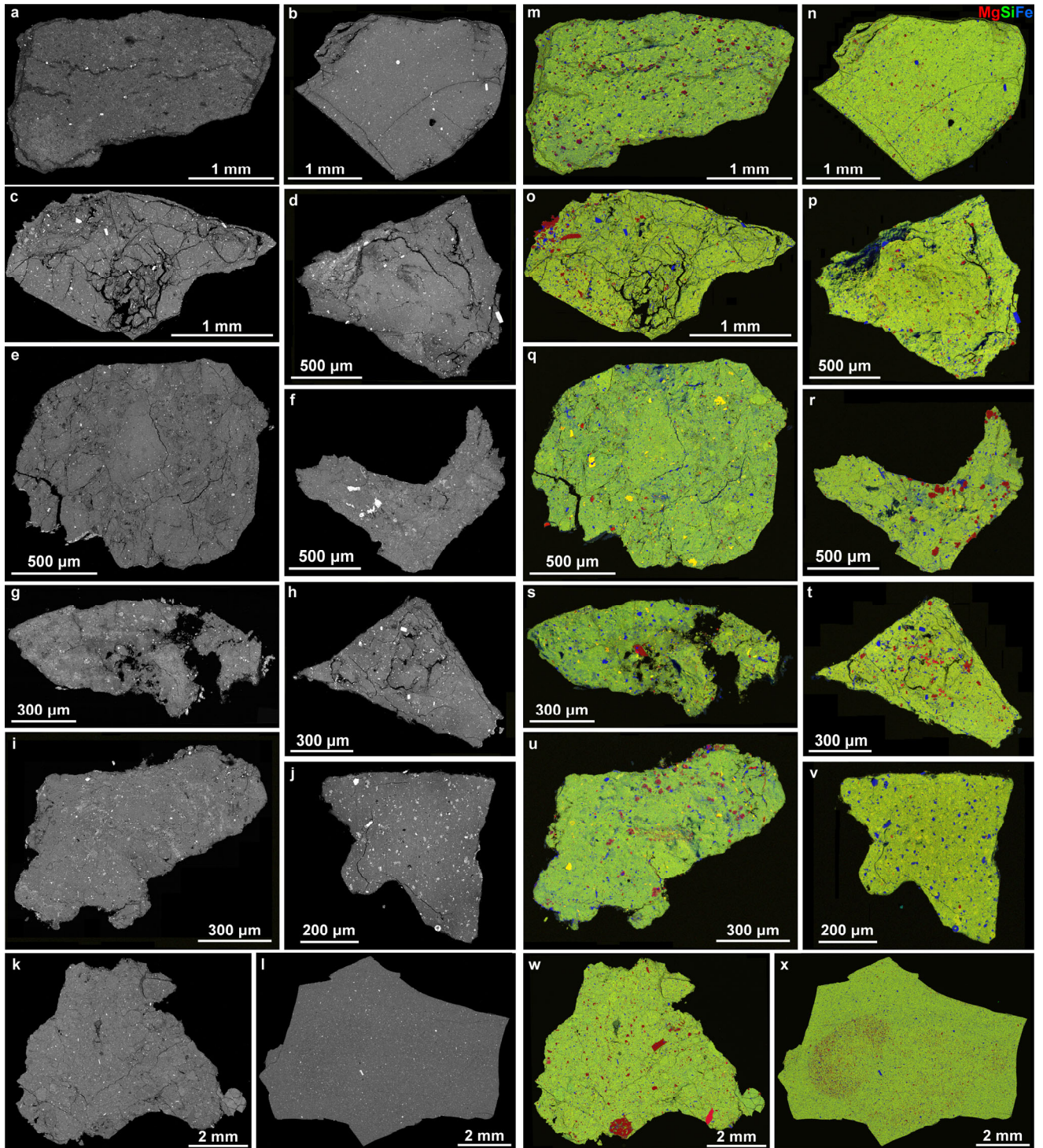


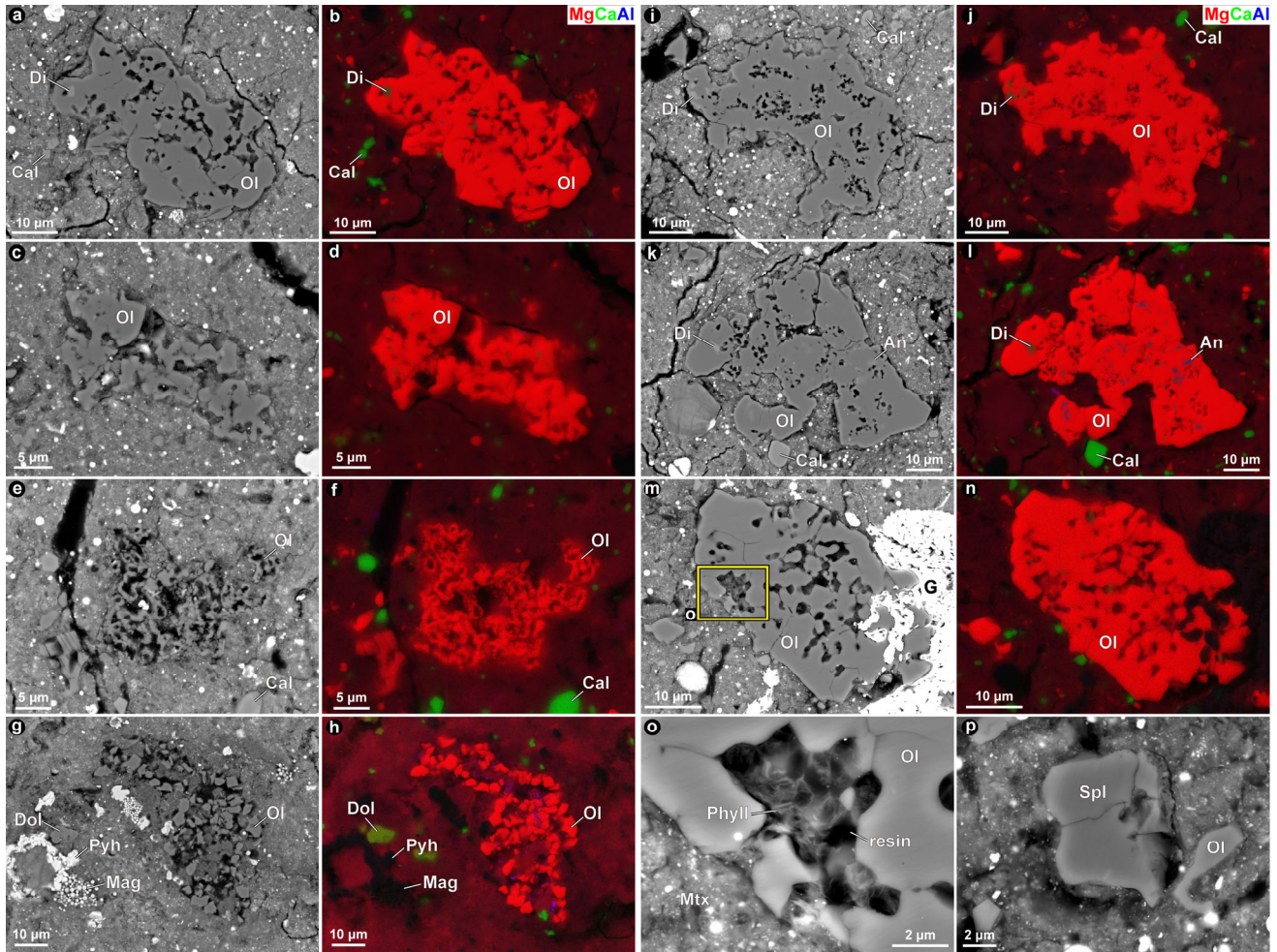
Supplementary Information for

Refractory inclusions in Bennu samples indicative of outer Solar System accretion

