

Supplementary Table 1: Major element compositions of chondrule-like objects and CAIs in the Ryugu samples measured with FE-EPMA^a and TEM^b

| Sample name | Analysis # ^c | Target | SiO ₂ | TiO ₂ | Al ₂ O ₃ | Cr ₂ O ₃ | FeO | MnO | MgO | CaO | Na ₂ O | NiO | K ₂ O | SO ₃ | P ₂ O ₅ | Total | Mg# |
|-----------------|-------------------------|--------|------------------|------------------|--------------------------------|--------------------------------|--------|-------|--------|--------|-------------------|-------|------------------|-----------------|-------------------------------|--------|-------|
| C0002-P5-C1-Chd | 1499 | Ol | 42.390 | 0.022 | 0.052 | 0.592 | 1.560 | 0.413 | 56.240 | 0.182 | 0.039 | 0.090 | n.m. | n.m. | n.m. | 101.58 | 98.5 |
| | 1500 | Ol | 42.900 | 0.012 | 0.011 | 0.682 | 1.450 | 1.510 | 55.680 | 0.164 | 0.051 | 0.091 | n.m. | n.m. | n.m. | 102.55 | 98.6 |
| | 1501 | Ol | 42.400 | 0.038 | 0.042 | 0.549 | 1.350 | 0.320 | 55.790 | 0.191 | 0.051 | 0.076 | n.m. | n.m. | n.m. | 100.80 | 98.7 |
| C0002-P5-C2-Chd | 1476 | Ol | 42.660 | 0.000 | 0.020 | 0.276 | 1.169 | 0.472 | 58.020 | 0.020 | 0.014 | 0.132 | n.m. | n.m. | n.m. | 102.79 | 98.9 |
| | 1477 | Ol | 41.090 | 0.004 | 0.012 | 0.301 | 1.290 | 0.484 | 56.110 | 0.018 | 0.001 | 0.085 | n.m. | n.m. | n.m. | 99.39 | 98.7 |
| | 2496 | Ol | 46.990 | 0.020 | 0.094 | 0.328 | 1.155 | 0.464 | 46.590 | 3.030 | 0.021 | 0.124 | n.m. | n.m. | n.m. | 98.82 | 98.6 |
| C0040-02-Chd | TEM-1 | Ol | 41.636 | 0.170 | 0.000 | 0.448 | 0.424 | 1.005 | 56.129 | 0.132 | 0.000 | 0.000 | 0.056 | n.m. | n.m. | 100.00 | 99.6 |
| | TEM-2 | Ol | 42.171 | 0.000 | 0.000 | 0.535 | 0.253 | 0.916 | 55.994 | 0.131 | 0.000 | 0.000 | 0.000 | n.m. | n.m. | 100.00 | 99.7 |
| | TEM-3 | Ol | 42.311 | 0.000 | 0.000 | 0.181 | 0.000 | 0.761 | 56.748 | 0.000 | 0.000 | 0.000 | 0.000 | n.m. | n.m. | 100.00 | 100.0 |
| | TEM-4 | Ol | 42.487 | 0.180 | 0.000 | 0.269 | 0.509 | 0.502 | 55.941 | 0.066 | 0.000 | 0.000 | 0.056 | n.m. | n.m. | 100.00 | 99.5 |
| | TEM-5 | Ol | 41.975 | 0.085 | 0.000 | 0.361 | 0.341 | 0.843 | 56.394 | 0.000 | 0.000 | 0.000 | 0.000 | n.m. | n.m. | 100.00 | 99.7 |
| | TEM-6 | Di | 55.217 | 0.230 | 0.094 | 0.263 | 0.026 | 0.207 | 20.992 | 22.919 | 0.000 | 0.000 | 0.060 | n.m. | n.m. | 100.00 | 99.9 |
| | TEM-7 | Di | 55.260 | 0.000 | 0.397 | 0.000 | 0.270 | 0.013 | 20.942 | 23.283 | 0.000 | 0.000 | 0.000 | n.m. | n.m. | 100.16 | 99.3 |
| | TEM-8 | Di | 56.522 | 0.030 | 0.019 | 0.190 | 0.180 | 0.000 | 20.892 | 22.163 | 0.000 | 0.000 | 0.000 | n.m. | n.m. | 100.00 | 99.5 |
| | TEM-9 | Di | 56.108 | 0.000 | 0.298 | 0.355 | 0.084 | 0.166 | 20.994 | 21.994 | 0.000 | 0.000 | 0.000 | n.m. | n.m. | 100.00 | 99.8 |
| | TEM-10 | Di | 55.102 | 0.370 | 0.178 | 0.000 | 0.167 | 0.082 | 20.646 | 23.436 | 0.000 | 0.000 | 0.055 | n.m. | n.m. | 100.00 | 99.6 |
