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# Supplementary Materials for

## Oxygen isotopes of anhydrous primary minerals show kinship between asteroid Ryugu and comet 81P/Wild2

Noriyuki Kawasaki *et al.*

Corresponding author: Noriyuki Kawasaki, kawasaki@ep.sci.hokudai.ac.jp

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**The PDF file includes:**

Figs. S1 to S51
Tables S1 to S3
Legend for data S1

**Other Supplementary Material for this manuscript includes the following:**

Data S1

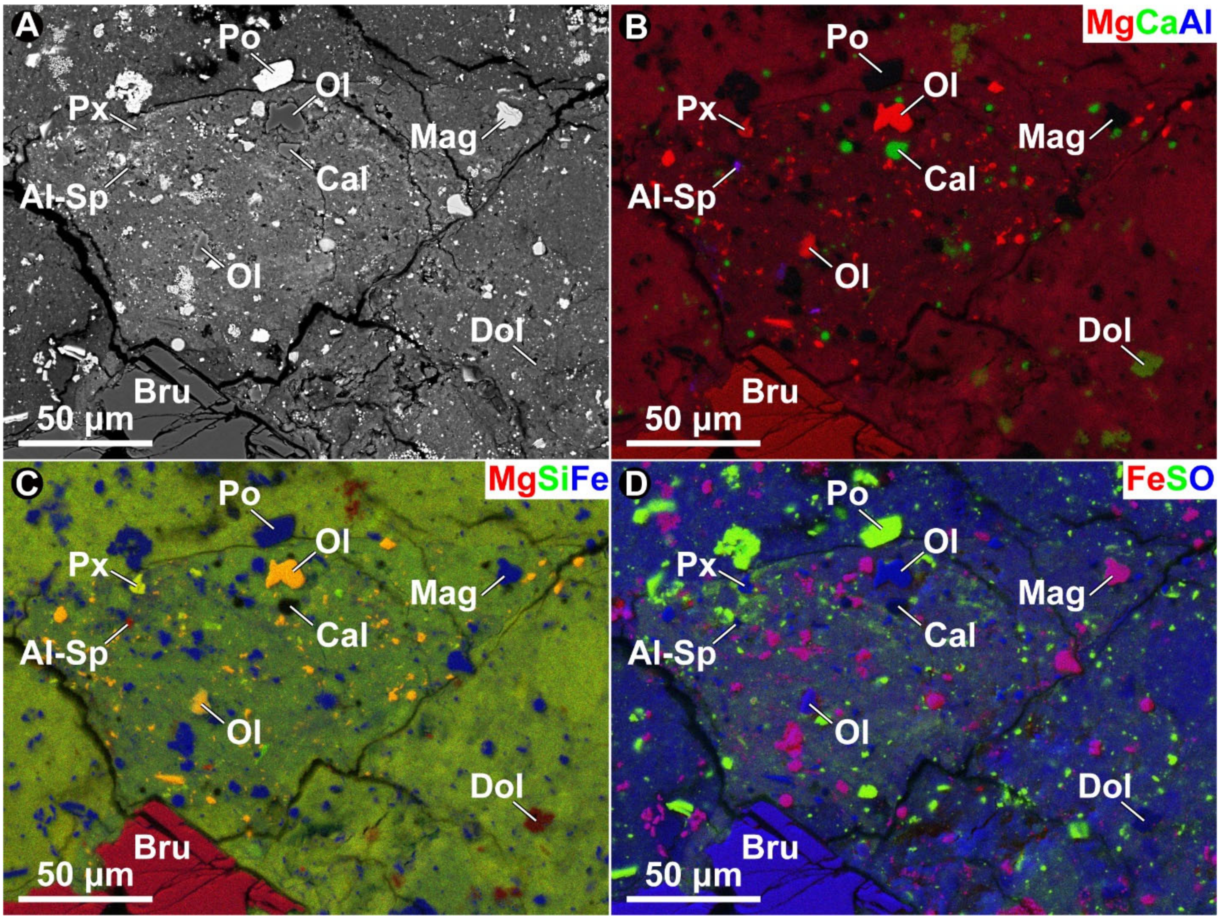


**Fig. S1. Occurrences of anhydrous primary minerals in Ryugu sample. (A)** BSE image of a primary mineral-rich clast. **(B)** Combined X-ray elemental map of (A) using Mg Kα, Ca Kα, and Al Kα lines assigned for RGB channels. **(C)** Combined X-ray elemental map of (A) using Mg Kα, Si Kα, and Fe Kα lines assigned for RGB channels. **(D)** Combined X-ray elemental map of (A) using Fe Kα, S Kα, and O Kα lines assigned for RGB channels. A location in the whole section is indicated as "2" in Fig. S3. Al-Sp: Mg-Al spinel, Bru: breunnerite, Cal: calcite, Dol: dolomite, Mag: magnetite, Ol: olivine, Po: pyrrhotite, Px: low-Ca pyroxene.

