicate an equilibrium temperature of 20 ± 29.5 °C (Table S9). O isotopes in dolomite indicate formation at 37±10 °C (*29*). All these temperature estimates are consistent.

Mössbauer spectra (conventional and synchrotron) were collected from 1-mm size fragments taken from C0061 and A0026 in N_2 conditions. These show that magnetite is not oxidized (Table S9). The Fe^{2+}/Fe_{total} ratios measured from the phyllosilicates are approximately 0.61 for C0061 and 0.48 for A0026 (Fig. S26). Magnetite, pyrrhotite, and silicates contain 40 to 50, 15 to 30, and 25 to 40 % total iron, respectively (by atom, Table S9). Micro-X-ray Fluorescence X-ray absorption Near Edge Structure (µ-XRF XANES) analysis of the Fe K-edge, a sudden increase of X-ray absorption just beyond the binding energy of the K-shell electrons of the Fe atom, using a 1.0 µm × 1.0 µm X-ray beam (*76*) was performed in N_2 condition using a 150-µm sized particle separated from sample C0025. The Fe^{2+}/Fe_{total} ratio in phyllosilicates was determined to be 0.6 to 0.7 (Fig. S27), consistent with the Mössbauer data.

The determination of Fe^{2+}/Fe_{total} ratio in other minerals, specifically saponite and serpentine, is required to determine the redox conditions during formation, because the stability of Fe^{2+} in each phase can be different. We used scanning transmission X-ray microscopy (STXM; (*77*)) analysis with a ~50 nm spatial resolution to measure Fe^{2+}/Fe_{total} in the saponite layers in A0067 (Fig. 6B), finding 0. 68±0.05 (Fig. 4E and F). The sample must have been oxidized to some degree during its storage in a desiccator for more than five months, so we regard this ratio as a lower limit. Based on (i) the relationship between Fe^{2+}/Fe_{total} ratio and oxidation reduction potential E_h determined for the minerals nontronite and high Fe-bearing montmorillonite (*78*); and (ii) a reduction experiment we performed on terrestrial saponite with Fe^{2+}/ Fe^{3+} ratio determined by XANES (Fig. S28); we infer that the Fe^{2+}/Fe_{total} (> 0.68) obtained from A0067 indicates that the Eh of saponite formation was likely lower than -0.45 V. If we assume that the this Eh value is valid at neutral to alkaline pH conditions, and combine it with other µ-XRF-XANES data on a dominant oxidized arsenic form (As^{3+}) in As-bearing species in A0067 (Fig. S29), we infer fluid pH > ~9 based on the Eh-pH diagram of As compounds at 25°C (*79*). The presence of saponite on Ryugu also indicates an alkaline fluid (pH > 8) based on (i) the stability field of saponite in the Eh-pH diagram of Fe and (ii) the pH condition of terrestrial lakes where saponite has been found (*80*).

We conclude that aqueous alteration proceeded at ~25°C in alkaline conditions.

Chemical equilibrium modeling of aqueous alteration

Aqueous alteration cannot have begun until accreted ices melted in the interior of Ryugu's parent body, and likely continued until temperatures reached ~40 ºC (this study and (*29*)). We therefore performed chemical equilibrium modeling of a water-gas-solid system at 0-40 ºC (*7*). Consistent with the muon analysis (Table S3), we assumed the initial accreted rock had the elemental composition of CI chondrites, but with modified amounts of H, C, O, S and Cl. Our model mixes this rock in different proportions with a water-ice rich component, which contains CO_2 and HCl, reflecting the presence of CO_2 and Cl in the fluid inclusion (Fig. 5) and the inferred C and Cl sources in carbonaceous chondrites (*81*, *82*). Although Ryugu material may not have reached chemical equilibrium during alteration, we ran our calculations to that stage.

Figures 7A-D show our calculated equilibrium composition of the water-gas-solid system at 40 ºC, as a function of the initial melted ice/rock and the water/rock (*W*/*R*) mass ratios. Only 10 % of organic matter is allowed to react *(7)*. The modeled mineralogy (Fig. 7A) at initial *W*/*R* of 0.06 to 0.1 reproduces the least-altered lithology we found in the Ryugu samples (Table S6). These and lower *W/R* ratios permit stable reduced phases (e.g. Fe-rich metal, phosphides), which could remain unaltered or form through alteration under water-poor and H_2-rich conditions. A higher *W/R* ratio of 0.1 to 0.2 matches the less-altered lithology, and *W/R* of 0.2 to 0.9 with pH > 9 (Fig. 7C) matches with the more extensively altered major lithology (Table S6). Analogues calculations were performed at temperatures below 40 ºC (0 ºC and 20 ºC) and the results are similar to those at 40 ºC *(7)*.

Our calculations show high Na concentrations at lower *W*/*R*, both in the fluid and in saponite (Fig. 7A and B), which are consistent with the Na-rich composition of the least- and less-altered lithologies of Ryugu (Table S7). The modeling suggests an initial Mg-Na-Cl solution with H_2O-CO_2 in the gas phase, which evolved towards a more reduced and Na-Cl alkaline brine that coexisted with a H_2-rich gas phase (Fig. 7B-D). No sulfates form in the model, due to the reduced conditions, which is consistent with our observation of the Ryugu samples. The formation of sulfates requires strong oxidants, such as O_2, H_2O_2 and H_2SO_4, in ices accreted on asteroids (*83*).

Formation of Ryugu's parent asteroid

The asteroid Ryugu was formed in a different orbit than its current near-Earth one. Orbital dynamics calculations have shown that the most likely origin is two asteroid families (Eulalia or Polana C) in the inner main asteroid belt (*3*, *4*, *84*, *85*). Our observation of CO_2-bearing aqueous fluid in Ryugu pyrrhotite is consistent with the parent asteroid having formed beyond the H_2O and CO_2 snow lines of the early Solar System, i.e. > 3-4 au from the Sun. This must have been followed by scattering inward, to the current orbit of the Polana and Eulalia families (< 2.5 au). We found many similarities between the Ryugu samples and CI chondrites, which suggests that CI chondrites might have a similar origin.

The Ryugu samples record a magnetic field (Fig. S6), which could have arisen from the nebular magnetic field, or the dynamo fields generated by differentiated objects (such as Jupiter). The homogeneous global reflectance spectra of Ryugu indicate its parent body was not differentiated (*2*, *3*). The stable component of NRM is likely carried by the framboidal magnetite (Fig. 3A-C). If the source was the nebular field (*86*), then the solar nebula had not yet dispersed when magnetite formed on Ryugu's parent body.