| C0040-02-CAI | 2482 | Sp | 0.091 | 0.931 | 73.670 | 0.093 | 0.816 | 0.000 | 24.340 | 1.249 | 0.000 | 0.058 | n.m. | n.m. | n.m. | 101.25 | |
| | 2483 | Sp | 0.058 | 0.768 | 73.620 | 0.110 | 0.853 | 0.000 | 24.860 | 1.149 | 0.004 | 0.067 | n.m. | n.m. | n.m. | 101.49 | |
| | 2484 | Hib | 0.162 | 5.500 | 80.230 | 0.067 | 0.855 | 0.008 | 7.100 | 6.760 | 0.001 | 0.000 | n.m. | n.m. | n.m. | 100.68 | |
| | 2485 | Hib | 0.233 | 5.050 | 79.280 | 0.109 | 0.761 | 0.019 | 9.310 | 6.050 | 0.008 | 0.071 | n.m. | n.m. | n.m. | 100.89 | |
| | 2486 | Sp | 0.348 | 0.035 | 71.540 | 0.141 | 0.892 | 0.000 | 27.720 | 0.014 | 0.002 | 0.047 | n.m. | n.m. | n.m. | 100.74 | |
| | 2487 | Sp | 1.288 | 0.232 | 67.800 | 0.121 | 1.029 | 0.000 | 27.550 | 0.110 | 0.018 | 0.031 | n.m. | n.m. | n.m. | 98.18 | |
| | 2811 | Phyl | 19.733 | 0.088 | 16.106 | 1.003 | 12.082 | 0.207 | 28.914 | 0.111 | 0.362 | 0.286 | 0.033 | 5.627 | 0.289 | 84.84 | |
| | 2812 | Phyl | 18.538 | 0.083 | 17.751 | 0.329 | 6.685 | 0.311 | 28.183 | 0.071 | 0.101 | 0.053 | 0.002 | 5.426 | 0.418 | 77.95 | |
| | 2813 | Phyl | 19.270 | 0.060 | 17.221 | 0.907 | 10.032 | 0.243 | 30.197 | 0.188 | 0.319 | 0.294 | 0.012 | 4.976 | 0.217 | 83.94 | |
| | 2814 | Phyl | 21.556 | 0.131 | 15.134 | 0.479 | 8.752 | 0.291 | 28.347 | 0.075 | 0.147 | 0.149 | 0.037 | 5.309 | 0.354 | 80.76 | |
| | 2815 | Phyl | 21.545 | 0.085 | 14.083 | 1.619 | 13.780 | 0.203 | 24.837 | 0.231 | 0.671 | 0.577 | 0.037 | 4.107 | 0.112 | 81.89 | |
| | 5845 | Sp | 0.210 | 0.172 | 70.420 | 0.154 | 0.712 | 0.000 | 28.440 | 0.020 | 0.000 | 0.073 | n.m. | n.m. | n.m. | 100.20 | |
| | 5846 | Sp | 0.500 | 0.191 | 70.470 | 0.149 | 0.676 | 0.002 | 28.430 | 0.016 | 0.002 | 0.023 | n.m. | n.m. | n.m. | 100.46 | |
| | 5847 | Sp | 0.758 | 0.235 | 69.610 | 0.151 | 0.697 | 0.009 | 27.740 | 0.008 | 0.009 | 0.000 | n.m. | n.m. | n.m. | 99.22 | |
| | 5848 | Sp | 0.525 | 0.175 | 71.340 | 0.145 | 0.707 | 0.008 | 28.700 | 0.005 | 0.007 | 0.050 | n.m. | n.m. | n.m. | 101.66 | |
| C0076-10-CAI | 5995 | Phyl | 35.573 | 0.097 | 21.736 | 0.435 | 5.463 | 0.070 | 27.765 | 0.263 | 0.109 | 0.381 | 0.001 | 0.898 | 0.075 | 92.87 | |
| | 5996 | Phyl | 44.318 | 0.104 | 7.891 | 0.474 | 5.654 | 0.148 | 22.368 | 0.127 | 0.232 | 0.543 | 0.030 | 1.027 | 0.063 | 82.98 | |
| | 5997 | Phyl | 34.901 | 0.093 | 3.631 | 0.440 | 8.596 | 0.230 | 19.874 | 0.588 | 0.149 | 0.572 | 0.021 | 2.163 | 0.109 | 71.37 | |
| | 5998 | Phyl | 40.911 | 0.073 | 5.108 | 0.444 | 4.975 | 0.109 | 17.203 | 0.115 | 0.196 | 0.367 | 0.021 | 0.842 | 0.089 | 70.45 | |
| | 5999 | Phyl | 34.076 | 0.091 | 3.239 | 0.436 | 8.726 | 0.145 | 19.287 | 0.113 | 0.060 | 0.617 | 0.000 | 2.575 | 0.049 | 69.41 | |
| | 6000 | Phyl | 37.744 | 0.099 | 3.173 | 0.566 | 6.476 | 0.181 | 21.578 | 0.296 | 0.120 | 0.499 | 0.044 | 1.418 | 0.103 | 72.30 | |

