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Supplementary Materials for

Abundant presolar grains and primordial organics preserved in carbon-rich exogenous clasts in asteroid Ryugu

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Figs. S1 to S10
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Other Supplementary Material for this manuscript includes the following:

Tables S1 and S3

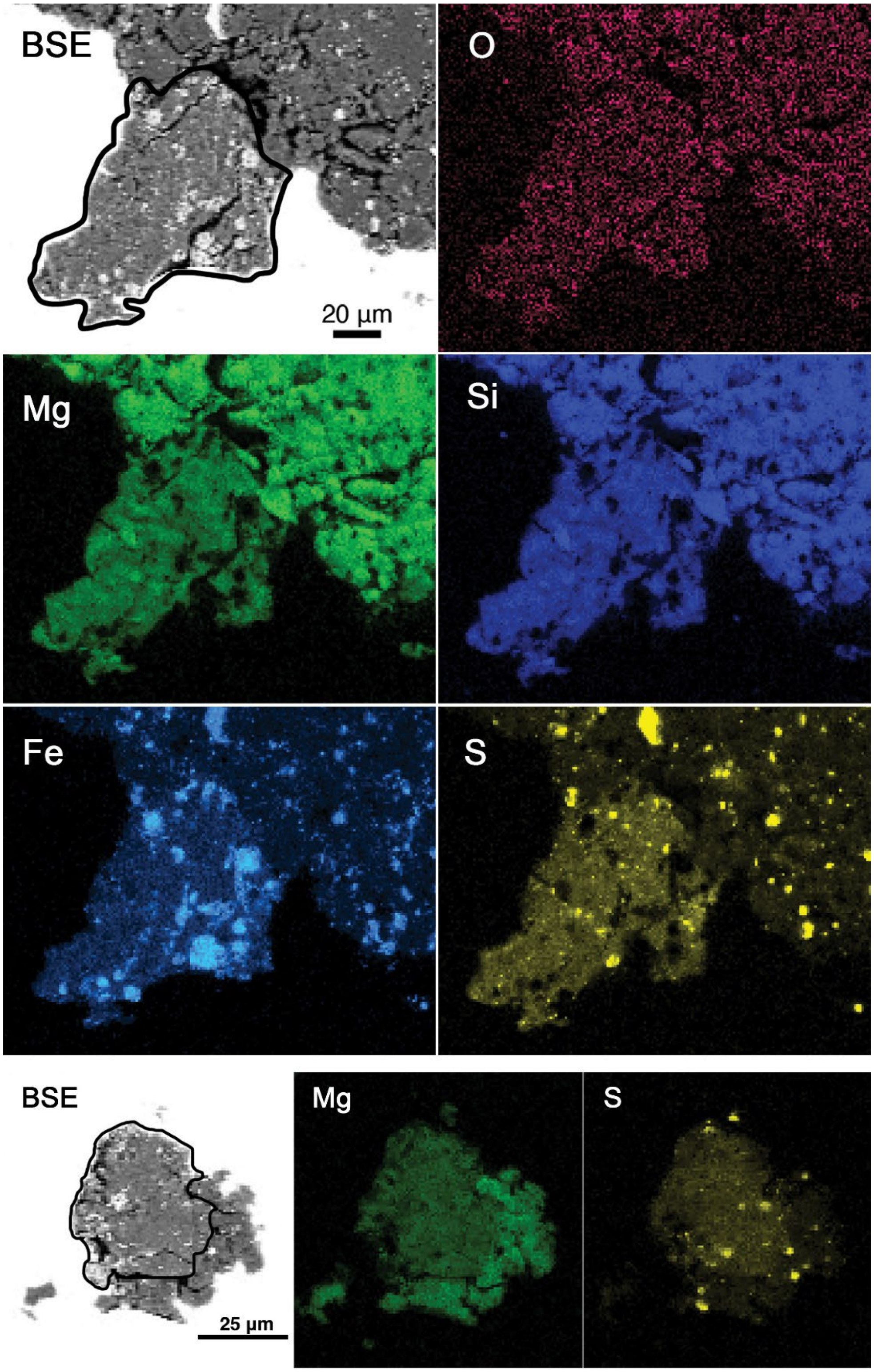

Fig. S1.

BSE image and elemental maps of discrete Clast 2 (top) and 3 (bottom) from grain A0040. The clasts are outlined in black in the BSE images. The clasts are rich in Fe and S and depleted in Mg, Si, and O compared to the surrounding matrix.