Our interpretation that Ryugu's parent asteroid formed far from the Sun is supported by the rarity and very small size of chondrules and CAIs in the samples (Fig. 3G-L), which are similar to those observed in comets *(58)*, the high abundance of carbonate (Table S6), and the presence of GEMS-like objects (Fig. 3F). However, the C/Si abundance ratio is not as high as those of comets (Table S3), based on measurements of cometary IDPs and ultra-carbonaceous micrometeorites (*30*, *87*, *88*). This indicates the parent body of Ryugu did not originate from comets themselves, but formed in the same region as CI chondrites, at a large heliocentric distance, possibly outside the orbit of Jupiter (*89*).

Thermal model of Ryugu's parent asteroid

We used the physical properties obtained from the sample analysis (Table 1) to calculate a thermal model of Ryugu's parent body. The radius of the parent body was chosen based on an estimate of the total mass of the Eulalia family (*85*). We set a radius of 50 km for the rocky part of the parent body, then added additional size according to the amount of water ice in each model. The initial internal and surface temperatures were set to – 200 ºC (70 K, see rationale (*7*)). The temperature was then allowed to increase due to heating by radioactive decay of ^{26}Al, which melts the water ice at 0 ºC. Subsequent formation of hydrous minerals (assumed to occur at 20 ºC) releases energy that causes further heating. We ran simulations for ranges of formation age (t_s) and initial *W/R* ratio.

Mn-Cr dating of Ryugu samples has indicated that carbonates formed at 37±10 °C, 5.2 Myr after the formation of the first solid materials in the solar system (i.e., CAIs) (*29*). That temperature is consistent with our mineralogical constraints (mostly $\lesssim$ 50°C). Our chemical modeling of the aqueous alteration found that a *W/R* ratio of 0.2-0.9 reproduces the mineralogy of the major lithology (Fig. 7A). An example thermal model that satisfies these constraints (t_s ~2.2 Myr and *W/R* = 0.6) is shown in Figure 7E. Inside the parent body (~ 51 km radius from the center), ice melts, hydrous minerals form, and carbonate minerals precipitate at ~4.8 Myr. While hydrous and carbonate minerals form throughout, the subsequent temperature increase is limited (reaching a peak of ~75 ºC), and therefore dehydration of the hydrous minerals does not occur. Within 14 km of the cold surface, ice melting is limited, so the initial mineralogy experiences very little alteration at low *W/R* ratios and low temperature (~0 °C). Therefore, the least-altered lithology (Fig. 3D-F) we found in the Ryugu samples might have been located close to the surface of Ryugu's parent body.

The formation age in the model required to satisfy the constraints from the sample analysis varies depending on the initial *W/R*. The major lithology is consistent with *W/R* = 0.2 to 0.9 (Fig. 7A), which corresponds to a range of formation ages from 1.8 Myr (*W/R* = 0.9) to 2.9 Myr (*W/R* = 0.2) after CAI formation, the birth of the Solar System (see Fig. S30). We assume instantaneous accretion of the parent body at the time of formation. On the other hand, if we assume slow accretion of the parent body, then the formation would have started earlier.

Catastrophic collision of Ryugu's parent body

Ryugu's parent body was disrupted by a large-scale impact to form the Eulalia or Polana asteroid family, including Ryugu itself (*3*, *90*). Using the physical properties measured from the samples (Table 1), we constructed an equation of state consistent with the Ryugu material and used it to calculate a destructive collision with the parent body (*7*) using the impact-Simplified Arbitrary Lagrangian Eulerian (iSALE) software (*91–93*). Figure 7F shows the head-on collision of a 6 km-radius impactor onto a 50-km-radius parent body at an impact speed of 5 km/s, typical for the main asteroid belt (*94*). In this simulation, the parent body is largely destroyed, with the diameter (*D*) of the largest surviving body being ~ 50 km (Fig. S31). This is consistent with the measured sizes of Eulalia (*D* = 40 km) or Polana (*D* = 55 km) (*85*).

Figure 7F illustrates that, during the impact disruption of the parent body, regions that experienced high shock pressure and temperature are limited in volume. 10 and 0.2 volume % of the parent body experienced pressures higher than 1 and 10 GPa, respectively. The temperature near the impact site (approximated as the size of the impactor) rises above 700 ºC, while regions away from the impact site do not rise above 90 ºC. The latter temperature is consistent with the amount of interlayer water found in Ryugu saponite (*29*). With this temperature limitation and the absence of evidence for shocks in most of our samples, we propose that Ryugu might have formed from fragments excavated from areas far from the impact site, such as on the far side. It is likely that some of the reaccumulated material originated from the surface and sub-surface layer of the parent body; such material would have experienced limited degrees of aqueous alteration at low temperature and low *W/R* ratio, consistent with the least-altered and the less-altered fragments found in our samples.

We conclude that the samples collected by the Hayabusa2 mission originating from multiple depths within Ryugu's parent body, which formed beyond the H_2O and CO_2 snow lines, possibly beyond the orbit of Jupiter.

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Author contributions:

Organizing the research, writing the manuscript, main sample analysis: TN

Writing the manuscript, main sample analysis: MM, YE, KA, MZolensky

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Muon analysis: KN, TT, TO, KT, TW, SW, ST, AT, IU, IC, MKK, SN, YM

Physical property measurements: ST, HN, MS, TM, YN, TT, YI, RE, TY, TI, AA, NS, RF, TK, YY

Numerical simulations: HG, MYZ, KK, SW, RH

Reflectance spectra: KA, EK, MM, REM, ET, SS, TH, KK, QHSC, FV, ARH, CJ, DLD, GD, ZG, TK, LR, SR, DT, YY, EP, CP, SMP, CS, CL, RB, AA, KS, GN

TOF SIMS analysis: AD, RJB, IRG

XRD analysis: KS, AJK

Inter-discipline science discussion: HY, RF, HY, HN, KS, ST, HCC, DSL

Hayabusa2 mission sample collection: MY, MY, KY, KY, YY, KY, HY, YY, DY, MY, TY, TY, KW, TU, RT, FT, HT, YT, AI, HS, KS, YS, HS, HS, TS, MO, GO, TO, NO, KO, RN, HN, MN, NN, SN, TM, AAM, AM, YM, KM, KK, TK, SK, KK, SK, TI, YI, MI, HI, SH, RH, CH, YH, NH, NH, TH, MH, KH, SF, RF, AF, YC, MA, MA, SW, YT

All authors discussed the results and commented on the manuscript and meet the journal authorship criteria.