^a Detection limits of individual elements are shown in Nakamura et al.¹.^b Total wt% is normalized to 100, and TEM analysis spots are not shown in any figure.^c Analysis spots are shown in supplementary figures.

Supplementary Table 2: Raw SIMS measured oxygen-isotope data of chondrule-like objects and CAIs in the Ryugu samples

| Analysis_# | Sample | $\delta^{18}\text{O}$ ‰ RAW | 2SE | $\delta^{17}\text{O}$ ‰ RAW | 2SE | $\Delta^{17}\text{O}$ ‰ RAW | 2SE | ^{16}O (Mcps) | OH correction (‰) ^a | IMF ^b | IMF | $\delta^{18}\text{O}$ ‰ | Error (2SD) | $\delta^{17}\text{O}$ ‰ | Error (2SD) | $\Delta^{17}\text{O}$ ‰ | Error (2SD) |
|-------------|---|--------------------------------|-------------|--------------------------------|-------------|--------------------------------|-------------|---------------------------|--------------------------------------|------------------|--------------|-------------------------|----------------|-------------------------|----------------|-------------------------|----------------|
| 20220424_52 | 3Hole_Disk_SCOI (San Carlos Olivine) | 0.69 | 2.68 | 0.75 | 4.05 | 0.39 | 4.28 | 0.32 | 0.42 | | | | | | | | |
| 20220424_53 | 3Hole_Disk_SCOI | 0.26 | 2.02 | -0.43 | 3.47 | -0.56 | 3.63 | 0.32 | 0.45 | | | | | | | | |
| 20220424_54 | 3Hole_Disk_SCOI | 1.09 | 2.69 | 8.90 | 4.90 | 8.33 | 5.10 | 0.32 | 0.42 | | | | | | | | |
| | Average Standard & 2SD for C0002-P5-C2-Chd & C1-Chd/52-54, 61-63 | 0.78 | 1.96 | 1.64 | 7.91 | 1.24 | 8.47 | | | | -4.51 | | | | | | |
| 20220424_57 | 3Hole_C0002-P5_C2_Chd spot1_OI | -44.96 | 3.98 | -45.22 | 5.94 | -21.84 | 6.29 | 0.29 | 0.34 | 0.22 | -4.30 | -39.81 | 1.96 | -43.63 | 7.91 | -22.93 | 8.47 |
| 20220424_58 | 3Hole_C0002-P5_C2_Chd spot2_OI | -52.05 | 1.73 | -48.85 | 5.97 | -21.78 | 6.04 | 0.28 | 0.34 | 0.22 | -4.30 | -47.49 | 1.96 | -47.82 | 7.91 | -23.13 | 8.47 |
| 20220424_59 | 3Hole_C0002-P5_C1_Chd spot1_OI | -1.52 | 3.55 | -2.69 | 6.33 | -1.90 | 6.60 | 0.21 | 0.53 | 0.22 | -4.30 | 2.56 | 1.96 | -2.46 | 7.91 | -3.79 | 8.47 |
| 20220424_60 | 3Hole_C0002-P5_C1_Chd spot2_OI | -5.99 | 3.16 | -4.77 | 6.23 | -1.65 | 6.44 | 0.20 | 0.30 | 0.22 | -4.30 | -1.35 | 1.96 | -3.73 | 7.91 | -3.03 | 8.47 |
| 20220424_61 | 3Hole_Disk_right_SCOI | -0.52 | 2.21 | 4.69 | 4.60 | 4.96 | 4.74 | 0.33 | 0.37 | | | | | | | | |
| 20220424_62 | 3Hole_Disk_right_SCOI | 1.20 | 2.36 | 1.24 | 6.08 | 0.62 | 6.21 | 0.32 | 0.37 | | | | | | | | |
| 20220424_63 | 3Hole_Disk_right_SCOI | 1.90 | 2.04 | -2.96 | 5.00 | -3.94 | 5.11 | 0.32 | 0.38 | | | | | | | | |
| 20220424_95 | 7 hole_Disk, SC-OI | 4.18 | 2.52 | 3.50 | 5.86 | 1.33 | 6.00 | 0.32 | 0.16 | | | | | | | | |
| 20220424_96 | 7 hole_Disk, SC-OI | 4.58 | 2.12 | 6.33 | 3.81 | 3.94 | 3.96 | 0.33 | 0.15 | | | | | | | | |
| 20220424_97 | 7 hole_Disk, SC-OI | 1.29 | 2.40 | 3.79 | 5.76 | 3.12 | 5.89 | 0.33 | 0.15 | | | | | | | | |
| | Average Standard & 2SD for C0040-02-CAI/95-97, 102-104 (N=6) | 1.81 | 2.43 | 2.09 | 4.81 | 1.15 | 4.05 | | | | -3.49 | | | | | | |
| 20220424_98 | 7 hole_C0040-02-CAI spot1_Hib | -46.46 | 2.61 | -49.21 | 6.43 | -25.04 | 6.57 | 0.23 | 0.44 | -3.04 | -6.52 | -39.11 | 2.43 | -46.47 | 4.81 | -26.13 | 4.05 |
| 20220424_99 | 7 hole_C0040-02-CAI spot2_Sp | -51.45 | 2.80 | -46.45 | 6.94 | -19.69 | 7.09 | 0.23 | 0.24 | -3.33 | -6.81 | -43.14 | 2.43 | -42.65 | 4.81 | -20.22 | 4.05 |
| 20220424_10 | 7 hole_C0040-02-CAI spot3_Sp | -47.61 | 3.12 | -44.67 | 7.62 | -19.91 | 7.79 | 0.22 | 0.19 | -3.33 | -6.81 | -42.49 | 2.43 | -44.01 | 4.81 | -21.92 | 4.05 |
| 20220424_10 | 7 hole_C0040-02-CAI spot4_Sp | -50.26 | 3.31 | -46.74 | 4.32 | -20.60 | 4.65 | 0.23 | 0.32 | -3.33 | -6.81 | -43.09 | 2.43 | -44.16 | 4.81 | -21.75 | 4.05 |
| 20220424_10 | 7 hole_Disk, SC-OI | 1.57 | 2.98 | 1.07 | 5.49 | 0.25 | 5.70 | 0.32 | 0.18 | | | | | | | | |
| 20220424_10 | 7 hole_Disk, SC-OI | 0.63 | 1.85 | -1.48 | 4.32 | -1.81 | 4.43 | 0.34 | 0.16 | | | | | | | | |
| 20220424_10 | 7 hole_Disk, SC-OI | 0.98 | 2.02 | 2.67 | 4.06 | 2.16 | 4.20 | 0.33 | 0.15 | | | | | | | | |
| | Average Standard & 2SD for C0040-02-Chd & C0076-10-CAI/102-104, | 1.33 | 1.33 | 2.20 | 5.39 | 1.51 | 5.15 | | | | -3.97 | | | | | | |
| 20220424_10 | 7 hole_C0040-02-Chd spot1_OI | -48.28 | 2.52 | -46.57 | 4.98 | -21.46 | 5.15 | 0.29 | 0.11 | 0.22 | -3.75 | -44.39 | 1.33 | -46.02 | 5.39 | -22.94 | 5.15 |
| 20220424_10 | 7 hole_C0076-10-CAI spot1_Sp | -51.65 | 2.34 | -48.95 | 7.65 | -22.09 | 7.74 | 0.23 | 0.16 | -3.33 | -7.29 | -43.96 | 1.33 | -46.27 | 5.39 | -23.41 | 5.15 |
| 20220424_10 | 7 hole_C0076-10-CAI spot2_Sp | -47.04 | 3.37 | -47.72 | 6.44 | -23.26 | 6.68 | 0.24 | 0.17 | -3.33 | -7.29 | -40.26 | 1.33 | -45.99 | 5.39 | -25.06 | 5.15 |
| 20220424_10 | 7 hole_Disk, SC-OI | 1.37 | 1.88 | 6.62 | 5.22 | 5.91 | 5.31 | 0.35 | 0.14 | | | | | | | | |
| 20220424_10 | 7 hole_Disk, SC-OI | 1.84 | 3.17 | 2.18 | 6.19 | 1.22 | 6.40 | 0.34 | 0.13 | | | | | | | | |
| 20220424_11 | 7 hole_Disk, SC-OI | 2.29 | 2.27 | 3.75 | 4.45 | 2.56 | 4.61 | 0.35 | 0.13 | | | | | | | | |