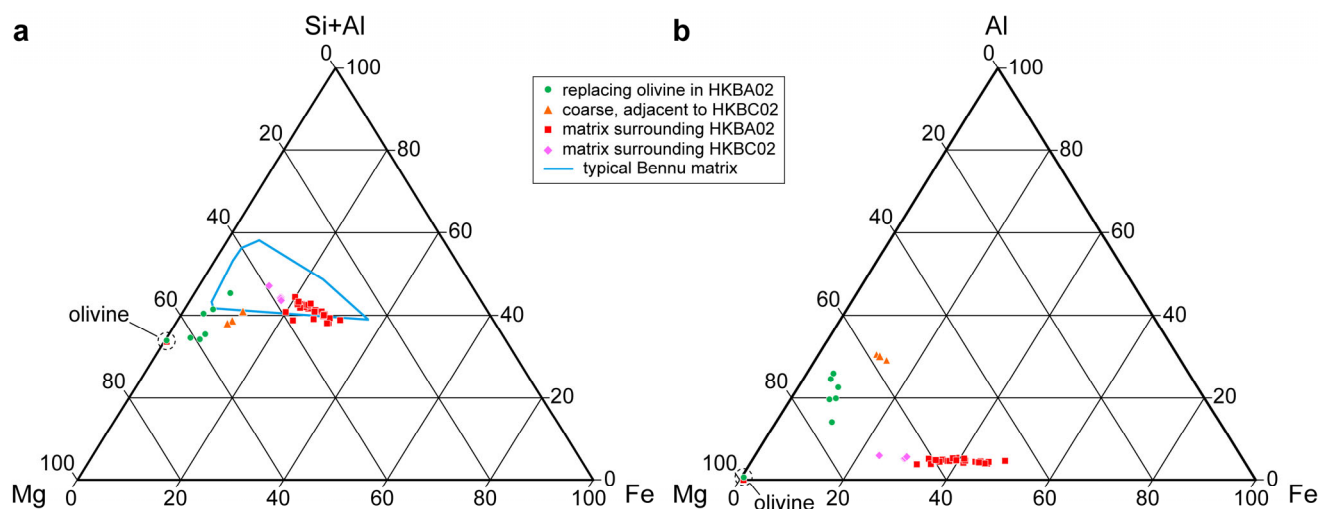
by Kawasaki et al.



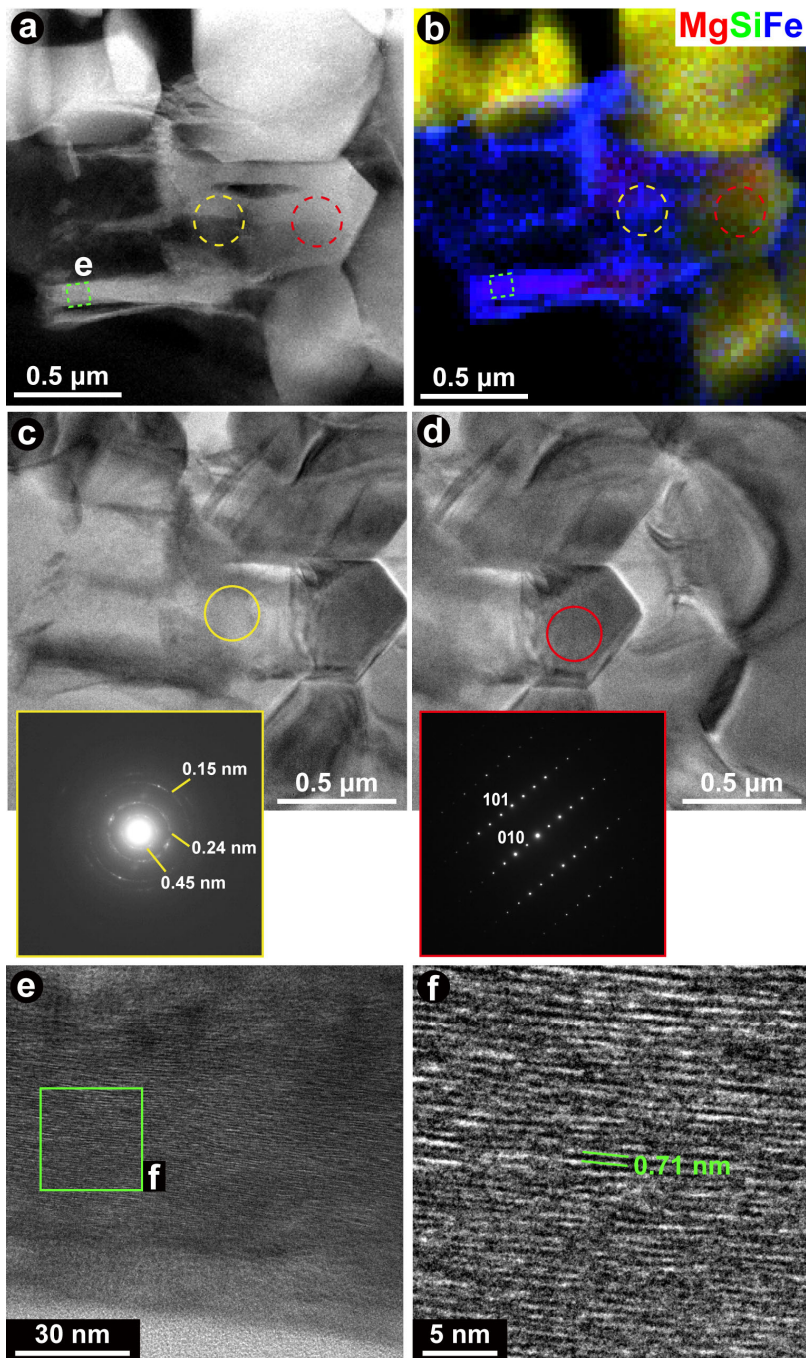
Supplementary Fig. 1. Polished surfaces of Benu particles. **a** OREX-803111-0 (angular). **b** OREX-803112-0 (angular). **c** OREX-803113-0 (angular). **d** OREX-803114-0 particle #3 (p#3; angular). **e** OREX-803114-0 p#1 (hummocky). **f** OREX-803114-0 p#5 (angular). **g** OREX-803114-0 p#2 (hummocky). **h** OREX-803114-0 p#7 (angular). **i** OREX-803114-0 p#4 (hummocky). **j** OREX-803114-0 p#6 (angular). **k** OREX-800088-8 (hummocky). **l** OREX-800055-15 (angular). **m–w** Combined X-ray elemental map of **a–l** using Mg K α , Si K α , and Fe K α lines assigned for RGB color channels.