Competing interests: We declare no competing interests.

Data and materials availability:

All images and data used in this study are available at the JAXA Data Archives and Transmission System (DARTS) at https://data.darts.isas.jaxa.jp/pub/hayabusa2/paper/sample/Nakamura_2022/ . Other data on the Ryugu sample and from the Hayabusa2 mission are available at the DARTS archive at https://www.darts.isas.jaxa.jp/curation/hayabusa2 and https://www.darts.isas.jaxa.jp/planet/project/hayabusa2/, respectively. The returned samples are curated and will be distribute by JAXA Astromaterials Science Research Group. Details of sample distribution through Announcement of Opportunity is available at https://jaxa-ryugu-sample-ao.net.

Numerical simulation codes and scripts for the thermal modeling and SPH impact code used in this study are also available at DARTS. The input files used in the iSALE simulations and the output files used to depict figures are also available at DARTS.

Supplementary Materials

Materials and Methods

Supplementary Text

Figs. S1 to S47
Tables S1 to S15
References (*98-189*)
Movies S1 to S2

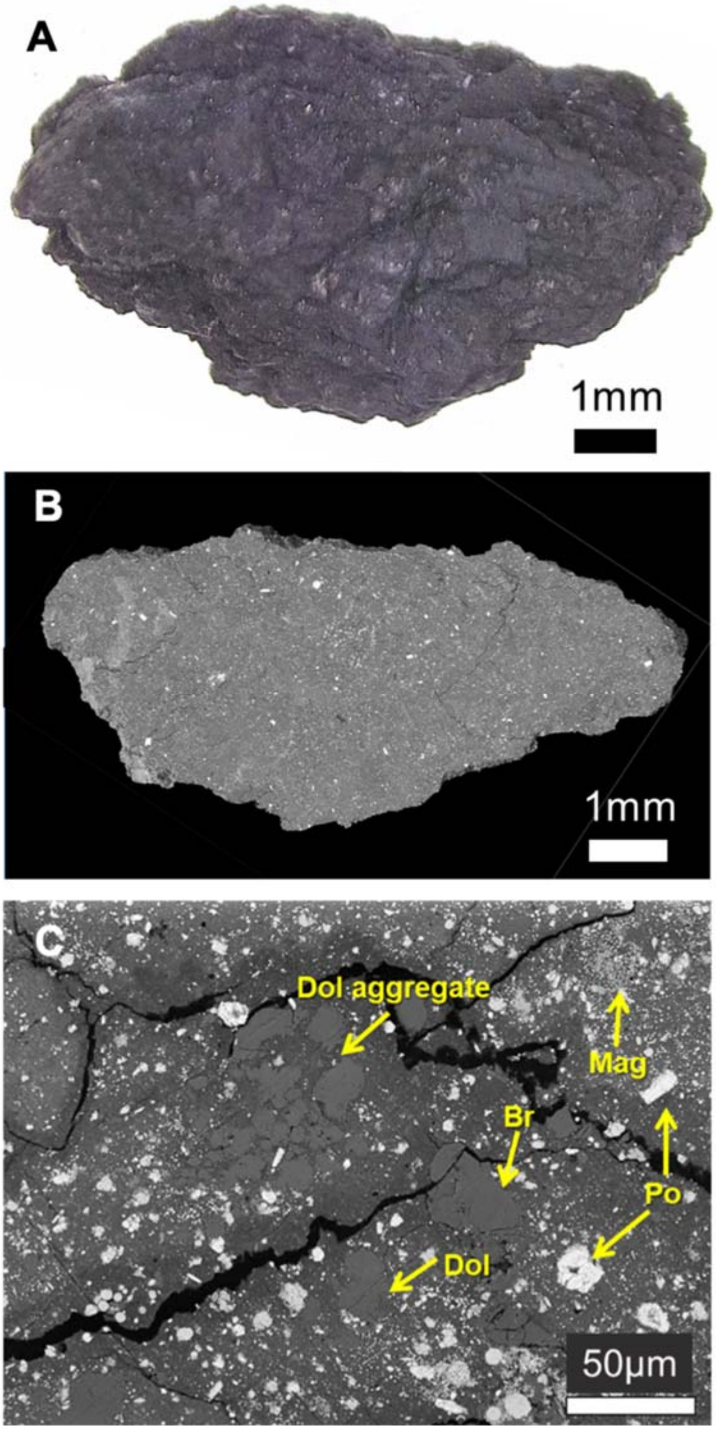

Fig. 1. Morphology and internal texture of C0002. (**A**) Optical micrograph of entire C0002 sample. (**B**) CT image of the largest cross section, showing the absence of chondrules and CAIs. 5 (**C**) Back-scattered electron (BSE) image of typical internal texture. Dolomite (Dol), breunnerite (Br), pyrrhotite (Po), and magnetite framboids (Mag) are labelled; these are embedded in a fine-grained phyllosilicate matrix.