^aOH correction (‰) = $^{16}\text{O}^1\text{H}^- \text{intensity} / [^{17}\text{O}^- \text{intensity} \times (^{17}\text{O}^- \text{tail} / ^{17}\text{O}^- \text{intensity})] \times 1000$; $^{17}\text{O}^- \text{tail} / ^{17}\text{O}^- \text{intensity} = 2.1 \times 10^{-5}$.

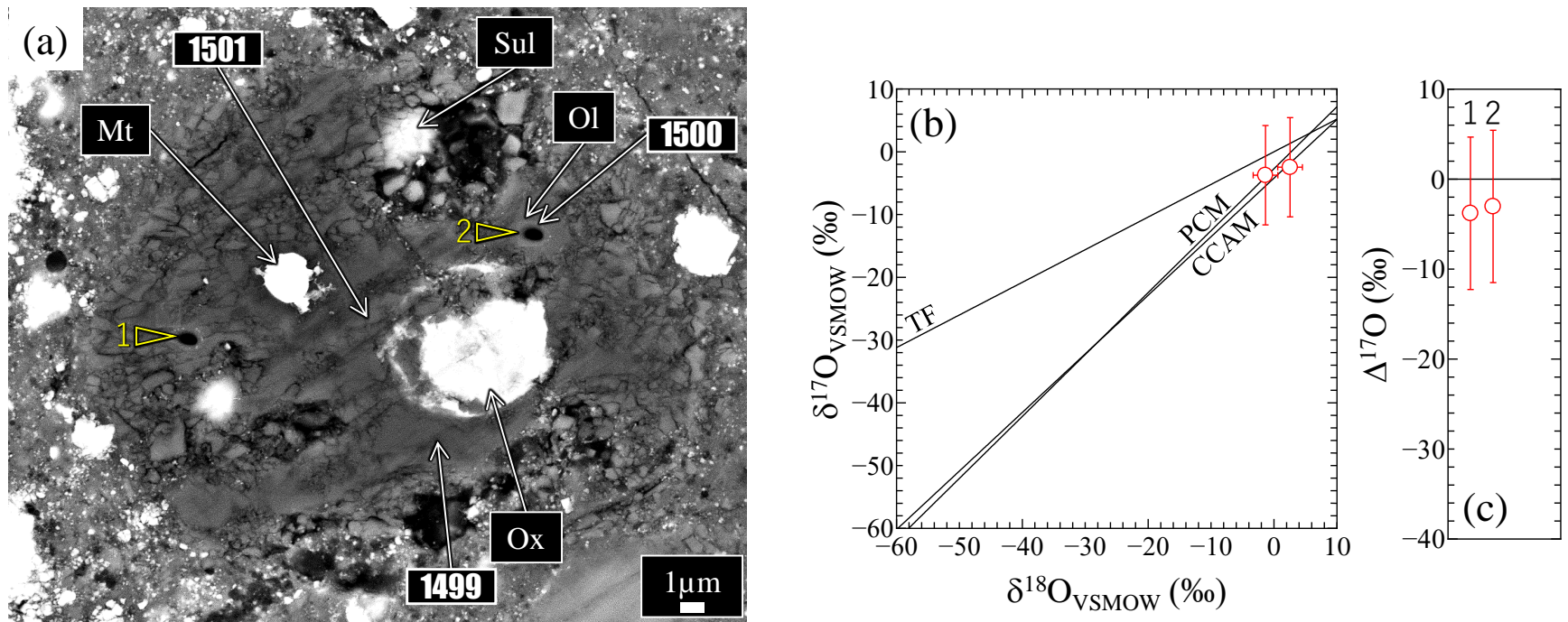
^bCorrection for instrumental bias using standards that have similar chemical compositions to the target phases.