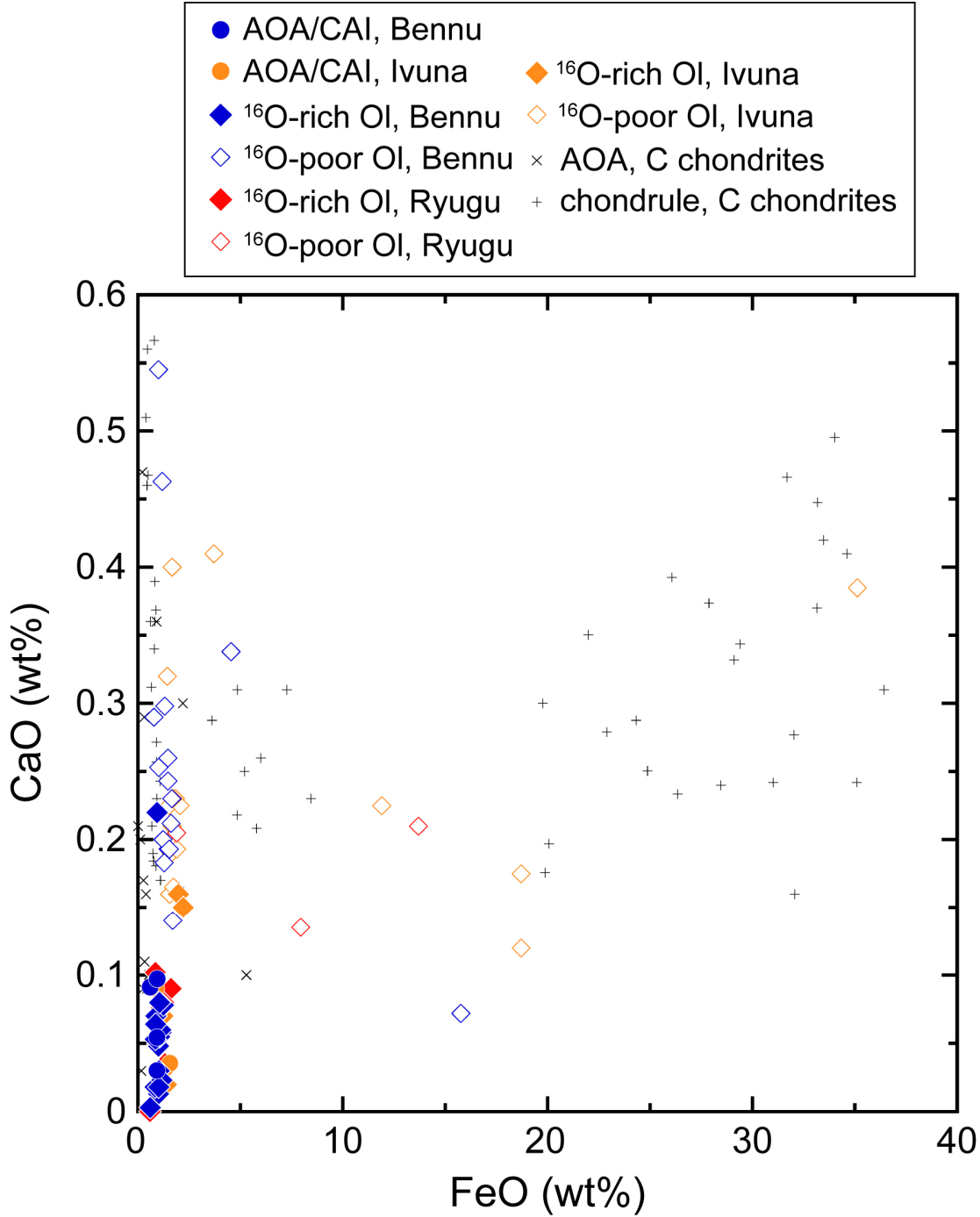
Supplementary Fig. 2. AOAs and isolated spinel grain in Bennu samples. **a** BSE image of AOA HKBA01 in OREX-803114-0 particle #1. **b** Combined X-ray elemental map of **a** using Mg K α , Ca K α , and Al K α lines assigned for RGB color channels. **c** BSE image of AOA HKBA04 in OREX-803114-0 particle #1. **d** Combined X-ray elemental map of **c** using Mg K α , Ca K α , and Al K α lines assigned for RGB color channels. **e** BSE image of AOA HKBA05 in OREX-803114-0 particle #1. **f** Combined X-ray elemental map of **e** using Mg K α , Ca K α , and Al K α lines assigned for RGB color channels. **g** BSE image of AOA HKBA06 in OREX-803111-0. **h** Combined X-ray elemental map of **g** using Mg K α , Ca K α , and Al K α lines assigned for RGB color channels. **i** BSE image of AOA HKBA02 in OREX-803114-0 particle #1. **j** Combined X-ray elemental map of **i** using Mg K α , Ca K α , and Al K α lines assigned for RGB color channels. **k** BSE image of AOA HKBA03 in OREX-803114-0 particle #1. **l** Combined X-ray elemental map of **k** using Mg K α , Ca K α , and Al K α lines assigned for RGB color channels. **m** BSE image of AOA HKBA03 in OREX-803114-0 particle #1 after repolishing. A bright area at the right side, marked G, is a remnant of the gold thin film. The yellow box indicates the area enlarged in **o**. **n** Combined X-ray elemental map of **m** using Mg K α , Ca K α , and Al K α lines assigned for RGB color channels. **o** Close-up BSE image of the yellow box in **n**, showing interstitial phyllosilicates among olivine grains. **p** BSE image of an isolated spinel grain in OREX-803114-0 particle #1. Cal: calcite, Di: diopside, Dol: dolomite, Mag: magnetite, Ol: olivine, Phyll: phyllosilicate, Pyh: pyrrhotite, Spl: spinel.