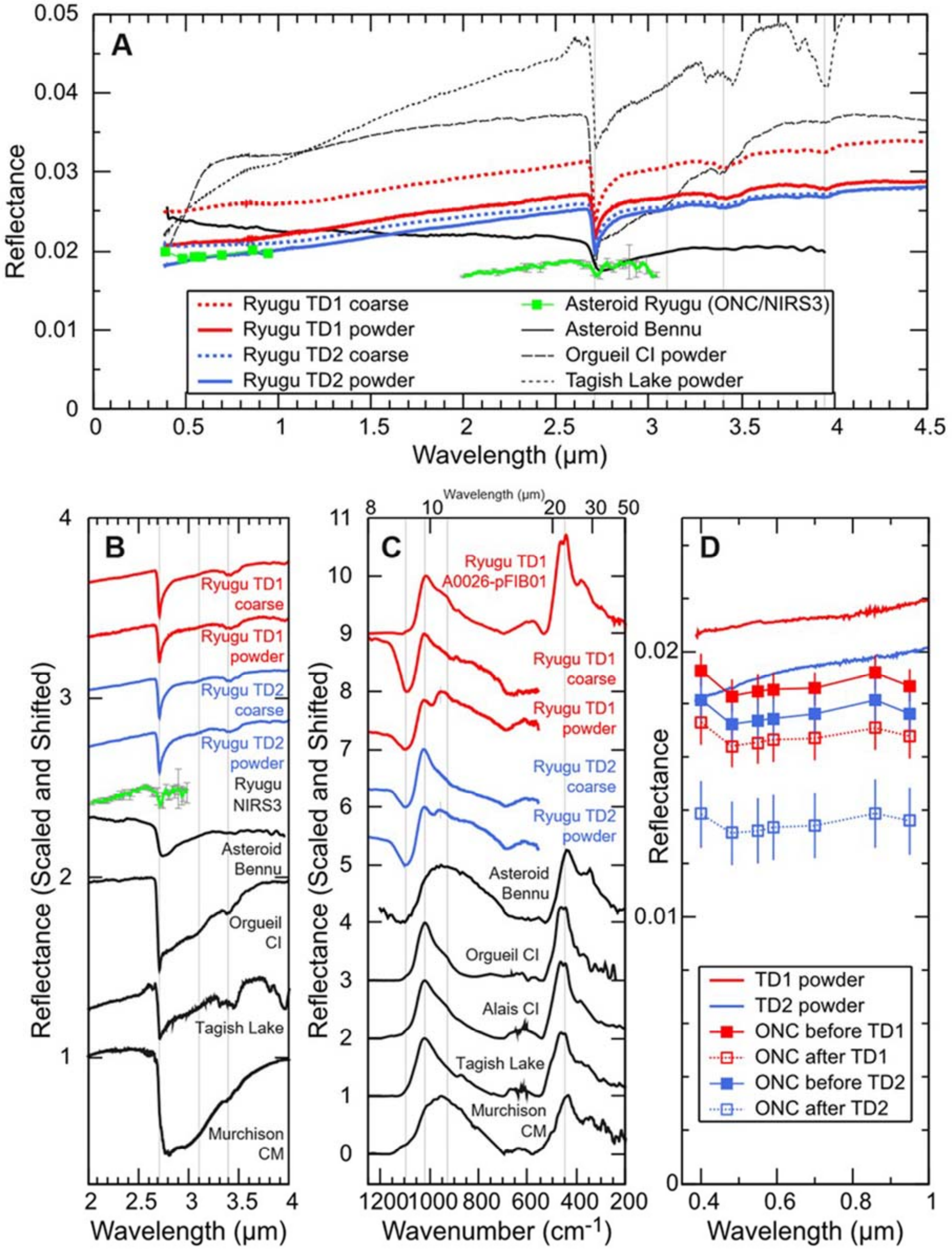

Fig. 2. Reflectance spectra of coarse and powder samples of Ryugu. (**A**) Vis-NIR reflectance spectra of coarse (dotted lines) and powder (solid lines) samples from the TD1 (red) and TD2

(blue) sites on Ryugu, compared to hydrated carbonaceous chondrites (dashed and dotted black lines), Hayabusa2 remote sensing observations of Ryugu (solid green lines) *(2, 3)*, and remote sensing observations of Bennu (solid black line) *(14)*. The vertical gray lines are at 2.71, 3.1, 3.4 and 3.95 µm. (**B**) Same data as panel A, but normalized at 2.595 µm and shifted arbitrary in the NIR wavelength region. (**C**) MIR-FIR spectra of TD1/TD2 coarse and powder samples, the flat surface of sample A0026, remote sensing observations of Bennu (*95*), pressed powders of meteorites (Alais and Tagish Lake), and meteorite coarse samples (Orgueil and Murchison). All spectra are scaled to have the same difference between reflectance minimum and maximum and shifted arbitrary. The vertical gray lines at 9.1, 9.8, 10.75, and 22.3 µm indicate respectively the Christiansen feature, an Si-O stretching peak, an additional shoulder of the main Si-O peak, and a peak of the doublet from saponite (*96*). The peaks at 10.5 µm in the powder samples are scattered light from the sapphire dish. (**D**)Visible reflectance spectra of Ryugu TD1/TD2 powder samples measured in the laboratory compared to the TD1/TD2 landing sites before and after the touchdowns *(7)*.

Table 1. Summary of the physical properties measured from the Ryugu samples *(7)*.

Mechanical properties	value	uncertainty	unit	measurement condition	measured sample(s)
compressive hardness	0.18	0.1	GPa	ambient	[#]C0002 plate 3
Young's modulus	5.3	1.6	GPa	ambient	[#]C0002 plate 3
bending strength	4.9	1.9	MPa	ambient	C0002 plate 3 and 4
longitudinal velocity	2.08	0.13	km/s	ambient	*avg. of C0002 plate 3 and 4
shear velocity	1.37	0.15	km/s	ambient	*avg. of C0002 plate 3 and 4
thermal expansivity	2.6×10^{-5}	2×10^{-6}	/K	210-400K, nitrogen gas	C0002 plate 3
cohesive force	0.17	0.02	µN	ambient	[$]C0002 plate 4
Thermal properties					
heat capacity at 298K	865	16	J/kg/K	213-373 K, nitrogen gas	avg. of C0002 plate 4 and A0026
thermal diffusivity	3.2×10^{-7}	0.3×10^{-7}	m^2/s	300 K, vacuum	avg. of C0002 plate 3 and 4
Electrical properties					
resistivity	2.5×10^{6}	0.3×10^{-6}	ohm・m	300 K, vacuum	avg. of C0002 plate 3 and 4
relative permittivity	6.8	0.8	-	300 K, vacuum	avg of C0002 plate 3 and 4
Magnetic properties					
magnetic susceptibility	8.39×10^{-5}	4.0×10^{-6}	m^3/kg	300 K, direct current, alternating current (1-1000 Hz)	avg. of C0002 and A0026
saturation magnetization	11.6	5.1×10^{-3}	Am^2/kg	300 K	avg. of C0002 and A0026
saturation remanence	1.05	6.3×10^{-3}	Am^2/kg	300 K	avg. of C0002 and A0026
coercivity	12.2	9.3×10^{-2}	mT	300 K	avg. of C0002 and A0026
coercivity of remanence	61.3	$\underline{4.1\times10^{-1}}$	mT	300 K	avg. of C0002 and A0026

[#] Average of 26 analysis of fine-grained matrix

* Two fragments from plate 4.