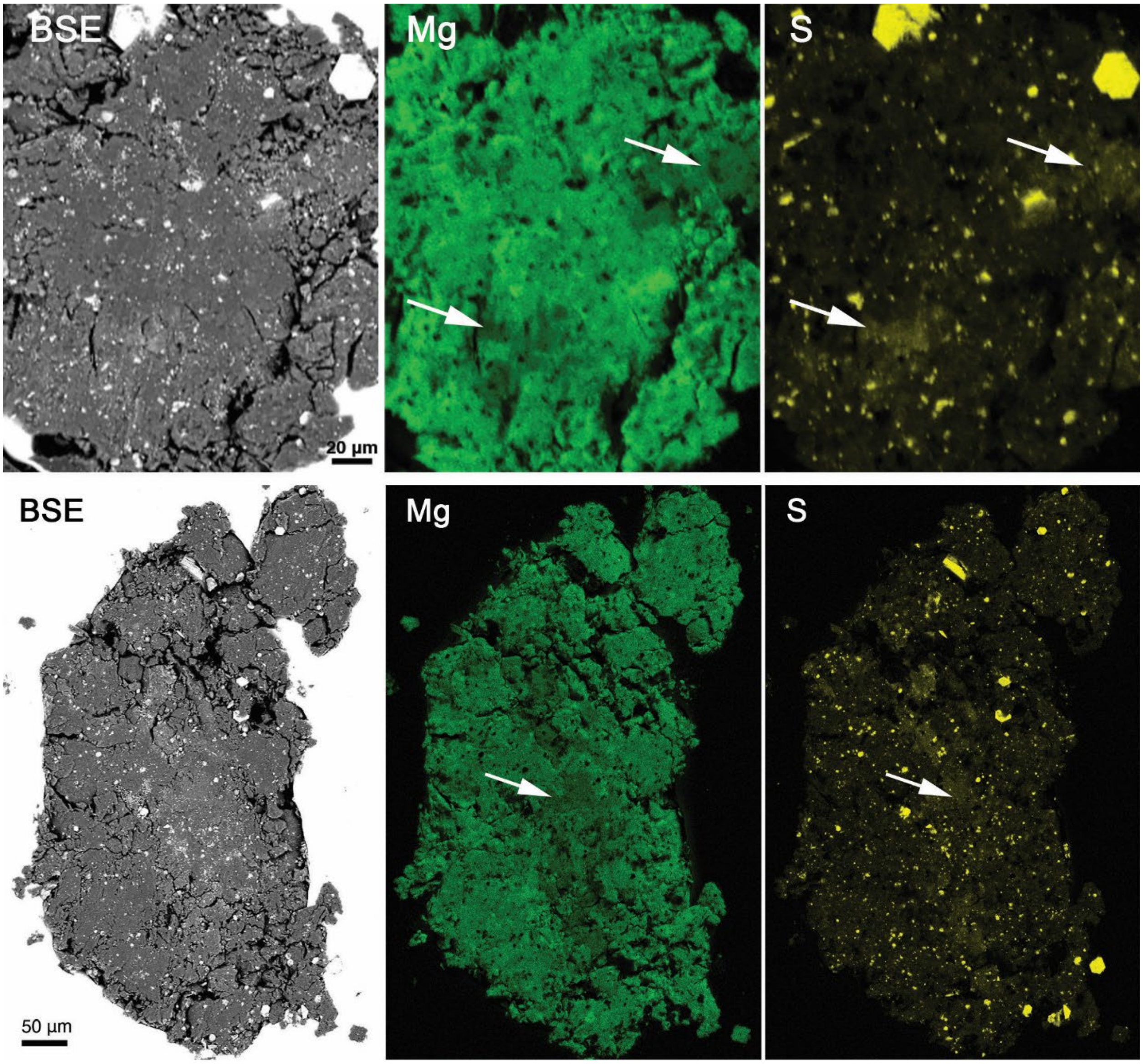

Fig. S2.

BSE images and elemental maps of the more diffuse Clast 4 (top) and Clast 5 (bottom) from A0040. Arrows indicate the location of these Mg-poor and S-rich clasts within the fragments. The boundaries between these clasts and Ryugu matrix are not well-defined.