Supplementary Fig. 3. Ternary diagrams of Mg, Si + Al, and Fe (a) and of Mg, Al, and Fe (b) showing the chemical compositions of phyllosilicates. Compositions of typical Benu matrix phyllosilicates are taken from Zega et al. (18). Chemical compositions of olivine grains in the AOA HKBA02, measured with TEM-EDS (green circles) and SEM-EDS (red squares) during the same session as phyllosilicates, are also shown.



Supplementary Fig. 4. TEM observations of phyllosilicate and olivine in a Bennu AOA (HKBA02). **a** HAADF-STEM image of HKBA02, also shown in Fig. 3. Dashed circles indicate the approximate positions of the SAED patterns shown in **c** and **d**, and the dashed square corresponds to the approximate area shown in **e**. **b** Combined X-ray elemental map of **a** using Mg K α , Si K α , and Fe K α lines assigned for RGB color channels. **c** BF-TEM (Bright-Field TEM) image and SAED pattern of phyllosilicate. The SAED pattern, obtained from the area marked by the yellow open circle, shows the characteristic of poorly crystalline phyllosilicates. **d** BF-TEM image and SAED pattern of olivine, obtained from the area marked by the red open circle. **e** High-resolution BF-TEM image of the area indicated by the green box in **a**. **f** Close-up BF-TEM image of the green box in **e**, showing serpentine with a ~ 0.7 nm lattice fringe.



Supplementary Fig. 5. CaO versus FeO contents of olivine in Bennu, Ryugu, the CI chondrite Ivuna, and the most primitive carbonaceous chondrites Acfer 094 and Yamato 81020. Olivine in CAIs and AOAs show chemical compositions similar to those of ^{16}O -rich isolated olivine grains in Bennu, Ryugu, and Ivuna, supporting a genetic relationship among these minerals. Data for olivine in AOAs and a CAI from Bennu are from this study; all other data are from literature^{6,13,14,17,35}. Note that the counting-statistical detection limit (3σ) of CaO contents in this study is ~ 0.06 wt%.

Supplementary Table 1. Chemical compositions of refractory inclusions.

Particle ID	OREX-803114-0 particle #1			OREX-803114-0 particle #2			OREX-803114-0 particle #1		
Sample	<i>Isolated grain</i>	<i>HKBC01</i>	<i>HKBC03</i>		<i>HKBC02**</i>		<i>HKBA01</i>	<i>HKBA02</i>	<i>HKBA03</i>
mineral	spinel*	hibonite	olivine	spinel	diopside	diopside	olivine*	olivine*	olivine*
<i>wt%</i>									
MgO	28.6	0.7	57.0	28.1	13.5	9.6	56.6	56.3	55.9
Al ₂ O ₃	70.3	88.8	bdl	69.8	13.5	15.7	bdl	bdl	bdl
SiO ₂	bdl	bdl	43.1	bdl	46.9	37.3	42.6	42.2	42.1
CaO	bdl	8.4	bdl	bdl	25.0	24.3	0.1	bdl	0.1
TiO ₂	0.3	1.4	0.1	0.2	0.5	9.7	bdl	bdl	bdl
V ₂ O ₅	0.5	bdl	bdl	0.2	bdl	bdl	bdl	bdl	bdl
Cr ₂ O ₃	0.2	bdl	0.4	0.8	0.2	0.2	0.2	0.3	0.4
MnO	bdl	bdl	0.8	0.1	bdl	bdl	0.2	0.2	0.4
FeO	1.0	1.1	0.9	1.3	0.9	0.7	0.6	0.9	1.0
Total	100.8	100.4	102.3	100.5	100.4	97.6	100.3	99.9	99.7
<i>Cations</i>									
Mg	1.01	0.11	1.96	1.00	0.73	0.54	1.98	1.98	1.97
Al	1.96	11.70	bdl	1.96	0.57	0.70	bdl	bdl	bdl
Si	bdl	bdl	1.00	bdl	1.69	1.42	1.00	1.00	0.99
Ca	bdl	1.00	bdl	bdl	0.97	0.99	0.00	bdl	0.00
Ti	0.00	0.12	0.00	0.00	0.01	0.28	bdl	bdl	bdl
V	0.01	bdl	bdl	0.0	bdl	bdl	bdl	bdl	bdl
Cr	0.00	bdl	0.01	0.01	0.00	0.01	0.00	0.01	0.01
Mn	bdl	bdl	0.0	0.0	bdl	bdl	0.00	0.00	0.01
Fe	0.02	0.10	0.02	0.03	0.03	0.02	0.01	0.02	0.02
Total	3.00	13.03	3.01	3.00	4.00	3.96	3.00	3.00	3.00
Per oxygen	4	19	4	4	6	6	4	4	4
Mg#	98.1	-	99.0	97.1	-	-	99.5	99.0	99.0

bdl: below detection limit, *average of duplicate analysis, **only typical data are shown.