Supplementary Table 3: The instrumental bias relative to SCOl (San Carlos Olivine) among different standards.

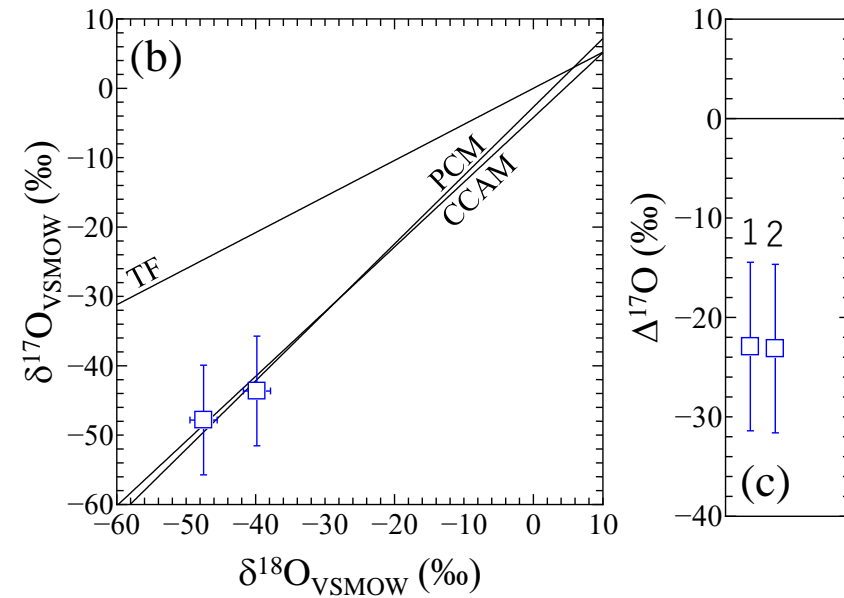
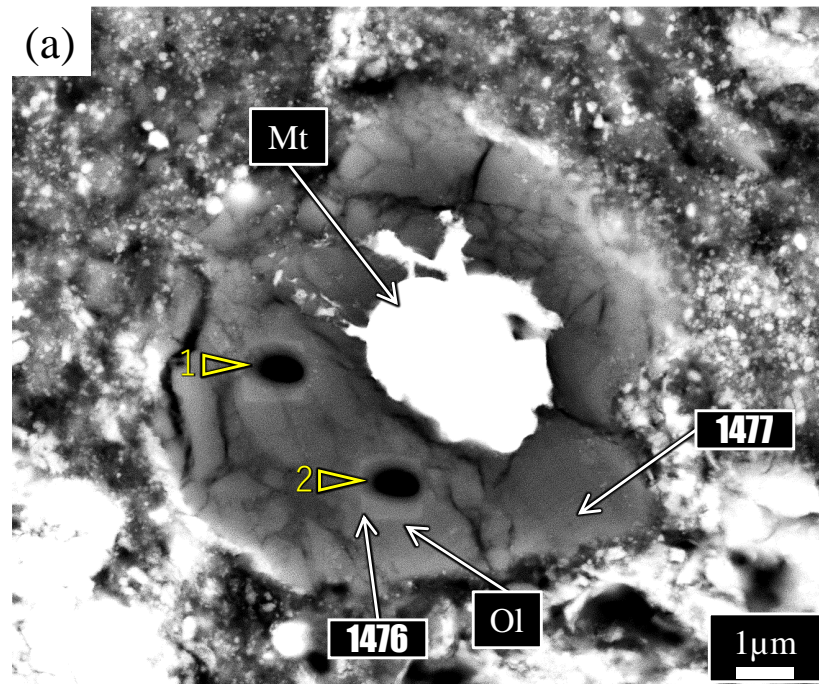
| Standard name | Mineral | Standard | | | | | SCOl (bracketing analyses) | | | | Bias relative to laser Fluorination | | | |
|---------------------|----------|---|------|------------------------------------|------|---|----------------------------------|------|------------------------------------|----------------------------------|-------------------------------------|-------|------|-----------|
| | | $\delta^{18}\text{O} \pm 2\text{SD} (\text{‰})$ | | Bias $\pm 2\text{SE} (\text{‰})^a$ | N | $\delta^{18}\text{O} \pm 2\text{SD} (\text{‰})$ | Bias $\pm 2\text{SE} (\text{‰})$ | N | SCOl $\pm 2\text{SE} (\text{‰})^b$ | $\delta^{18}\text{O} (\text{‰})$ | Ref | | | |
| HN-Ol | For100 | 4.85 | 2.31 | -4.02 | 1.16 | 4 | 1.06 | 4.12 | -4.24 | 1.46 | 8 | 0.22 | 1.86 | 8.90 [2] |
| Spinel#1 | Spinel | 10.87 | 2.72 | -6.20 | 1.36 | 4 | 2.42 | 1.03 | -2.88 | 0.37 | 8 | -3.33 | 1.41 | 17.18 [3] |
| Madagascar hibonite | Hibonite | 4.85 | 0.99 | -5.91 | 0.49 | 4 | 2.42 | 1.03 | -2.88 | 0.37 | 8 | -3.04 | 0.61 | 10.83 [3] |