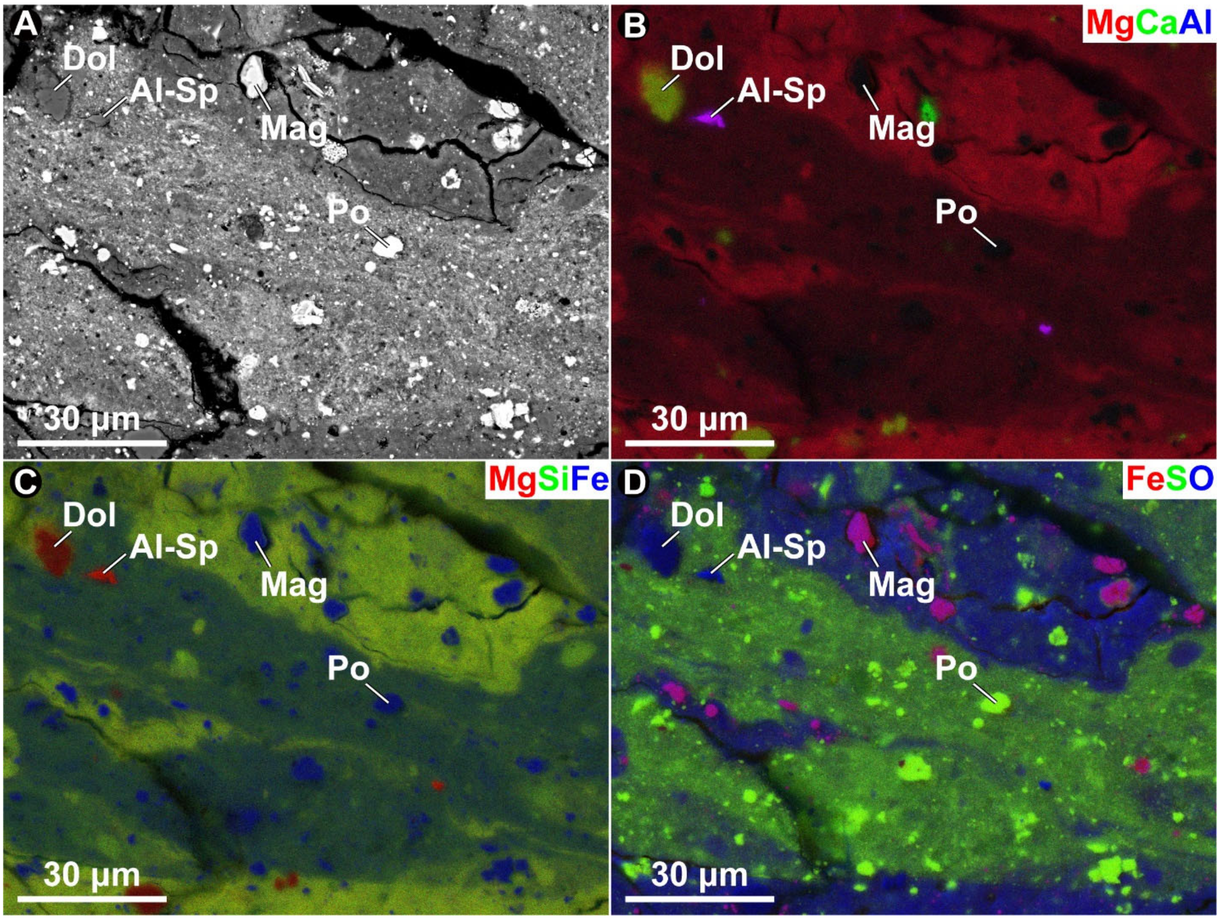


**Fig. S2. Occurrences of anhydrous primary minerals in Ryugu sample. (A)** BSE image of a primary mineral-rich clast. **(B)** Combined X-ray elemental map of (A) using Mg Kα, Ca Kα, and Al Kα lines assigned for RGB channels. **(C)** Combined X-ray elemental map of (A) using Mg Kα, Si Kα, and Fe Kα lines assigned for RGB channels. **(D)** Combined X-ray elemental map of (A) using Fe Kα, S Kα, and O Kα lines assigned for RGB channels. A location in the whole section is indicated as "S2" in Fig. S3. Al-Sp: Mg-Al spinel, Dol: dolomite, Mag: magnetite, Po: pyrrhotite.