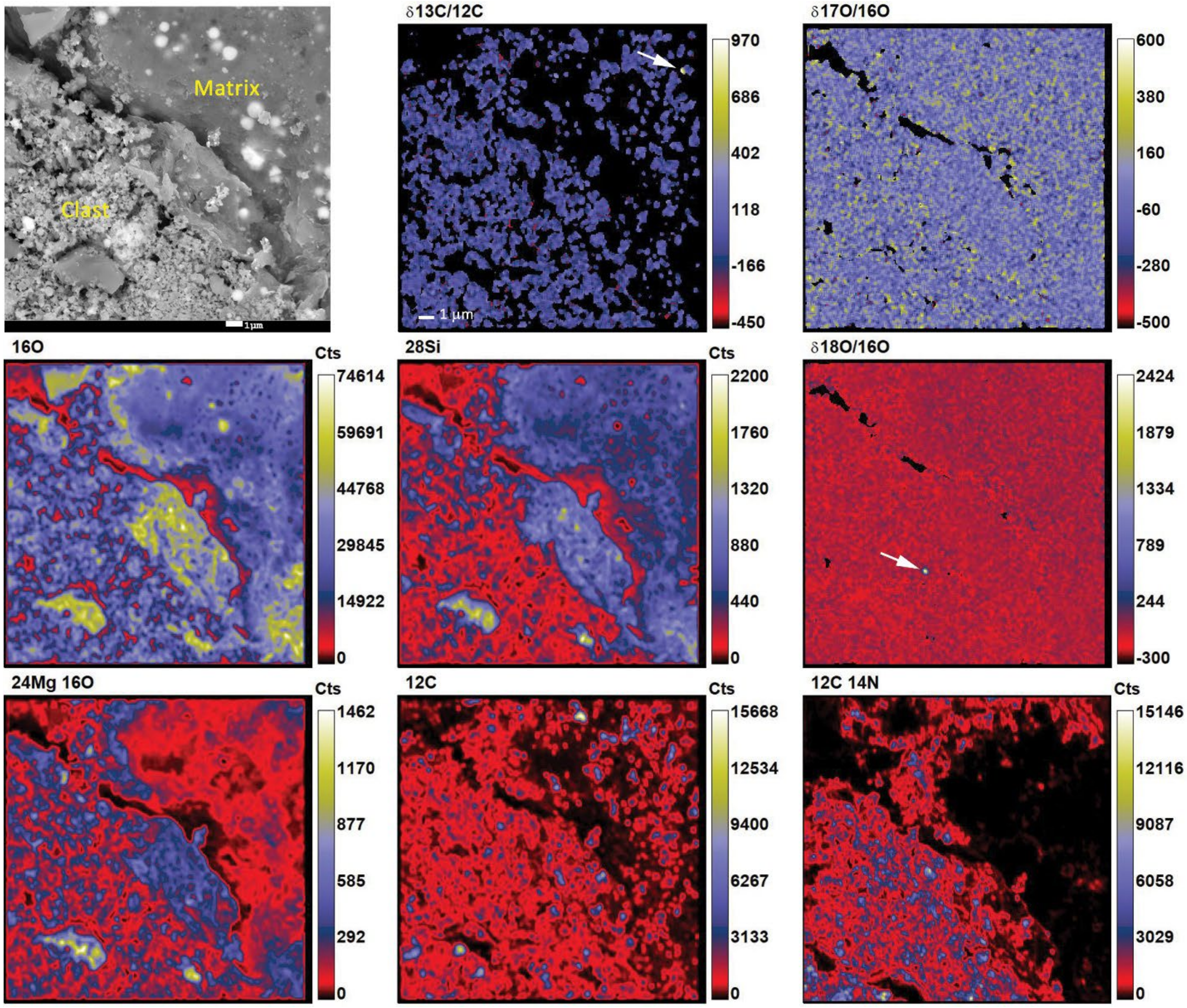

Fig. S3.

BSE (top left) and corresponding NanoSIMS images of a region containing primitive Clast 1 and hydrated Ryugu matrix in grain C0002. The clast shows a well-defined boundary with the surrounding matrix in the BSE image. The NanoSIMS ion images show the clast is depleted in ^{28}Si and enriched in ^{12}C, ^{12}C^{14}N and ^{24}Mg^{16}O relative to the neighboring matrix. The ^{12}C and ^{12}C^{14}N images show the clast is highly enriched in N-rich organic matter relative to the matrix. The ^{12}C^{14}N image was acquired in a subsequent analysis and is shifted up 3 μm relative to the other images. The arrows in the NanoSIMS ratio images indicate ^{18}O-rich supernova silicate C0002-C2 in the clast, and ^{13}C-rich presolar SiC grain C0002-5 in the hydrated matrix. Ratios are given as deviations from the standard values in per mil (‰). Small variations in the isotope ratio images are due to statistical fluctuations.

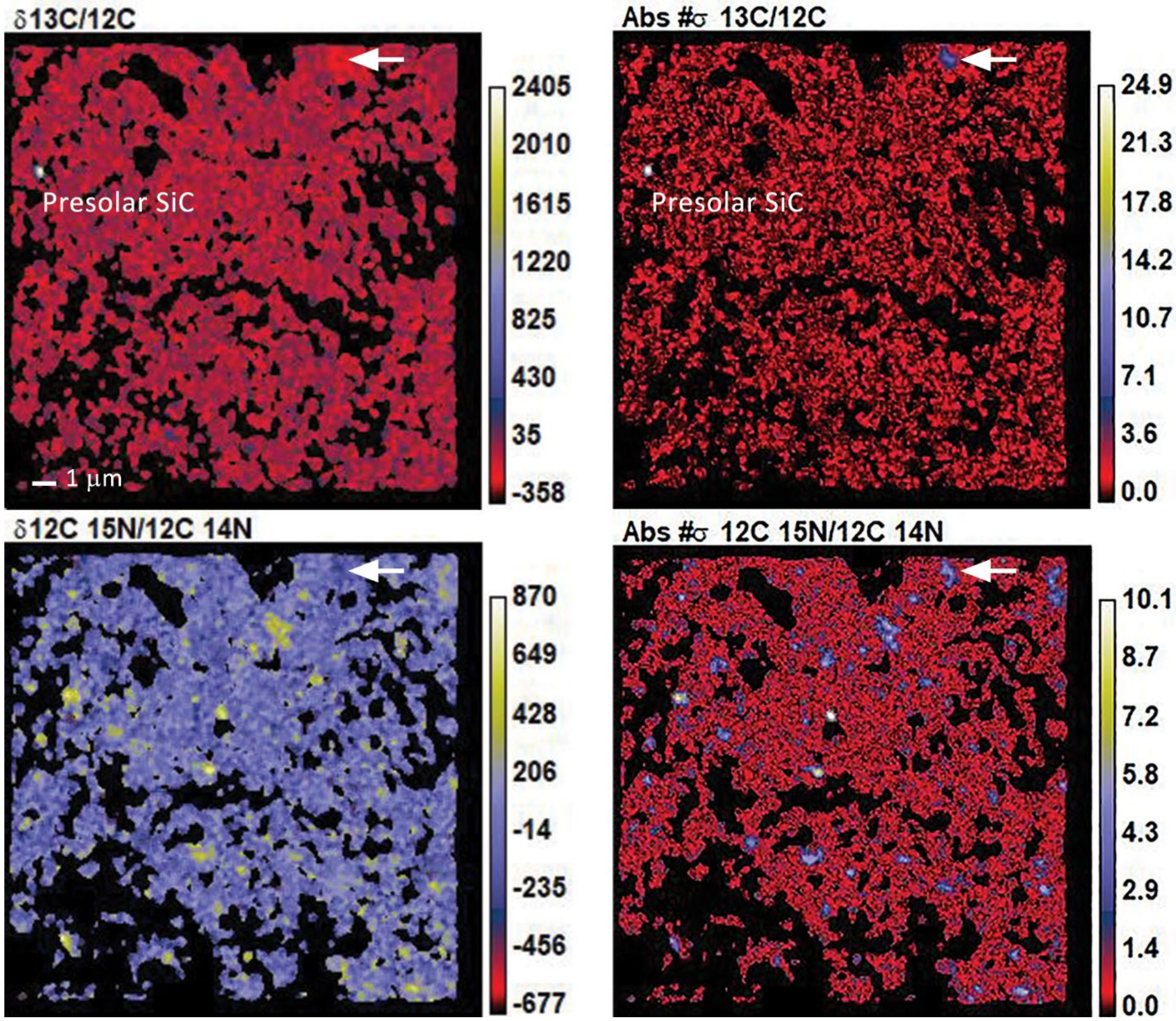

Fig. S4.