^aInstrumental bias in $\delta^{18}\text{O}$ from $\delta^{18}\text{O}$ values determined by laser fluorination.

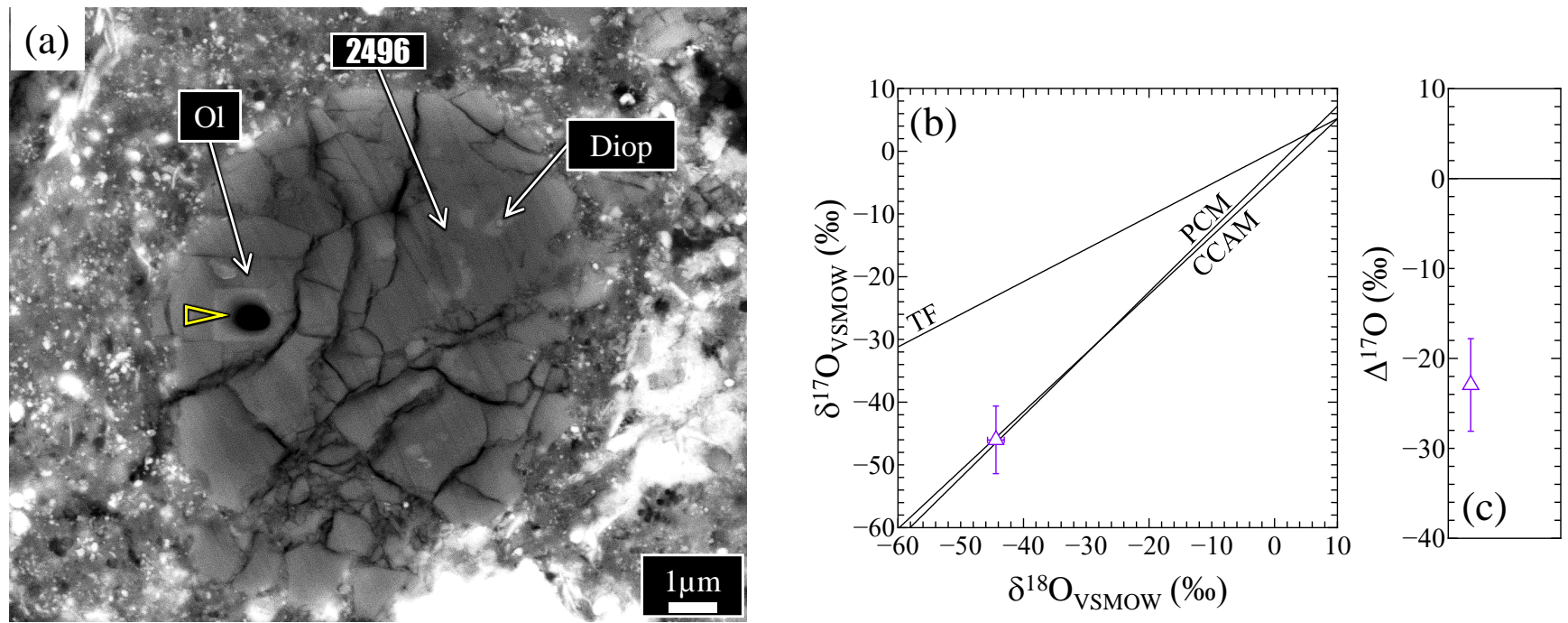
^bCorrection factors of instrumental bias caused by chemical compositions of the chondrule-like objects and CAIs (matrix effect).