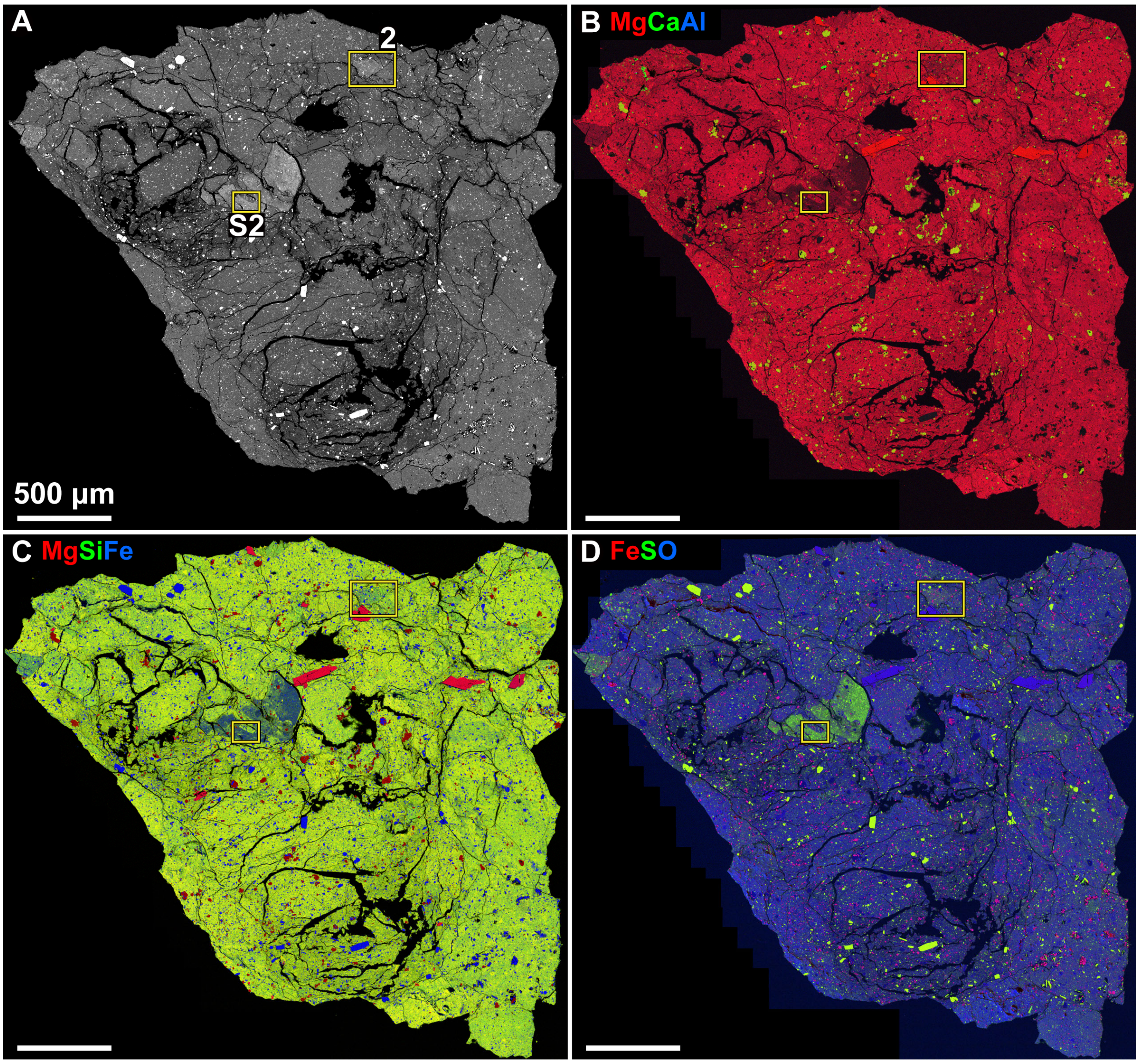


**Fig. S3. Polished surface of the Ryugu C0002-C0001. (A)** BSE image. **(B)** Combined X-ray elemental map of (A) using Mg Kα, Ca Kα, and Al Kα lines assigned for RGB channels. **(C)** Combined X-ray elemental map of (A) using Mg Kα, Si Kα, and Fe Kα lines assigned for RGB channels. **(D)** Combined X-ray elemental map of (A) using Fe Kα, S Kα, and O Kα lines assigned for RGB channels. Yellow boxes indicate the areas shown in Fig. 2/S1 and S2.

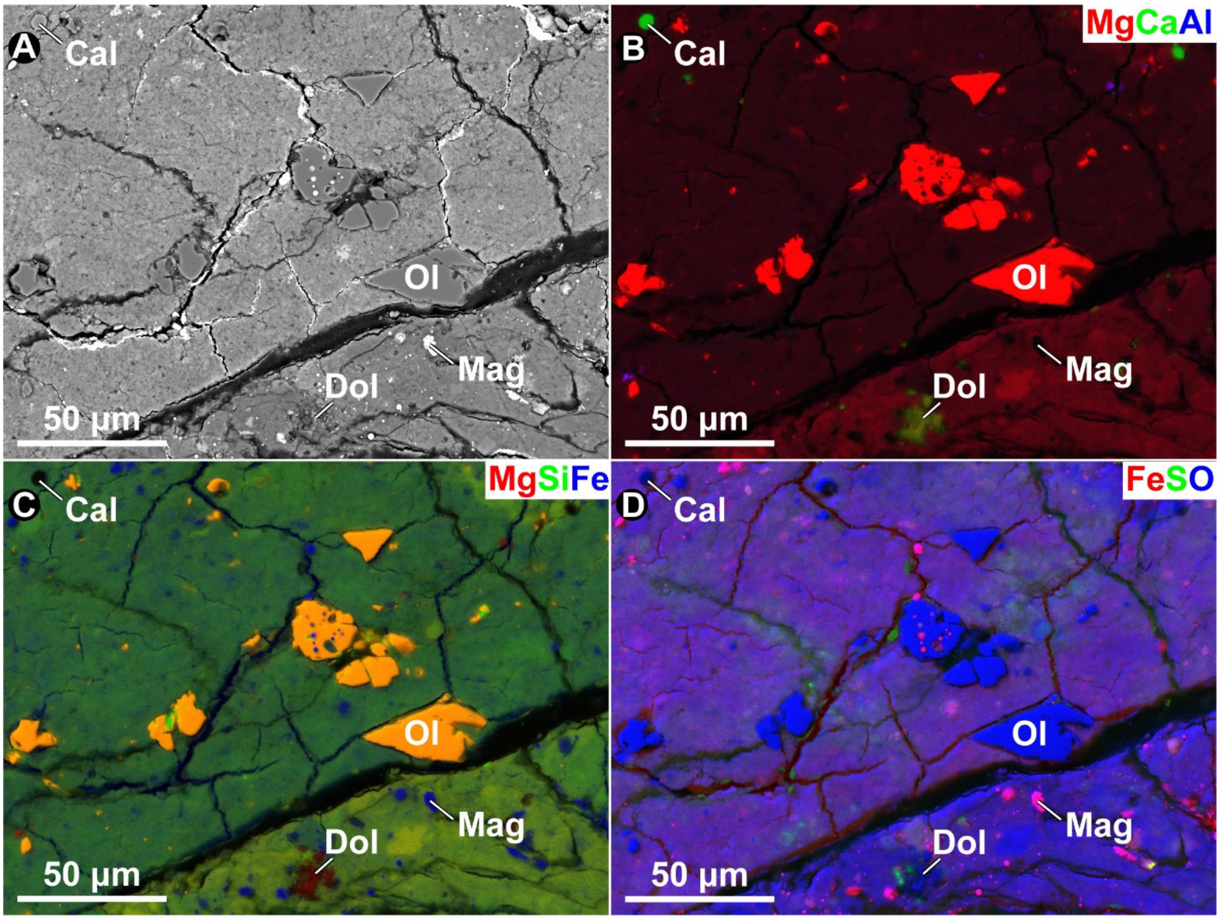


**Fig. S4. Occurrences of anhydrous primary minerals in Ivuna. (A)** BSE image of a primary mineral-rich clast. **(B)** Combined X-ray elemental map of (A) using Mg Kα, Ca Kα, and Al Kα lines assigned for RGB channels. **(C)** Combined X-ray elemental map of (A) using Mg Kα, Si Kα, and Fe Kα lines assigned for RGB channels. **(D)** Combined X-ray elemental map of (A) using Fe Kα, S Kα, and O Kα lines assigned for RGB channels. A location in the whole section is indicated by yellow box in Fig. S5. Cal: calcite, Dol: dolomite, Mag: magnetite, Ol: olivine.