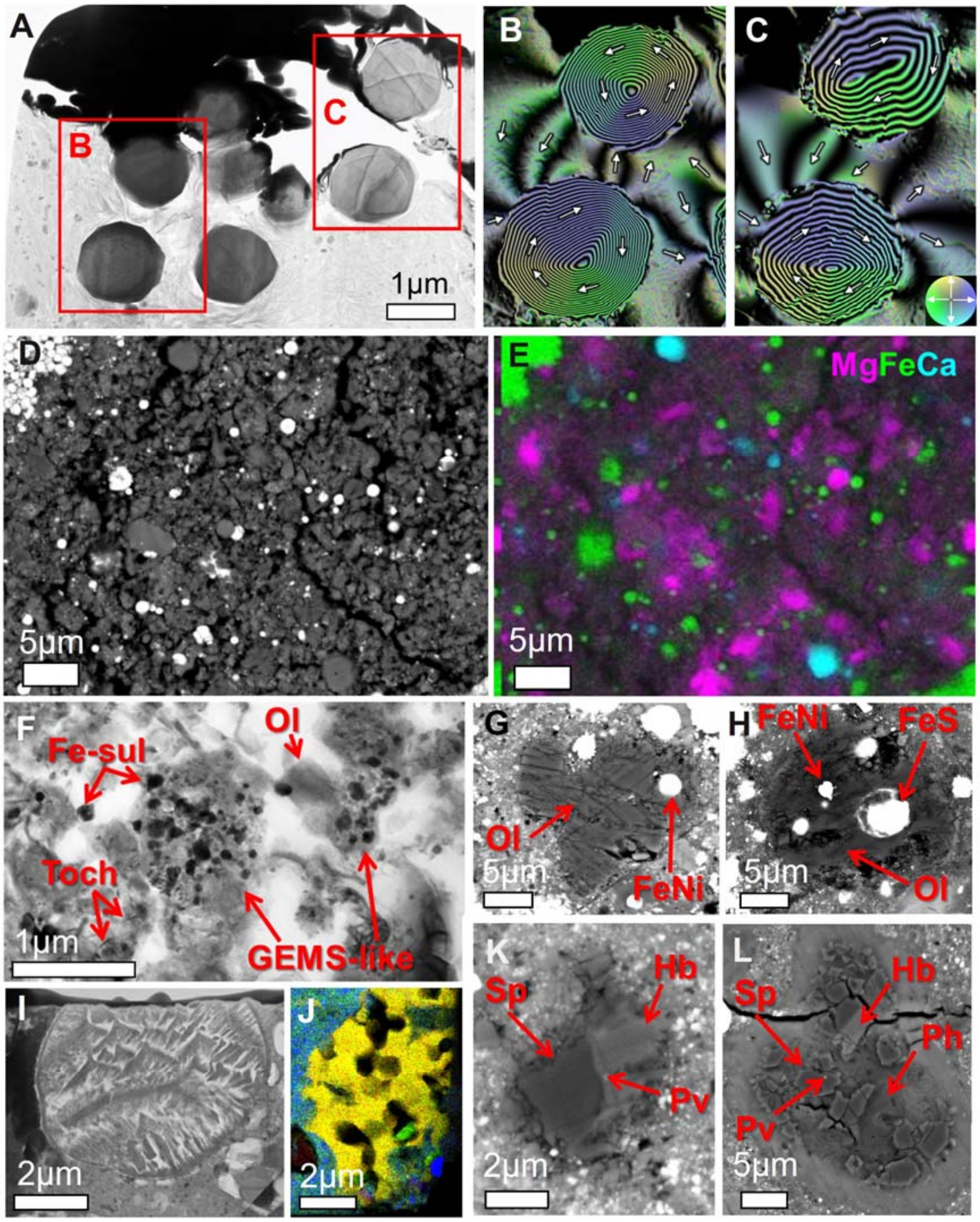

Fig. 3. Characteristic textures, magnetic structures, and embedded objects in the Ryugu samples. (**A**) TEM image of typical magnetite framboids (dark-grey rounded objects) from A0064. The light-grey area is phyllosilicate from the major lithology, and the upper black area is tungsten contamination. (**B, C**) Color maps of the magnetic flux direction obtained from the

reconstruction of remanent magnetism, for the magnetite framboids in red boxes in panel A observed using electron holography *(7)*. Each particle has a concentric circular magnetic field (vortex structure) indicated by white arrows, which show the direction of the magnetic flux as shown in the color-wheel in C. Figure S5 shows the composition and electron diffraction data for this region. (**D**) Enlarged view of the least-altered fragment 4 in sample C0002, showing high porosity. (**E**) Compositional map of (D), showing high abundances of Mg-rich olivine and Mg-rich low-Ca pyroxene (magenta), magnetite and pyrrhotite (green), and minor Ca carbonate (light blue). (**F**) TEM image of a part of the least-altered fragment 5 in C0002, showing a very porous aggregate with labelled GEMS-like objects, Fe sulfide (Fe-sul), Mg-rich olivine (Ol), and tochilinite (Toch). (**G, H, I**) Chondrule-like objects. Objects in (G) and (H), both from C0002, show textures similar to type-I chondrules, consisting of Mg-rich olivine (Ol) and an FeNi metal inclusion. An FeS inclusion occurs only in (H). The object in (I) from C0076 shows a barred-olivine texture, consisting of several sets of parallel olivine bars and an olivine rim. (**J**) TEM/energy-dispersive spectrometer (EDS) color map of a porous olivine (yellow) from C0076, including a small Al, Ti-rich diopside crystal (green). RGB indicates the concentration of Mg, Si, and Fe, respectively. (**K, L**) Small CAIs-like objects. Object in (K) from C0040 consists of Al spinel (Sp), hibonite (Hb), and a small inclusion of perovskite (Pv). Object in (L) from C0002 consists of Al spinel (Sp), hibonite (Hb), a small inclusion of perovskite (Pv) and phyllosilicate (Ph). (A, F, I) are bright-field TEM images and (D, G, H, K, L) are BSE images.