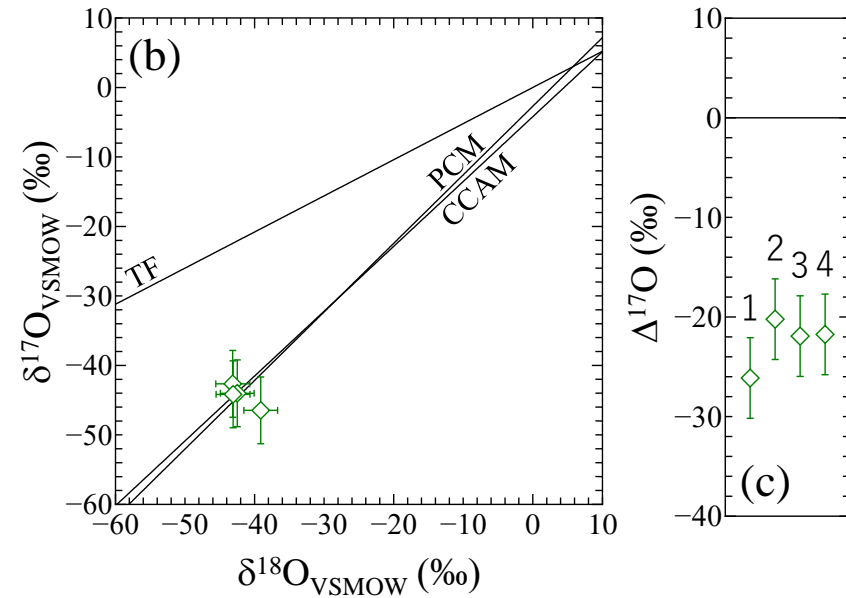
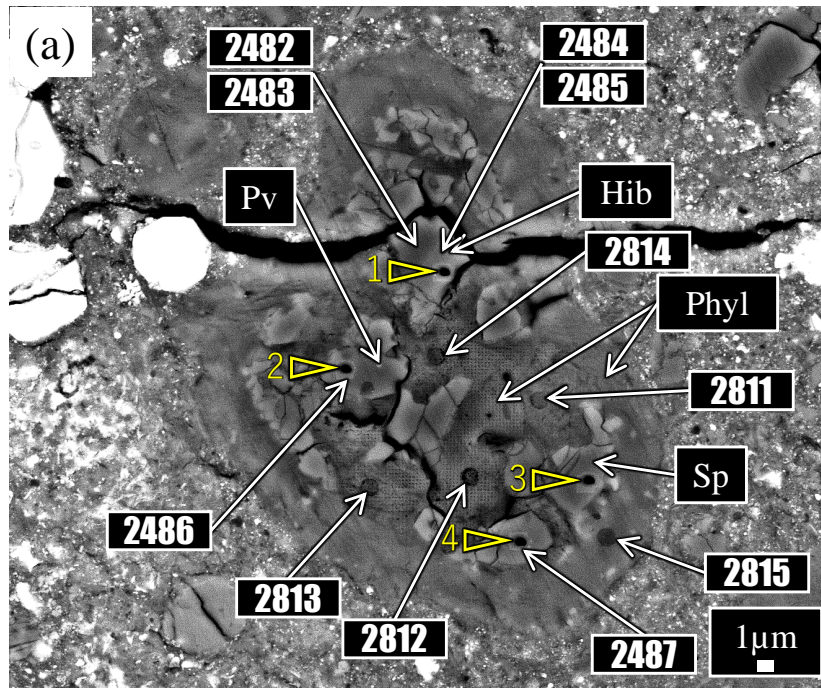
Supplementary Fig. 1: The BSE image of C0002-P5-C1-Chd (a), oxygen three-isotope ratios of C0002-P5-C1-Chd (b), and $\Delta^{17}\text{O}$ values of C0002-P5-C1-Chd (c). Four-digit numbers in panel a correspond to analysis numbers of FE-EPMA (Supplementary table 1). Abbreviations in panel a: Ol, olivine; Mt, Fe-Ni metal; Sul, Fe-sulfide; Ox, oxide. TF, PCM, and CCAM in panel b represent the Terrestrial Fractionation line, the Primitive Chondrule Mineral line⁴, and the Carbonaceous Chondrite Anhydrous Mineral line⁵. Numbers in panel c correspond to analysis numbers of SIMS (Supplementary table 2).