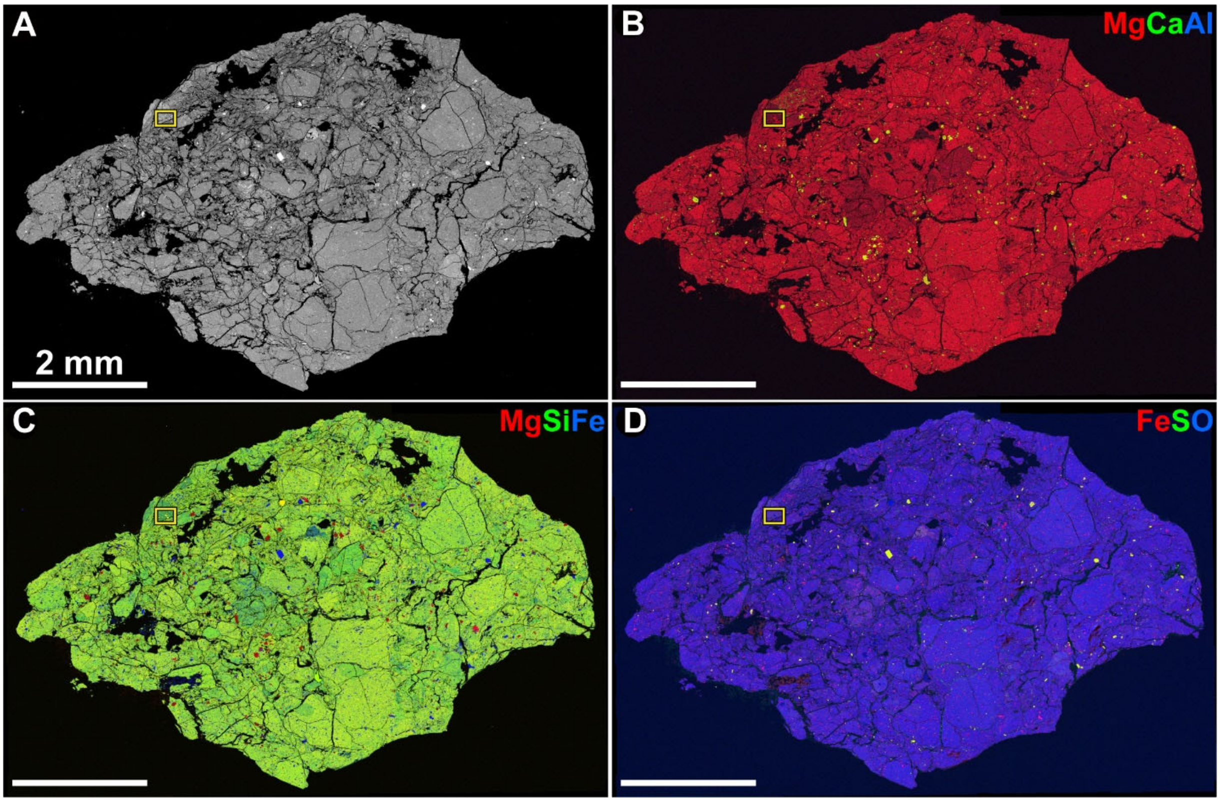


**Fig. S5. Polished surface of the Ivuna-HK2 section. (A)** BSE image. **(B)** Combined X-ray elemental map of (A) using Mg Kα, Ca Kα, and Al Kα lines assigned for RGB channels. **(C)** Combined X-ray elemental map of (A) using Mg Kα, Si Kα, and Fe Kα lines assigned for RGB channels. **(D)** Combined X-ray elemental map of (A) using Fe Kα, S Kα, and O Kα lines assigned for RGB channels. Yellow box indicates the area shown in Fig. S4.