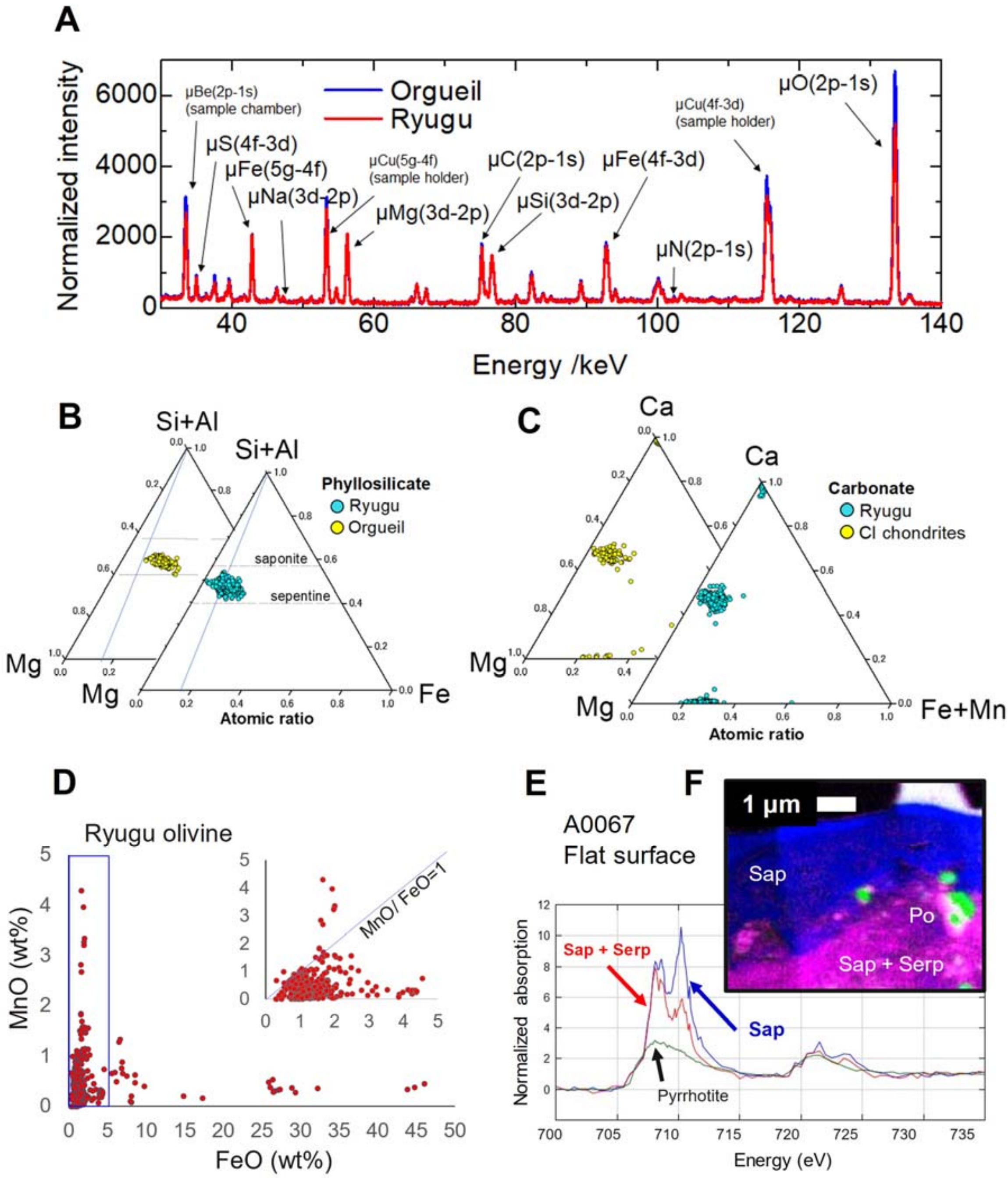

Fig. 4. Results of chemical analyses using muon, electron, and X-ray spectroscopy. (**A**) Muonic X-ray spectra, normalized by μSi 3d-2p X-ray (76 keV) intensities, for Ryugu (red) and Orgueil (blue). μSi 3d-2p X-ray represents the muonic Si X-ray emitted by transition of 3d to 2p muon atomic orbit. (**B**) Ternary diagrams of Mg, Fe and Si+Al, showing the chemical composition of Ryugu phyllosilicates (cyan, 774 analyses), compared with Orgueil (yellow). The blue line corresponds to Mg# = 85. The contribution from FeS was corrected based on S content *(7)*. (**C**) Ternary diagrams of Mg, Ca, and Fe+Mn showing the chemical composition of Ryugu carbonates (653 analyses), compared with CI chondrites (*48*, *52*). (**D**) MnO and FeO abundances

measured from Ryugu olivine (611 analyses). The inset shows an enlargement of the blue box area in the range from 0 to 5 FeO wt%. A blue line indicates MnO/FeO=1 and most olivine data are MnO/FeO < 1. (**E**) Fe $L_{2,3}$-edge XANES (X-ray absorption near-edge structure at Fe L_2-edge (706.8 eV) and L_3-edge (719.9 eV) regions) spectra of a saponite-rich layer (blue), phyllosilicates of the major lithology (red), and pyrrhotite (green). (**F**) XANES color map of the region shown in Fig. 6B, where three Fe species were found by the singular value decomposition analysis *(97)*, including Fe in saponite (pink), in serpentine-saponite (blue), and in pyrrhotite (green).