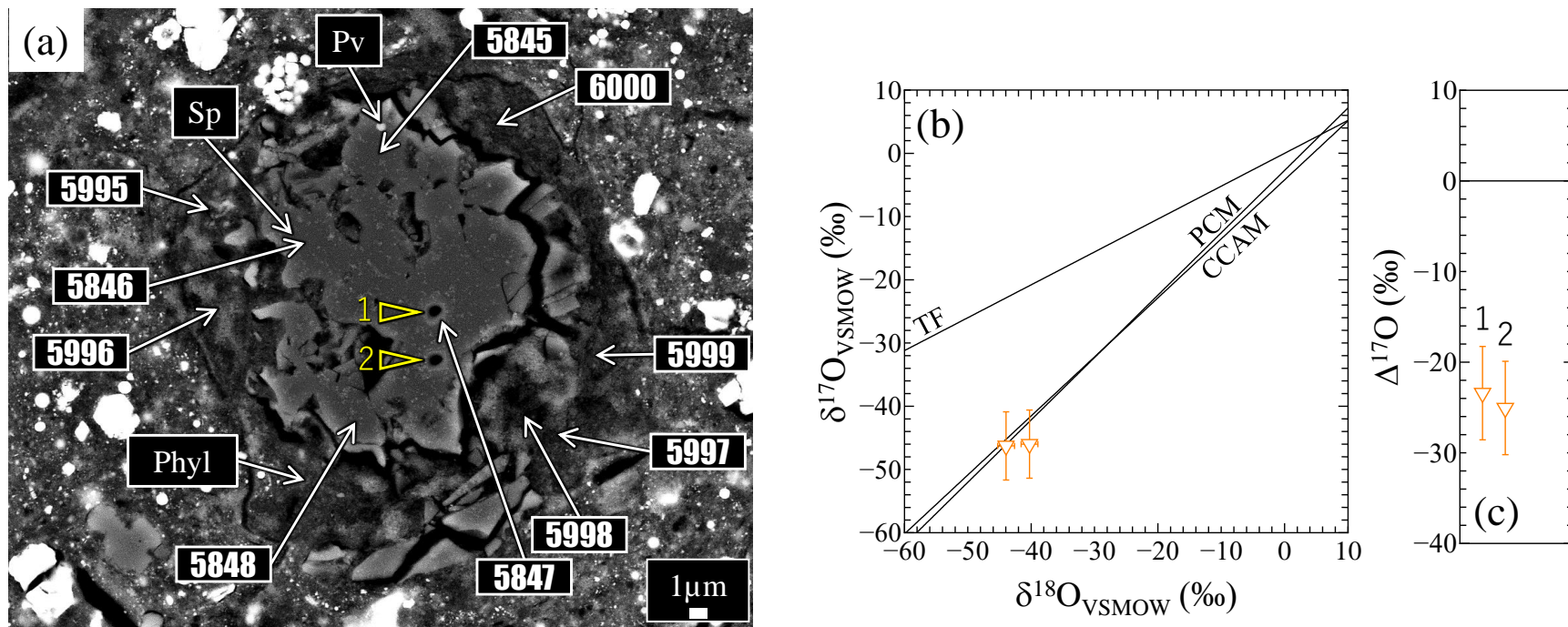
Supplementary Fig. 2: The BSE image of C0002-P5-C2-Chd (a), oxygen three-isotope ratios of C0002-P5-C2-Chd (b), and $\Delta^{17}\text{O}$ values of C0002-P5-C2-Chd (c). Four-digit numbers in panel a correspond to analysis numbers of FE-EPMA (Supplementary table 1). Abbreviations in panel a: Ol, olivine; Mt, Fe-Ni metal. TF, PCM, and CCAM in panel b represent the Terrestrial Fractionation line, the Primitive Chondrule Mineral line⁴, and the Carbonaceous Chondrite Anhydrous Mineral line⁵. Numbers in panel c correspond to analysis numbers of SIMS (Supplementary table 2).



Supplementary Fig. 3: The BSE image of C0040-02-Chd (a), oxygen three-isotope ratios of C0040-02-Chd (b), and $\Delta^{17}\text{O}$ value of C0040-02-Chd (c). The four-digit number in panel a corresponds to the analysis number of FE-EPMA (Supplementary table 1). Abbreviations in panel a: Ol, olivine; Diop, diopside. TF, PCM, and CCAM in panel b represent the Terrestrial Fractionation line, the Primitive Chondrule Mineral line⁴, and the Carbonaceous Chondrite Anhydrous Mineral line⁵.



Supplementary Fig. 4: The BSE image of C0040-02-CAI (a), oxygen three-isotope ratios of C0040-02-CAI (b), and $\Delta^{17}\text{O}$ values of C0040-02-CAI (c). Four-digit numbers in panel a correspond to analysis numbers of FE-EPMA (Supplementary table 1). Abbreviations: Sp, spinel; Hib, hibonite; Pv, perovskite; Phyl, phyllosilicates. TF, PCM, and CCAM in panel b represent the Terrestrial Fractionation line, the Primitive Chondrule Mineral line⁴, and the Carbonaceous Chondrite Anhydrous Mineral line⁵. Numbers in panel c correspond to analysis numbers of SIMS (Supplementary table 2).



Supplementary Fig. 5: The BSE image of C0076-10-CAI (a), oxygen three-isotope ratios of C0076-10-CAI (b), and $\Delta^{17}\text{O}$ values of C0076-10-CAI (c). Four-digit numbers in panel a correspond to analysis numbers of FE-EPMA (Supplementary table 1). Abbreviations: Sp, spinel; Pv, perovskite; Phyl, phyllosilicates. TF, PCM, and CCAM in panel b represent the Terrestrial Fractionation line, the Primitive Chondrule Mineral line⁴, and the Carbonaceous Chondrite Anhydrous Mineral line⁵. Numbers in panel c correspond to analysis numbers of SIMS (Supplementary table 2).

Supplementary reference

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