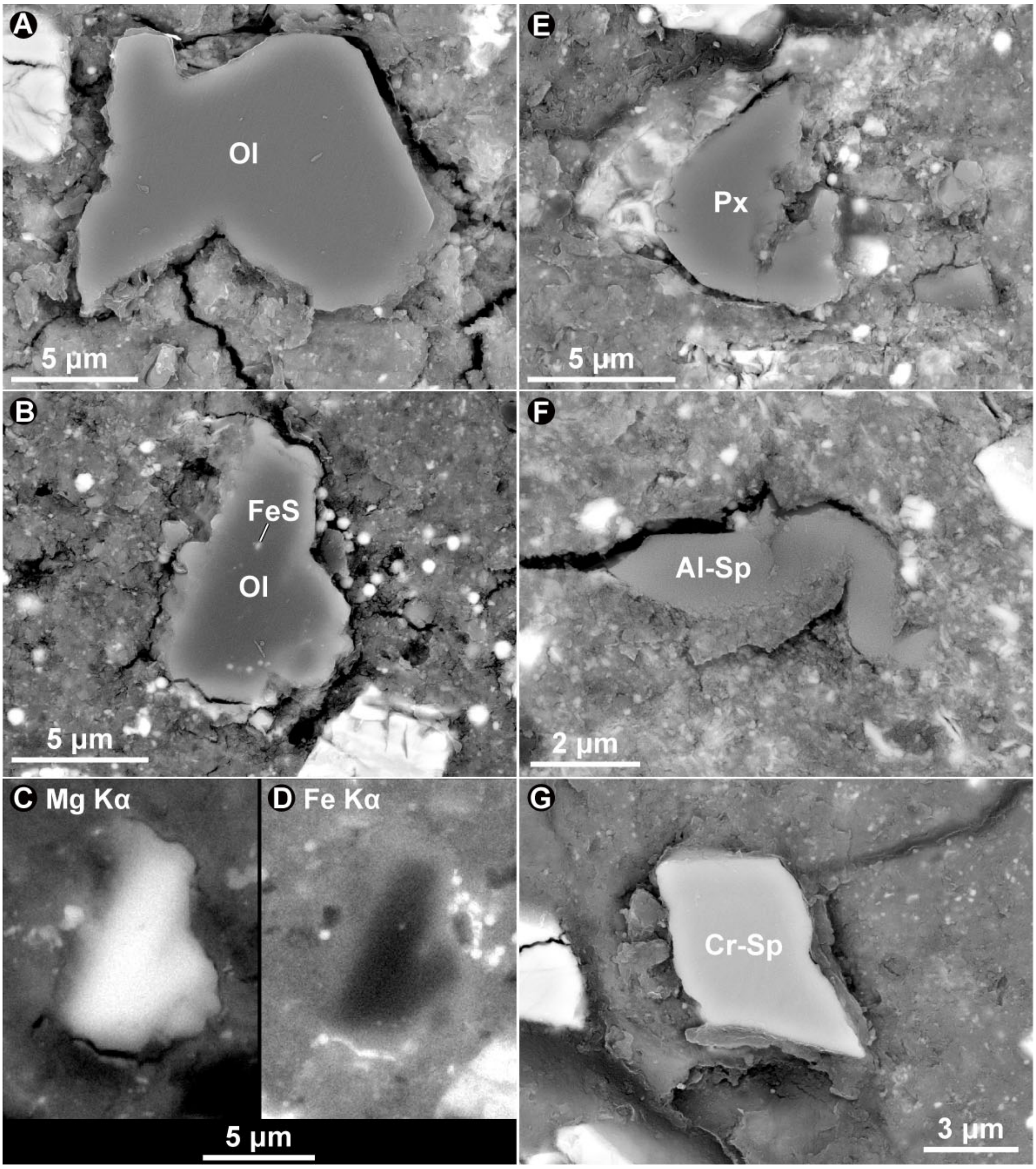


**Fig. S6. BSE images and elemental maps of anhydrous primary minerals in Ryugu.** BSE images of **(A, B)** olivine. **(C)** Mg Kα and **(D)** Fe Kα elemental maps of (B). BSE images of **(E)** low-Ca pyroxene, **(F)** Mg-Al spinel, and **(G)** Cr-spinel. Olivine (A, B) and low-Ca pyroxene (E) are located in a clast of Fig. 2/S1. Mg-Al spinel (F) is located in a clast of Fig. S2. Their $\Delta^{17}O$ values are (A) −24‰, (B) −4‰, (E) −4‰, (F) −23‰, and (G) −2‰, respectively.

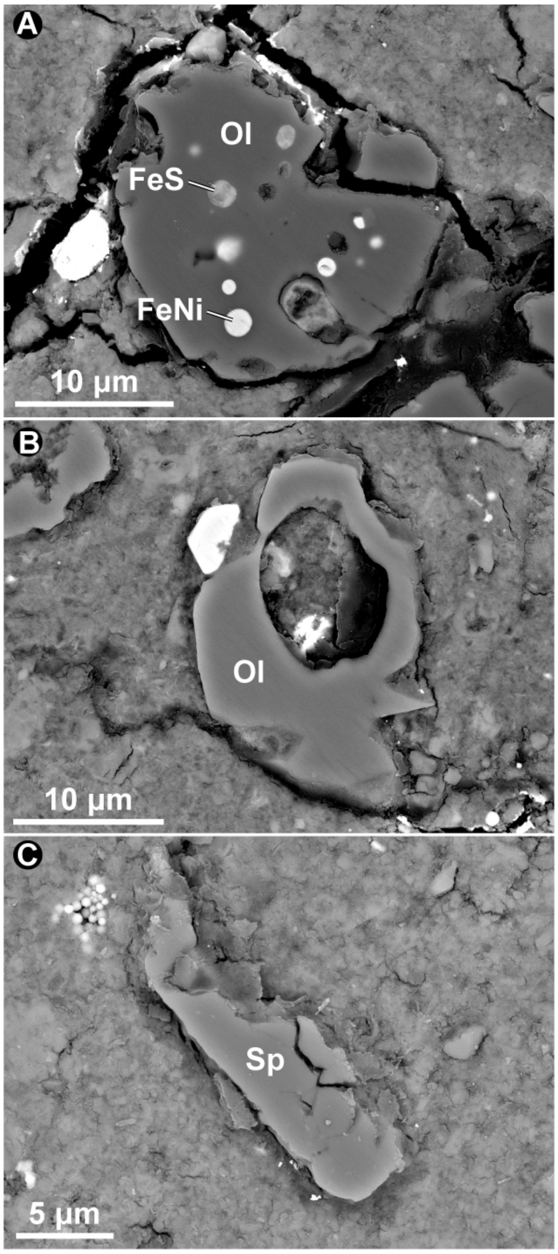


**Fig. S7. BSE images of anhydrous primary minerals in Ivuna. (A, B)** olivine and **(C)** spinel. Their $\Delta^{17}O$ values are −6‰, −24‰, and −23‰, respectively.