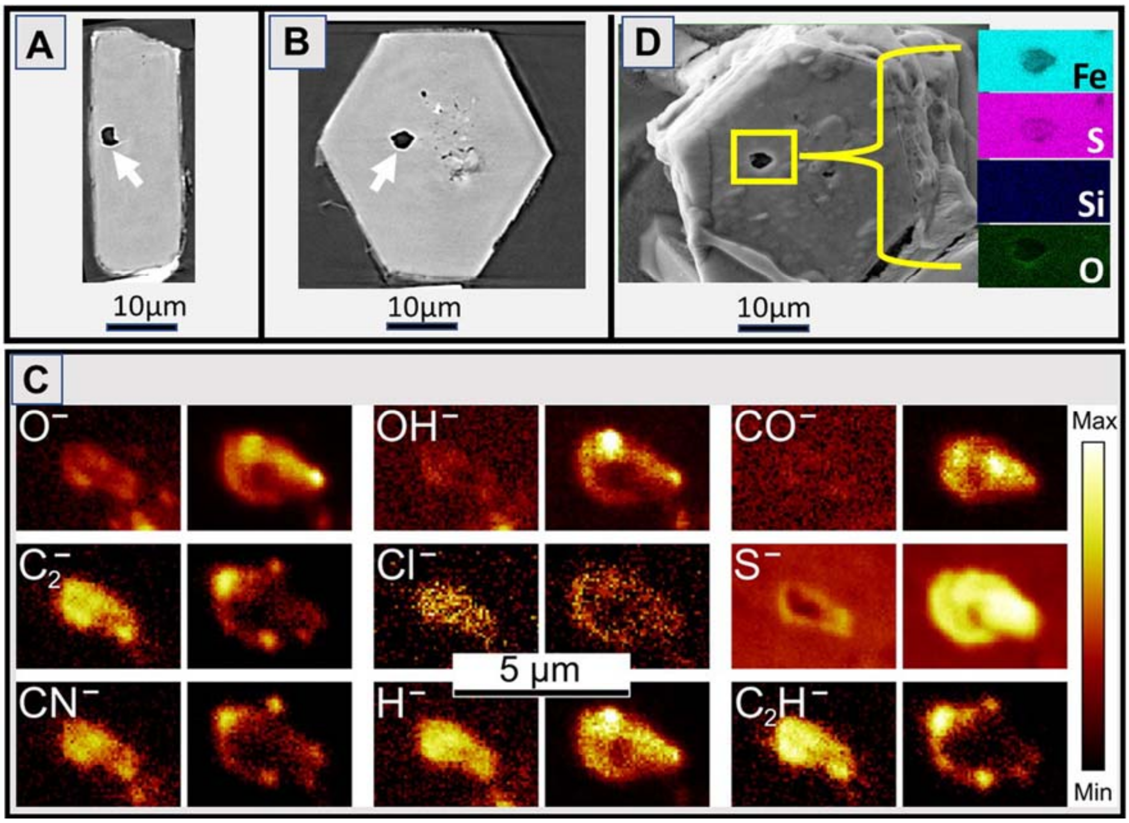

Fig. 5. A fluid inclusion in a Ryugu pyrrhotite crystal. TOF-SIMS and SR-CT measurements were performed on a crystal separated from sample C0002. (**A, B**) Slices through the SR-CT scan, showing the fluid inclusion (arrows) is unconnected to the surface, ~1.5 µm deep in (A). (**C**) TOF-SIMS maps of the fluid inclusion after being frozen (-120 ºC) and opened. Representative secondary ion species are labeled on each image pair, which are measured at the top (left images) and the mid-plane (right images) of the fluid inclusion. OH^- and CO^- are secondary ions of water and CO_2, respectively. S^- is an ion in the aqueous solution. The presence of CN^- indicates N-bearing organic compounds in the fluid, and Cl^- indicates that the trapped fluid was a brine. Differences in the distribution of each species within the inclusion, both within each map and between the top and midplane maps, are a result of the distribution of the various fluid components between the different solid phases (solid carbon dioxide, carbon dioxide clathrate, H_2O ice) that form during cooling of the fluid inclusion to -120°C. (**D**) BSE image of the final surface following the TOF-SIMS measurements, with the opened fluid inclusion in the yellow box. Insets show Fe, S, Si and O element maps by EDS of the region within the box, indicating FeS as the host phase.

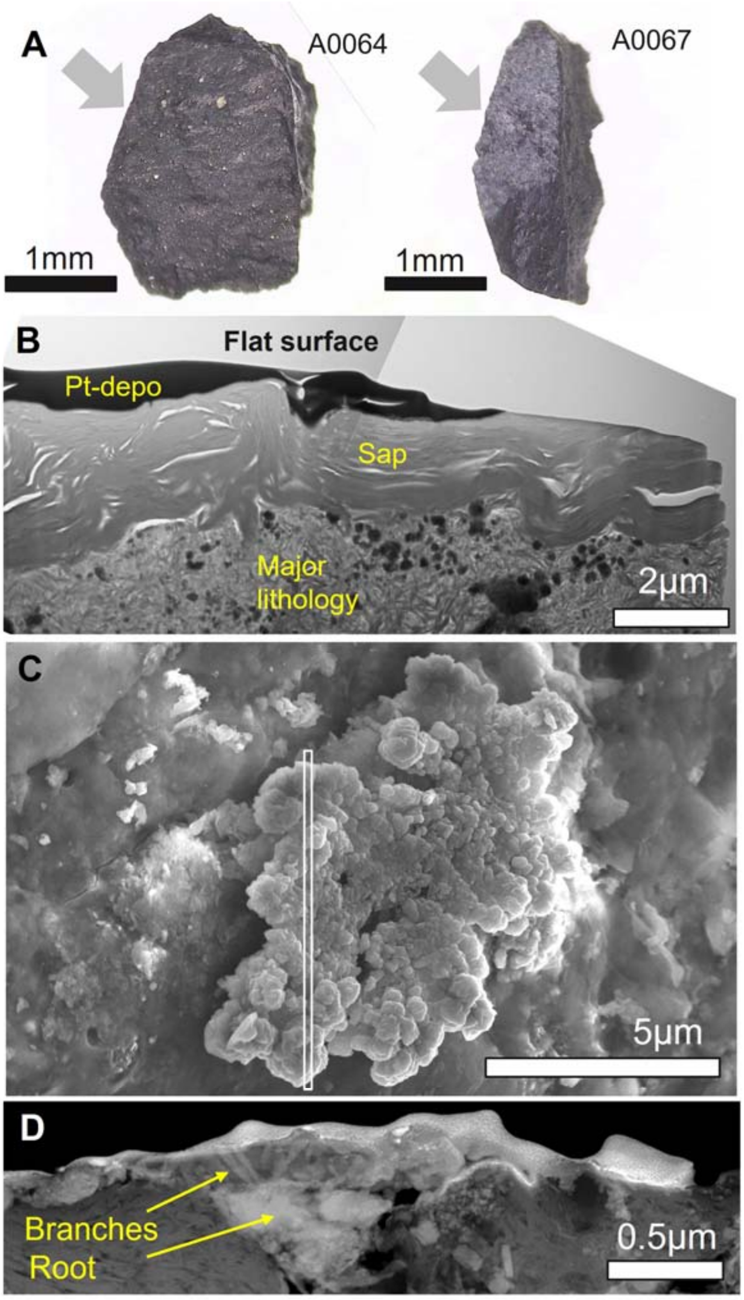

Fig. 6. Flat surface structures and a CuS table coral-shaped object. (**A**) Optical microscope images of flat surfaces (arrows) from two Ryugu samples. (**B**) Depth profile from a TEM image of a slice cut from the flat surface of A0067 to 5 µm depth. The black layer is contamination by Pt coating. A layer of saponite (interlayer spacing d= ~10 Å) makes the surface flat. (**C**) Secondary-electron image of a tabular coral-shaped CuS object on the flat surface of A0067, formed of a stack of submicron-sized disk-like crystals. (**D**) Scanning TEM dark-field image of a slice taken from the white box in (C), perpendicular to the surface to a depth of 10 µm using a focused-ion beam. The object has morphologies similar to a root, several branches, and a stack of disk-like crystals on top. The thin white layer on the top surface of the object is contamination by a Pt coating.