NanoSIMS $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratio images of a region of Clast 2 in A0040 containing presolar SiC grain A0040-F2-C6 and numerous organic grains with N isotopic anomalies. One organic grain, shown by the arrows, has depletions in ^{13}C and ^{15}N. Isotopic ratios are given as δ values in per mil (‰) on the left. Grains with moderate anomalies are more discernable in the sigma images on the right. The σ images display the significance of an anomaly as the number of standard deviations (σ) that a ratio is away from the standard ratio. Sigma is calculated as $\sigma_i=|R_i-R_o|/E_i$, where R_i and E_i are the ratio and error of the grain of interest, respectively, and R_o is the standard ratio.

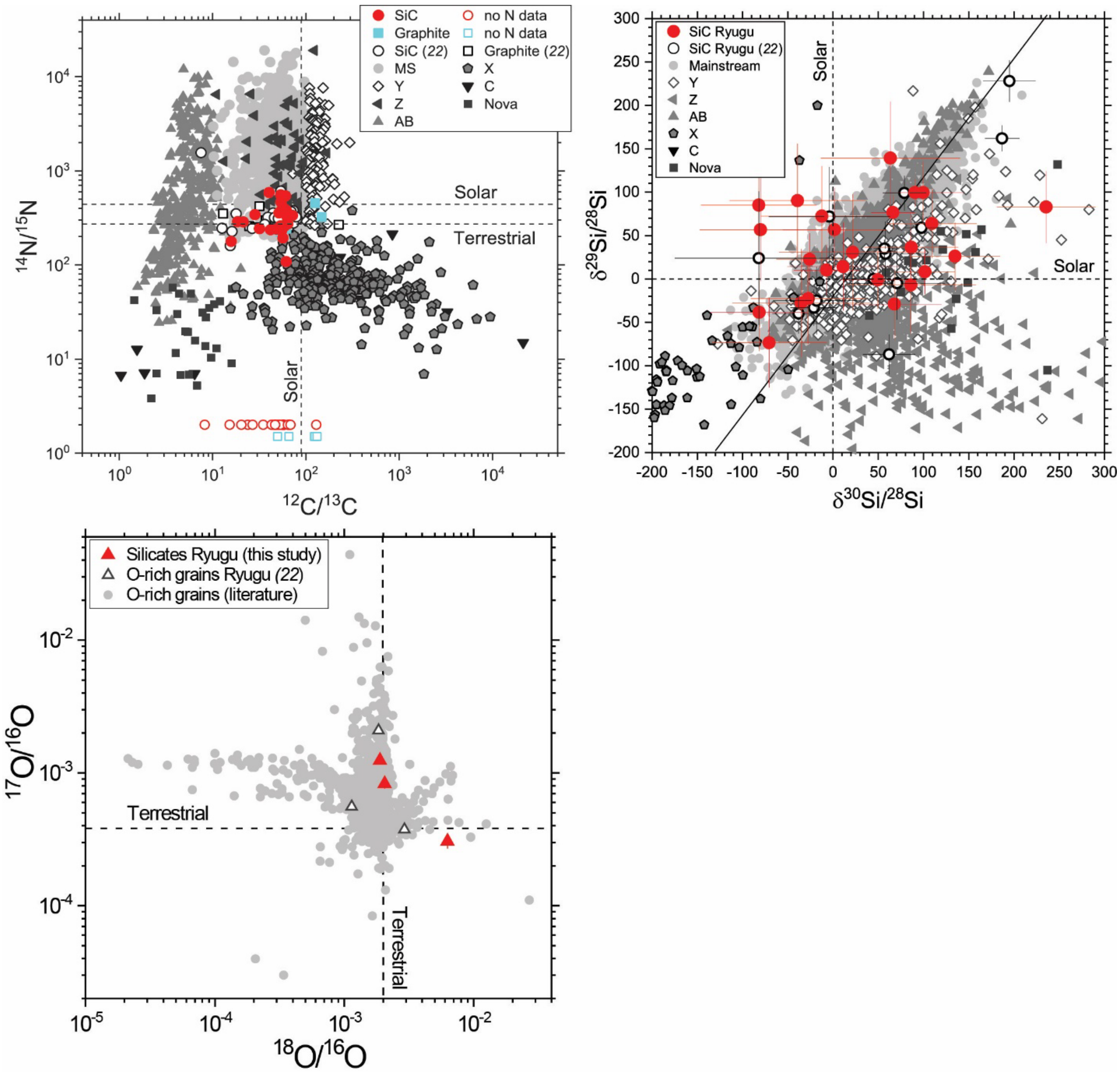

Fig. S5.

Isotopic compositions of presolar grains identified in Ryugu from our study (colored symbols) compared to literature data (greyscale symbols). Carbon, N, and Si isotopic ratios of presolar SiC and graphite grains in Ryugu (this study and (*22*)) compared to literature data (*52*) (top). MS, Y, Z, AB, X, C, and nova denote the different populations of presolar SiC grains. MS, Y, and Z grains have origins in AGB stars. Based on their isotopic compositions, most of the C-rich presolar grains in Ryugu come from AGB stars. The range of N, and possibly C, isotopic compositions for these grains in Ryugu is narrower than literature data, perhaps due to dilution with signal from surrounding organic matter. Oxygen isotopic ratios of presolar silicate grains in Clast 1 compared to literature data (*22, 53*) (bottom).