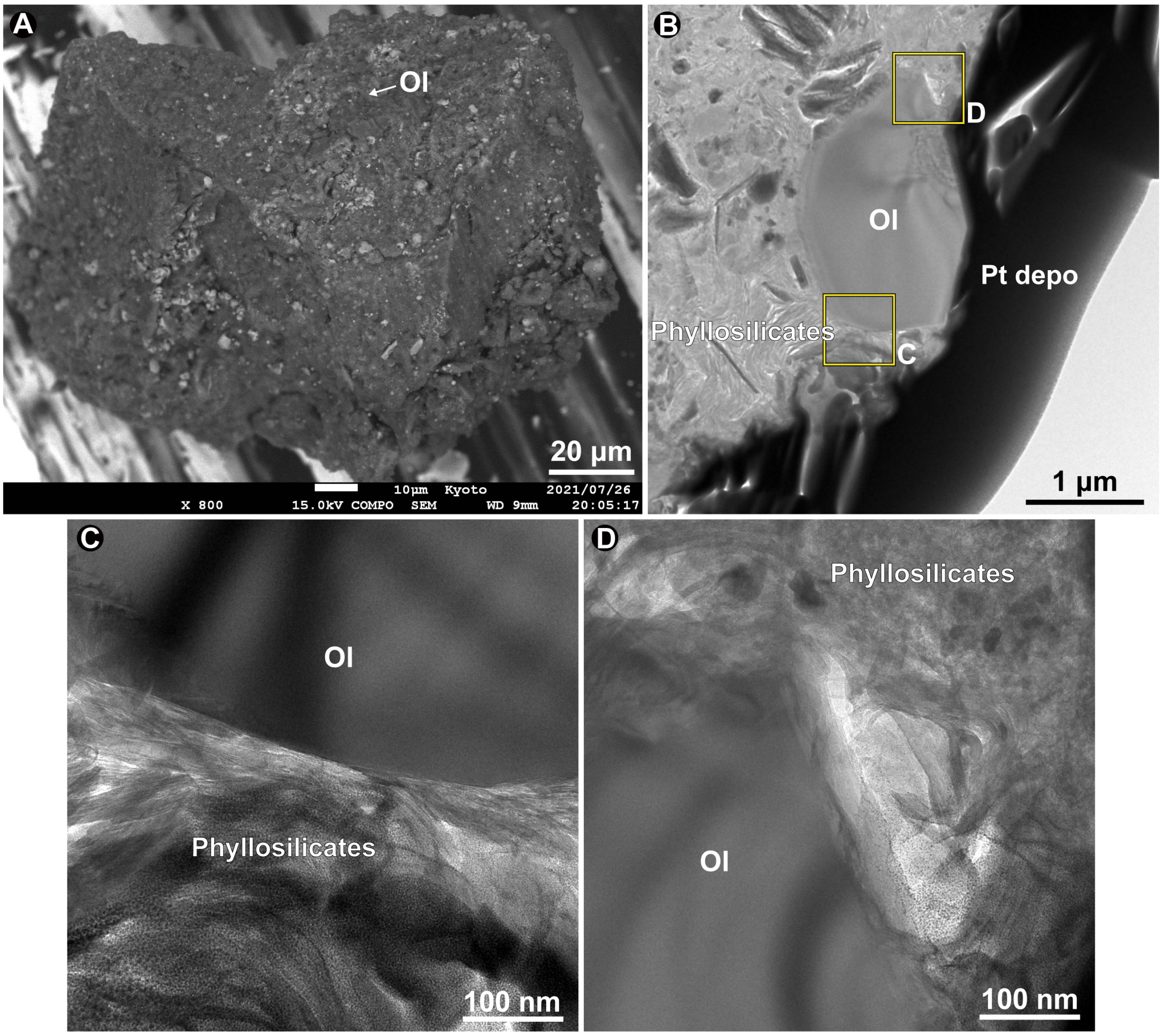


**Fig. S8. Bright-field-TEM images of an Mg-rich (Mg#~100) olivine grain in Ryugu sample A104-009008. (A)** BSE image of Ryugu sample A104-009008. **(B)** Low magnification TEM image of olivine grain. **(C, D)** High magnification images of areas indicated by yellow boxes in (B).

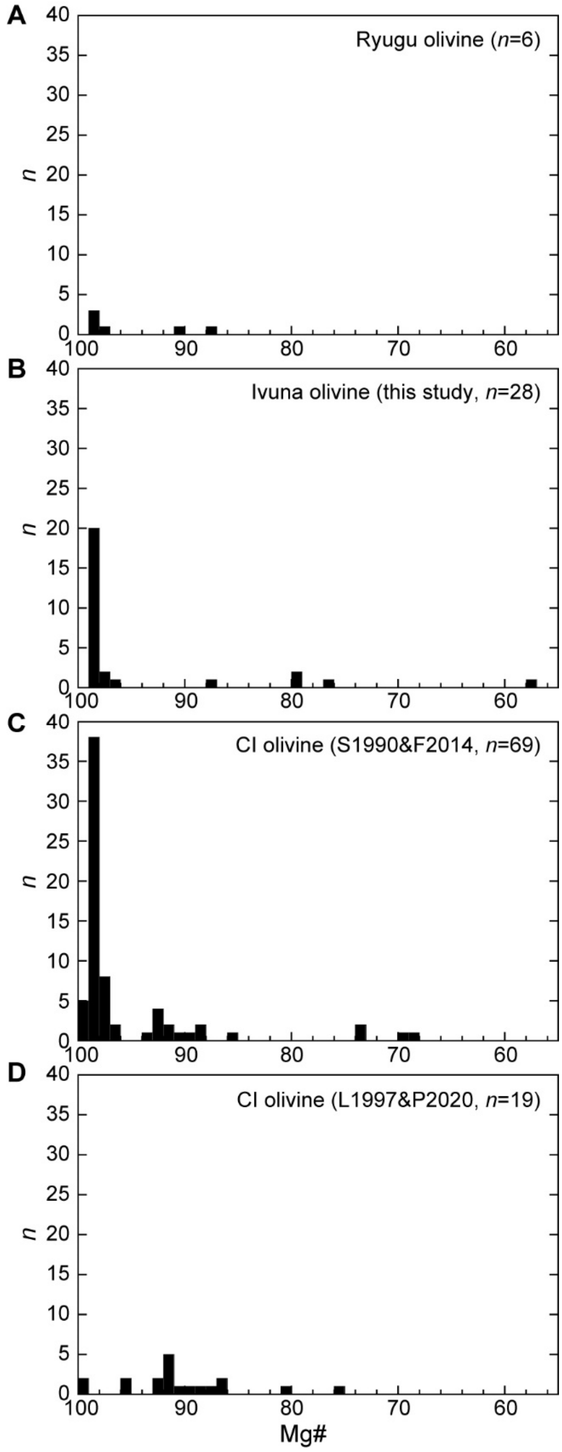


**Fig. S9. Histograms of Mg# for olivine grains. (A)** Ryugu. **(B)** Ivuna (this study). **(C)** Alais, Ivuna and Orgueil (*18, 19*). **(D)** Ivuna and Orgueil (*4, 6*). S1990=Steele (1990) [*18*]; F2014=Frank et al. (2014) [*19*]; L1997=Leshin et al. (1997) [4]; P2020=Piralla et al. (2020) [6].