Mg# = $[\text{Mg}/(\text{Mg}+\text{Fe})] \times 100$ in mol%

Supplementary Table 2. Oxygen-isotope compositions (‰) of refractory inclusions.

Mineral	Spot #	$\delta^{17}\text{O}_{\text{SMOW}}$	2σ	$\delta^{18}\text{O}_{\text{SMOW}}$	2σ	$\Delta^{17}\text{O}$	2σ	$^{16}\text{OH}^-$ count rate (cps)	$^{16}\text{OH}^-$ on $^{17}\text{O}^-$ (‰)
<i>Isolated spinel grain, OREX-803114-0 particle #1</i>									
spinel	308	-47.87	1.44	-45.06	0.89	-24.4	1.5	5.9×10^3	0.02
spinel	309	-48.33	1.63	-46.72	0.89	-24.0	1.7	1.1×10^4	0.03
<i>HKBC01, OREX-803114-0 particle #1</i>									
hibonite	511	-50.18	3.32	-50.93	1.74	-23.7	3.5	1.2×10^3	0.04
<i>HKBC02, OREX-803114-0 particle #2</i>									
diopside	284	-2.66	1.61	2.46	0.69	-3.9	1.8	9.0×10^3	0.02
<i>HKBC03, OREX-803114-0 particle #1</i>									
olivine	265	-48.73	1.20	-45.89	0.88	-24.9	1.3	9.3×10^3	0.02
olivine	266	-47.62	1.53	-46.65	0.88	-23.4	1.5	5.7×10^3	0.01
spinel	342	-50.74	2.99	-49.22	1.69	-25.1	3.0	1.4×10^3	0.04
spinel	349	-49.51	2.92	-47.92	1.69	-24.6	3.2	1.8×10^3	0.05
<i>HKBA01, OREX-803114-0 particle #1</i>									
olivine	61	-46.53	1.54	-45.75	0.86	-22.7	1.8	5.4×10^3	0.01
olivine	62	-46.54	1.59	-45.41	0.86	-22.9	1.8	5.9×10^3	0.01
olivine	63	-48.40	1.54	-45.48	0.86	-24.7	1.8	6.6×10^3	0.02
<i>HKBA02, OREX-803114-0 particle #1</i>									
olivine	58	-47.79	1.56	-46.66	0.86	-23.5	1.8	5.6×10^3	0.01
olivine	59	-47.69	1.54	-46.22	0.86	-23.7	1.8	6.0×10^3	0.01
olivine	132	-46.76	1.31	-47.39	0.72	-22.1	1.3	1.2×10^4	0.03
olivine	133	-48.22	1.61	-46.53	0.65	-24.0	1.6	1.2×10^4	0.03
<i>HKBA03, OREX-803114-0 particle #1</i>									
olivine	65	-48.12	1.54	-46.80	0.86	-23.8	1.8	6.9×10^3	0.02
olivine	66	-46.80	1.54	-45.50	0.86	-23.1	1.8	5.5×10^3	0.01
olivine	134	-46.38	1.29	-45.96	0.71	-22.5	1.3	8.6×10^3	0.02

Supplementary Table 4. DOIs of data products used in this study, available via the AstroMat repository.

Sample	Data	DOI
OREX-803111-0	SEM/EDS of particle	10.60707/js8c-s209
OREX-803112-0	SEM/EDS of particle	10.60707/2bdv-8x41
OREX-803113-0	SEM/EDS of particle	10.60707/d77e-7107
OREX-803114-0	SEM/EDS of particle	10.60707/w5k7-pm30
OREX-800088-8	SEM/EDS of particle	10.60707/n2jz-6m61
OREX-800055-15	SEM/EDS of particle	10.60707/w3ms-qa48
OREX-803114-100	TEM/EDS of section	10.60707/f3bj-dz60
OREX-803114-0	SIMS data	10.60707/nc75-pa53