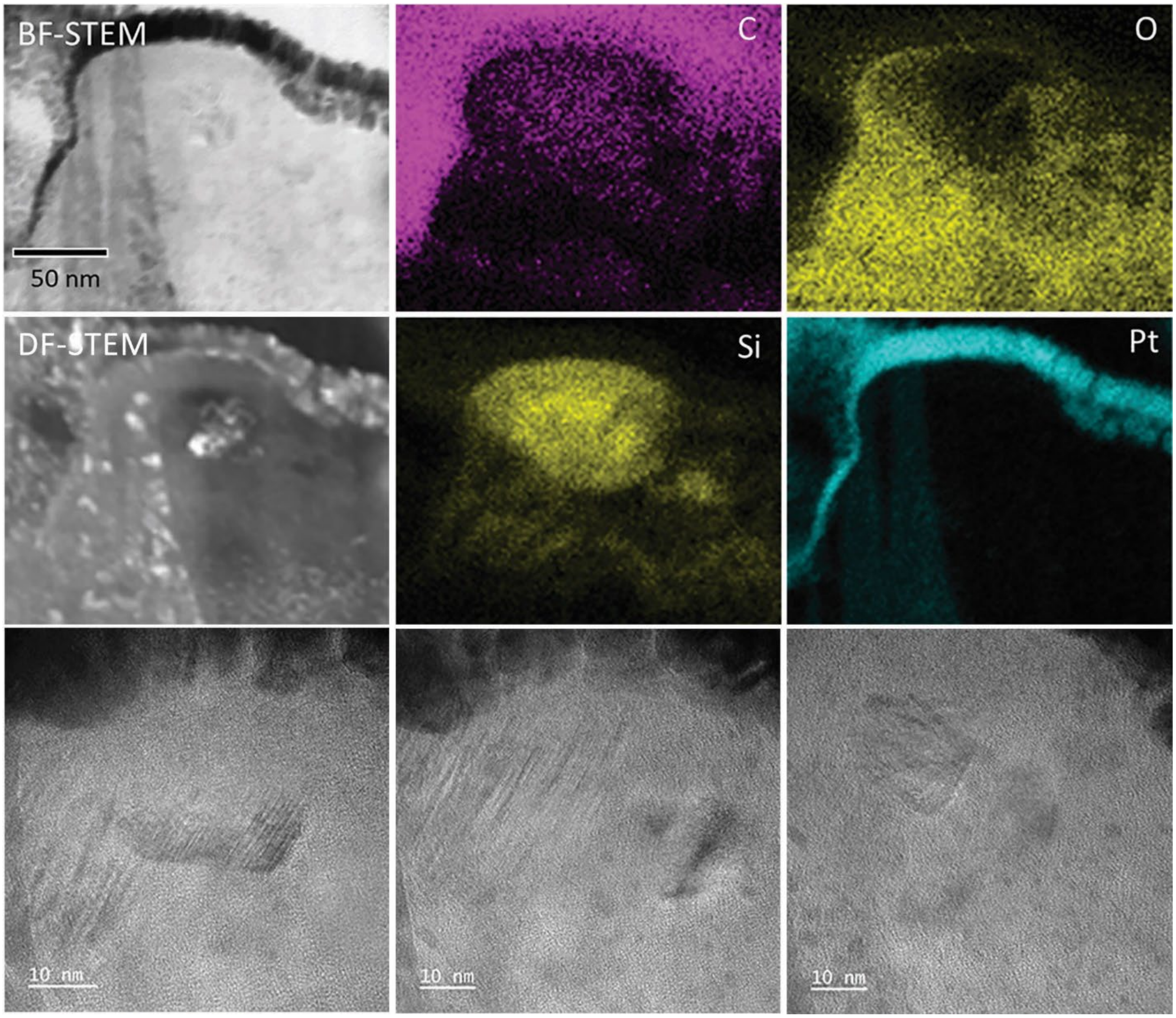

Fig. S6.

Bright-field (BF) and dark-field (DF) STEM images and corresponding elemental maps of a FIB cross-section of presolar SiC C0002-C11 from Clast 1 in C0002. The Pt was deposited on top of the grain as a marker to ensure the correct grain was targeted. The three images on the bottom are a series of high-resolution (HR) TEM images at various tilt angles showing several 20-50 nm subgrains.