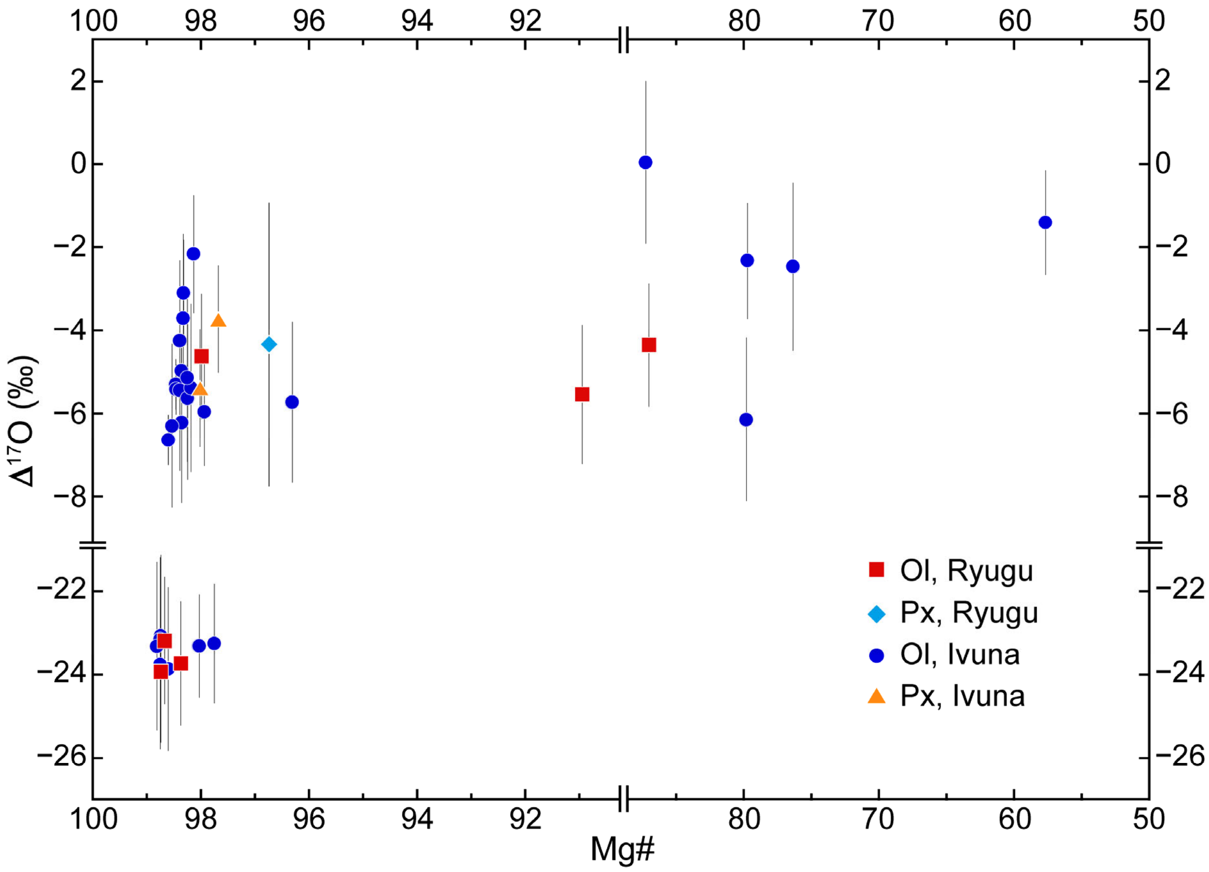


**Fig. S10. $\Delta^{17}$O *vs.* Mg# in olivine and low-Ca pyroxene grains in Ryugu and Ivuna.**

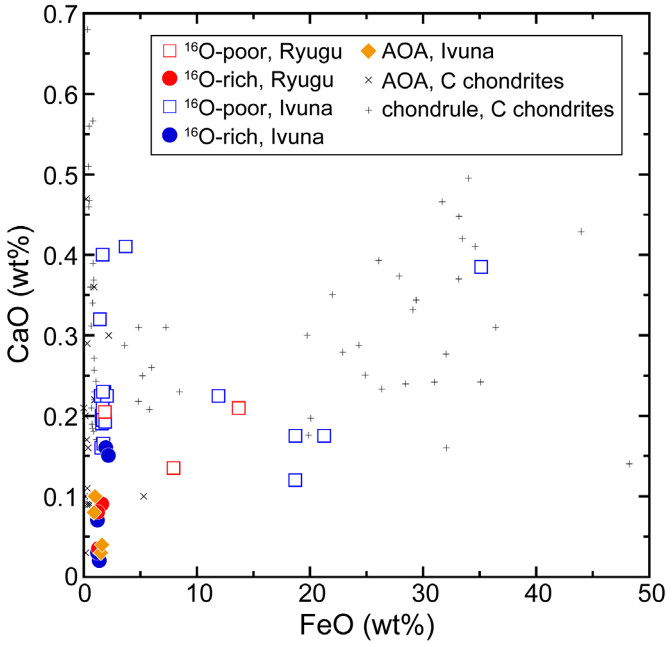


**Fig. S11. CaO *vs.* FeO contents of olivine.** Ryugu and Ivuna: this study. AOA of C (carbonaceous) chondrites: Acfer 094 and Yamato 81020 (*30, 31*). Chondrules of C chondrites: Acfer 094 and Yamato 81020 (*13, 14*). A wide spread of FeO contents and CaO contents larger than ~0.15 wt% and their covariation in the $^{16}O$-poor Ryugu and Ivuna olivines are consistent with those observed for chondrule olivines of those primitive carbonaceous chondrites. Note that counting detection limit (3 sigma) of CaO contents of this study is 0.06 wt%.