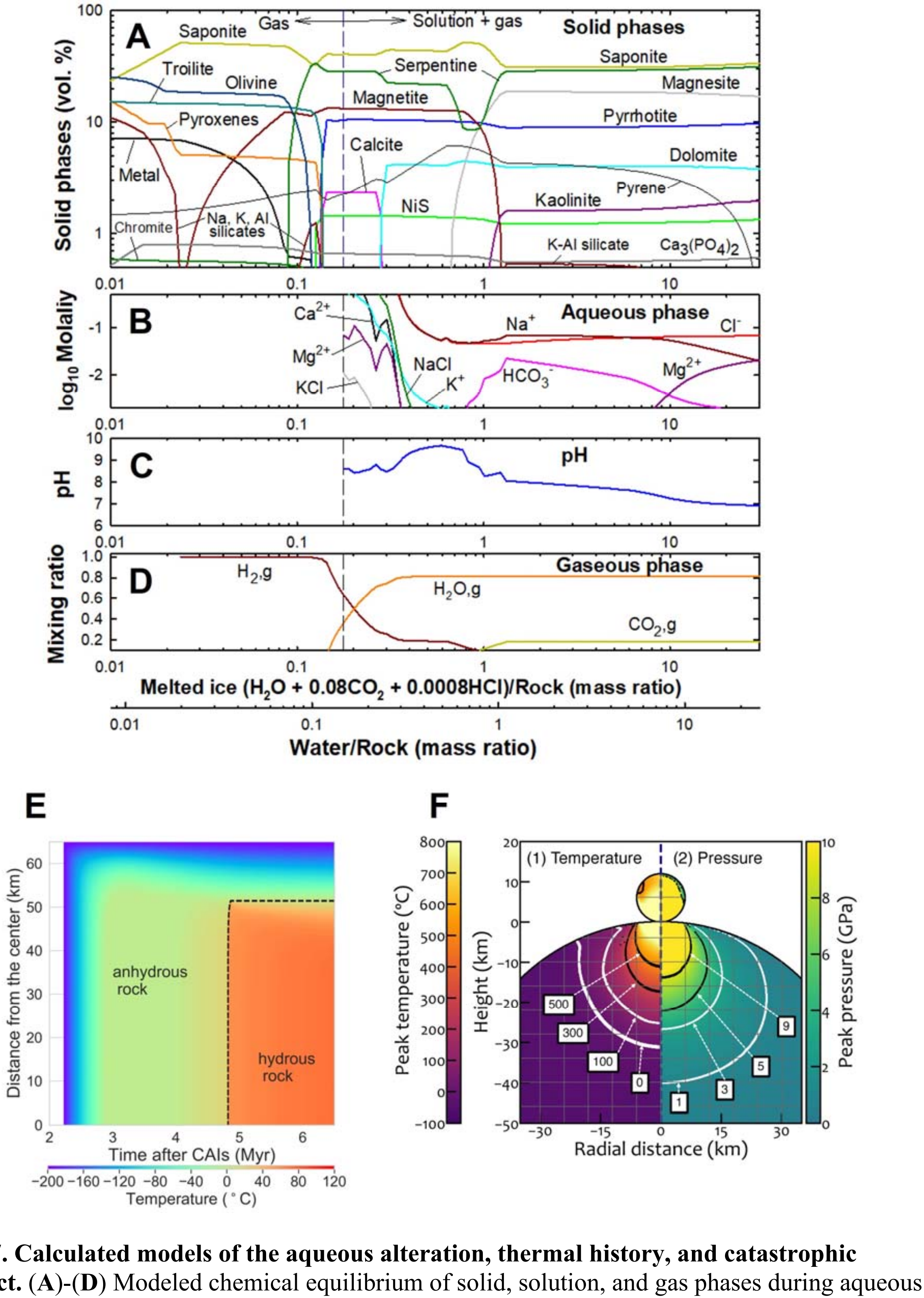

Fig. 7. Calculated models of the aqueous alteration, thermal history, and catastrophic impact. (**A**)-(**D**) Modeled chemical equilibrium of solid, solution, and gas phases during aqueous alteration on the Ryugu parent body at 40 ºC, the pressure of water saturation (7.4 × 10^{-2} bar), and 10 % chemically active organic matter. Each line indicates a different species or the pH, as

labelled. The vertical dashed lines indicate boundaries between aqueous and water-free conditions. Two horizontal scales: melted ice/rock and *W/R*. The ice includes CO_2 and HCl in addition to water and thus the melted ice/rock is larger than the *W/R* (The *W/R* is 0.835 times melted ice/rock). (**E**) Temperature evolution of the Ryugu parent body. The calculation assumes a 65 km radius with *W/R* = 0.6 and formation 2.23 Myr after CAI formation. Color shows the temperature at each location and time. The black dashed line indicates the boundary between the hydrous rock and anhydrous rock, where the highly altered lithology shifts to the less altered lithology. (**F**) Impact shock model (*7*), with coordinates measured from the center of the parent body. The images show peak temperature (left) and peak pressure (right) during the impact. The grid of tracer points, placed at multiples of the impactor radius, is shown as grey lines. Isotherms of the peak temperatures are shown as colored curves at 500 ºC, 300 ºC, 100 ºC, and 0 ºC. Isobaric lines of the peak pressures are shown at 9, 5, 3, and 1 GPa. We infer that the material that later accumulated to form Ryugu was further from the impact than the 100 ºC isotherm and the 1 GPa isobar in each panel.