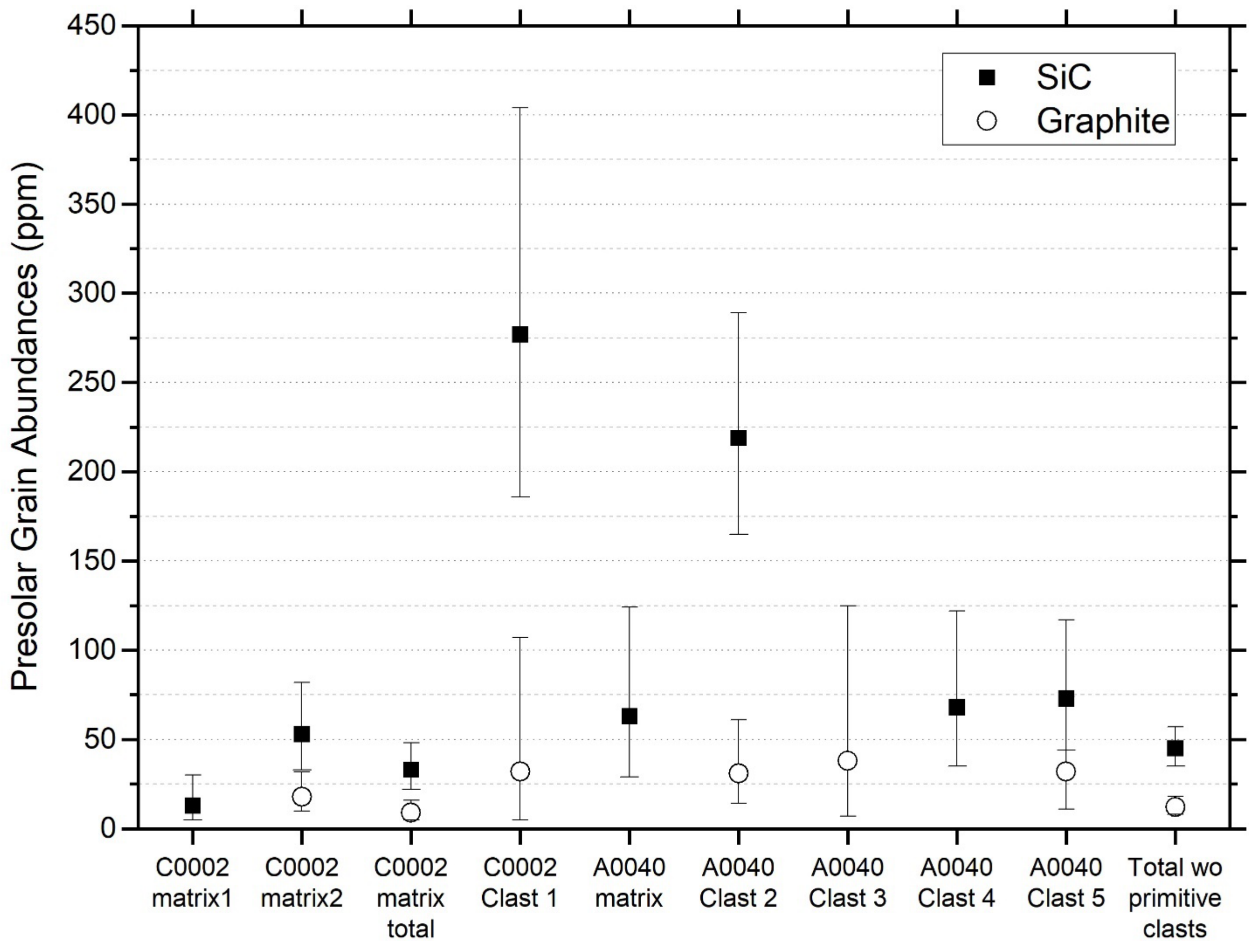

Fig. S7.

Abundances of presolar SiC and graphite among the different analysis regions and lithologies in Ryugu grains C0002 and A0040. Errors are 1σ. "wo" = without.

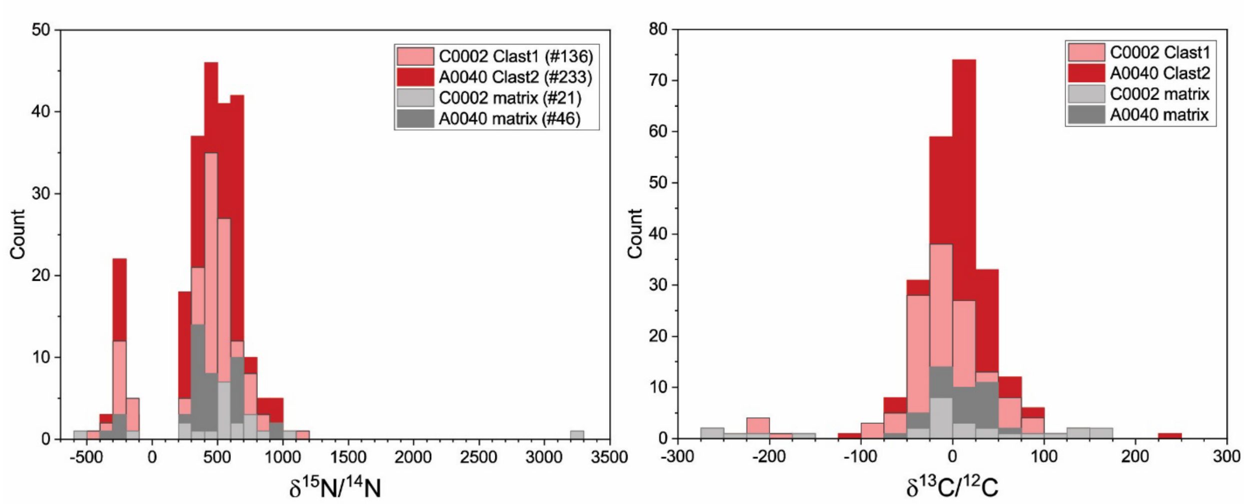

Fig. S8.

Histograms of $\delta^{15}N$ and $\delta^{13}C$ values of IAOM in Ryugu matrix and Clasts 1 and 2. The isotopic distributions are similar between the different lithologies. Most IAOM have N isotopic anomalies with no associated anomaly in C isotopes. Three grains were found to be isotopically anomalous in C with normal N isotopic compositions. Organic grains that are not isotopically anomalous in N or C are not included in the histograms. The number of isotopically anomalous organic grains identified in the various lithologies are denoted in the legend of the $\delta^{15}N$ histogram.

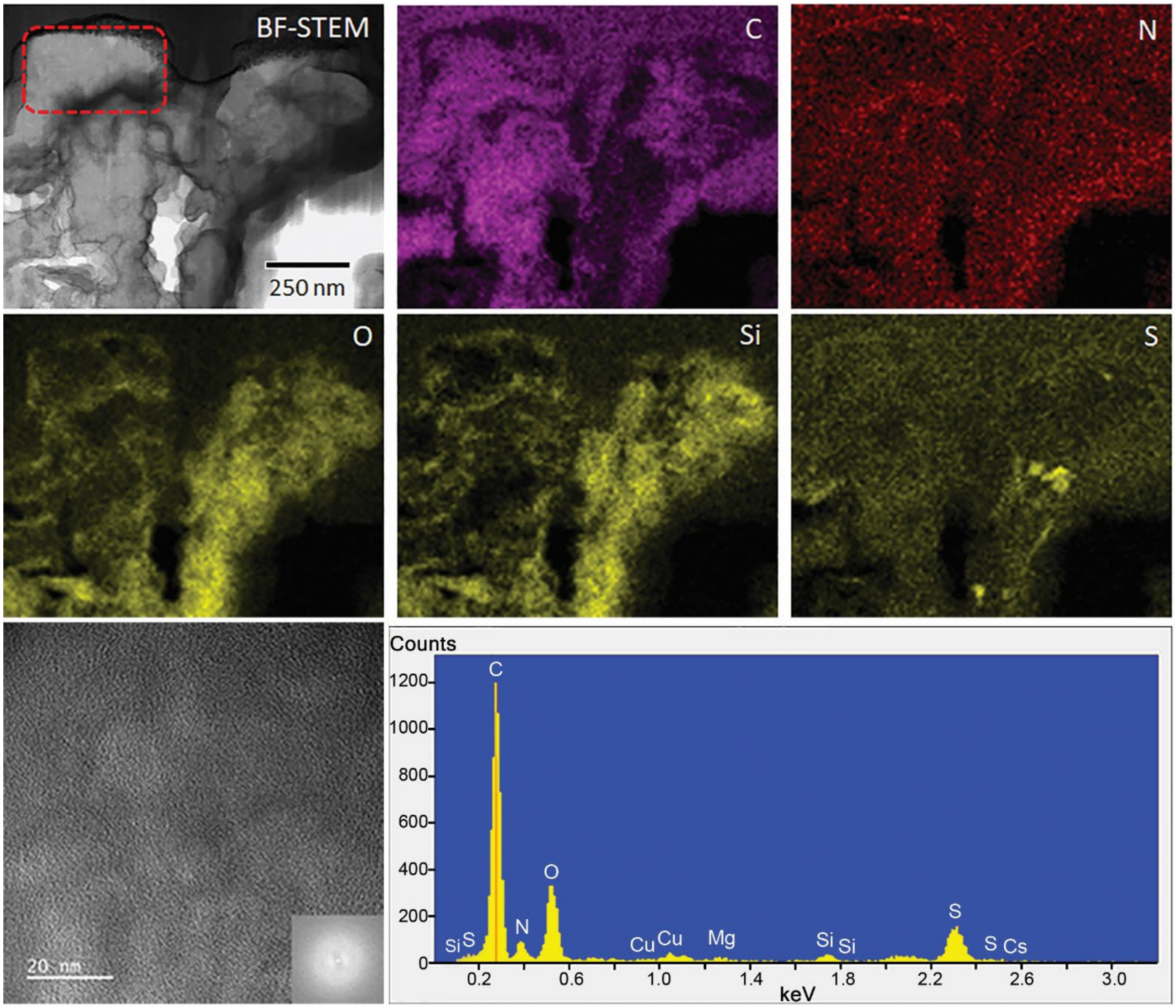

Fig. S9.

TEM images and elemental maps of a FIB cross-section containing a ^{13}C- and ^{15}N-poor organic grain (outlined in red in BF-STEM image). The inset in the HR-TEM image (bottom left) shows diffuse scattering and no long-range order. The grain had porosity on the 30-nm scale. The spectrum (bottom right) shows that this 300 nm-sized amorphous grain contains C, N, O, and S, likely associated with N-based and carbonyl (C=O) functionality and an organo-S component.

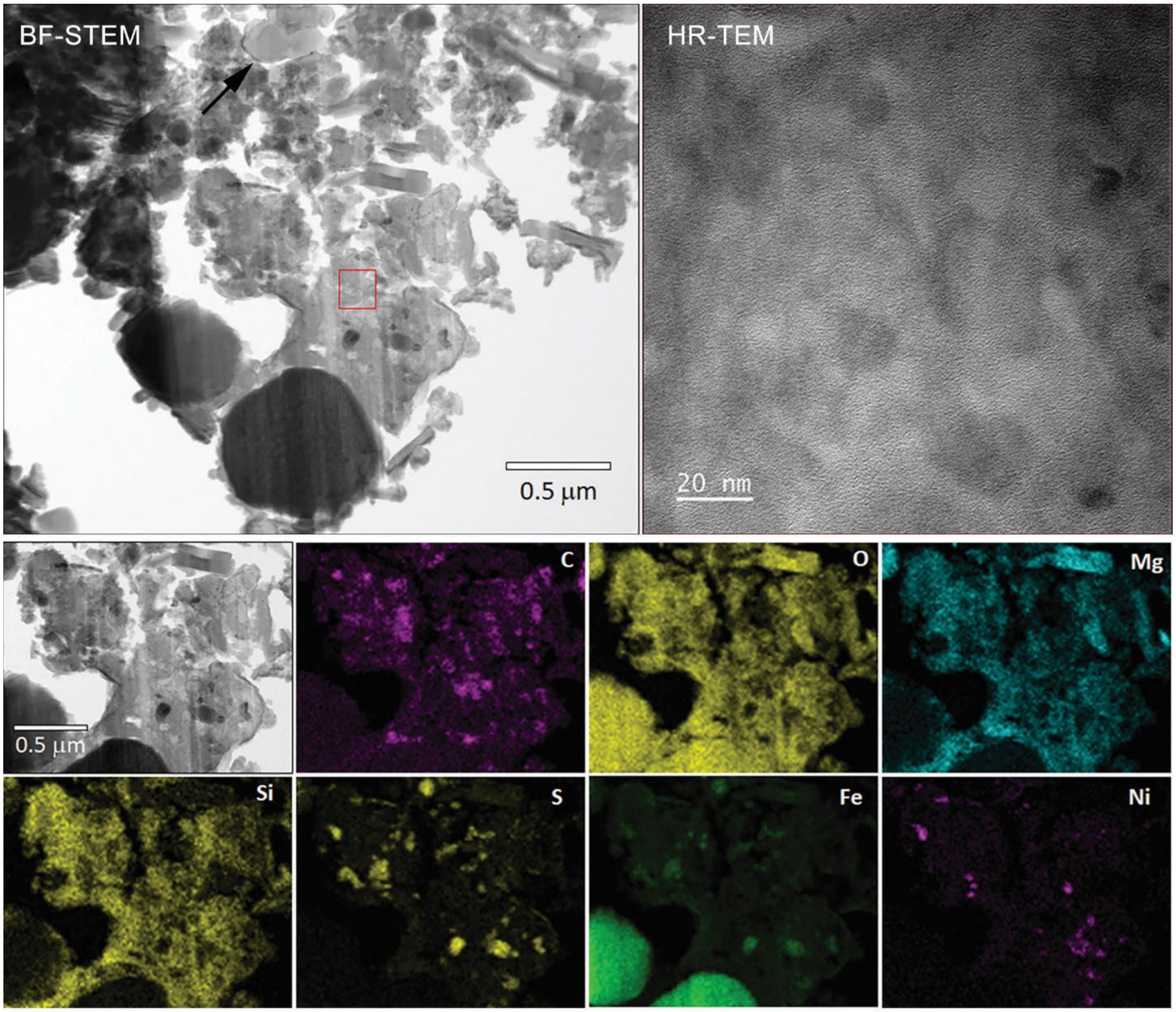

Fig. S10.

TEM images and X-ray elemental maps of a FIB section from Clast 1 in C0002 showing amorphous silicates with nanophase FeNi sulfide inclusions, carbon nanoglobules, and magnetite grains. A cluster of nanoglobules is indicated by the black arrow in the BF-STEM image (upper left). The HR-TEM image (upper right) from the region within the red box shows a lack of crystalline order and absence of well-crystallized phyllosilicates. The X-ray elemental maps (lower panels) show the distribution of amorphous silicates, carbonaceous material, and FeNi sulfides. Olivine and GEMS-like material were observed in another FIB section of the clast. The mineralogy of Clast 1 is similar to the less altered fragments found by *(3)* in Ryugu. However, the less altered fragments from *(3)* contained carbonate, phosphate, and tochilinite, which were not observed in Clast 1.

Table S2.

Presolar grain abundances in different lithologies analyzed in Ryugu samples. Abundances are given as parts per million (ppm) and errors are 1σ. Clasts 1, 2, and 3 are discrete while Clasts 4 and 5 are diffuse.

Sample / Lithology	Area Analyzed (μm^2)	Presolar Silicate		Presolar SiC		Presolar Graphite	
		#	Abundance	#	Abundance	#	Abundance
C0002 Clast 1	1748	3	104^{+102}_{-57}	9	277^{+127}_{-91}	1	32^{+75}_{-27}
C0002 matrix 1	9351	0	0	2	13^{+17}_{-8}	0	0
C0002 matrix 2	9402	0	0	7	53^{+29}_{-20}	4	18^{+14}_{-8}
Total C0002 matrix	*18754*	*0*	*5**	*9*	33^{15}_{11}	*4*	9^{7}_{4}
A0040 Clast 2	4907	0	18*	16	219^{+70}_{-54}	3	31^{+30}_{-17}
A0040 Clast 3	1462	0	0	0	0	1	38^{+87}_{-31}
A0040 Clast 4	3494	0	0	4	68^{+54}_{-33}	0	0
A0040 Clast 5	5324	0	0	6	73^{+44}_{-29}	2	32^{+42}_{-21}
A0040 matrix	3401	0	0	3	63^{+61}_{-34}	0	0
Total A0040 wo Clast 2	*13681*	*0*	*7**	*13*	62^{+22}_{-17}	*3*	17^{+16}_{-9}
Total C0002 + A0040 wo Clasts 1, 2	**32435**	**0**	**3***	**22**	$\mathbf{45^{+12}_{-10}}$	**7**	$\mathbf{12^{+6}_{-4}}$

*Upper limits for abundances of O-rich presolar grains.
# denotes number of grains identified
wo = without

Table S1.

Isotopic compositions, diameters, and likely phases of presolar grains in Ryugu grains C0002 and A0040.

Separate excel file.

Table S3.

C and N isotopic compositions, Si/C and CN/C ratios, and diameters of IAOM in Ryugu grains C0002 and A0040.

Separate excel file.

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