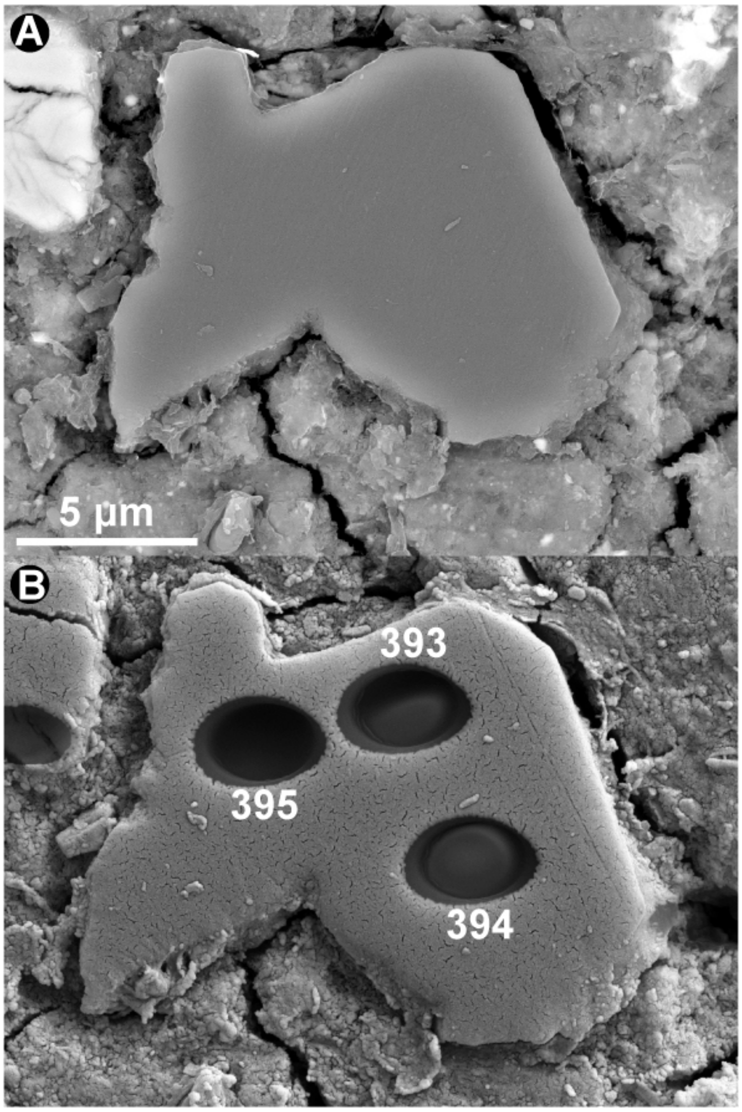


**Fig. S12. Olivine grain in Ryugu (C0002 *Ol 5-1*). (A)** BSE image taken before SIMS analysis. **(B)** secondary electron (SE) image after SIMS analysis.

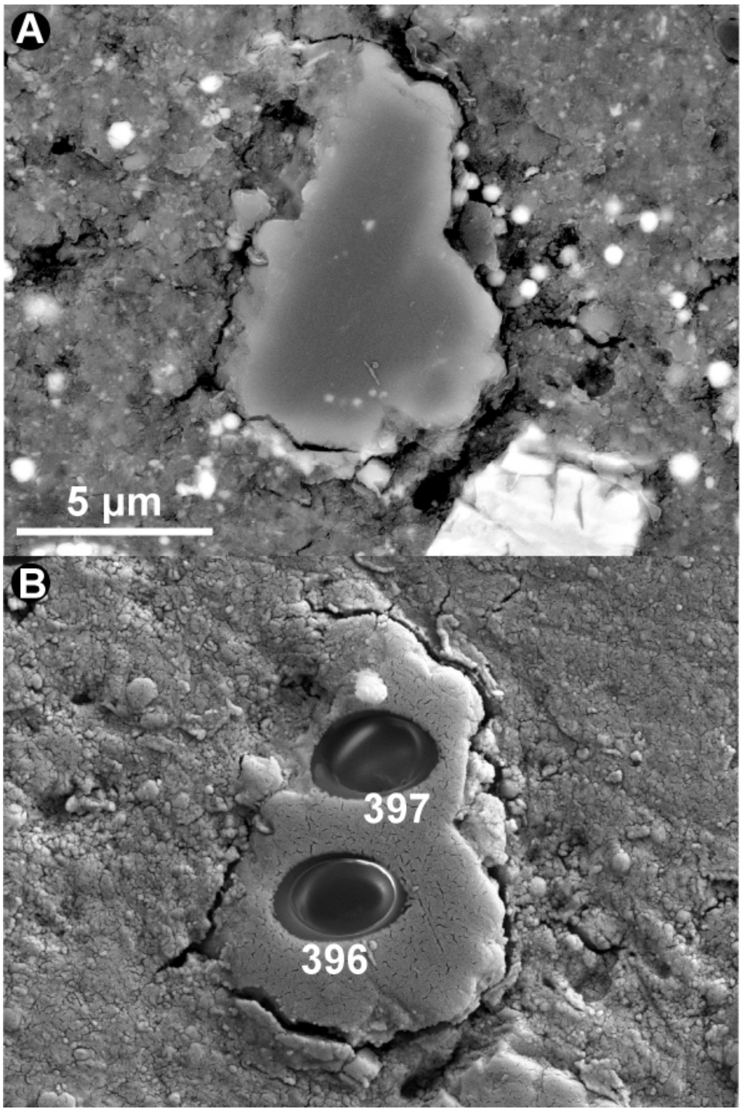


**Fig. S13. Olivine grain in Ryugu (C0002 *Ol 5-2*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

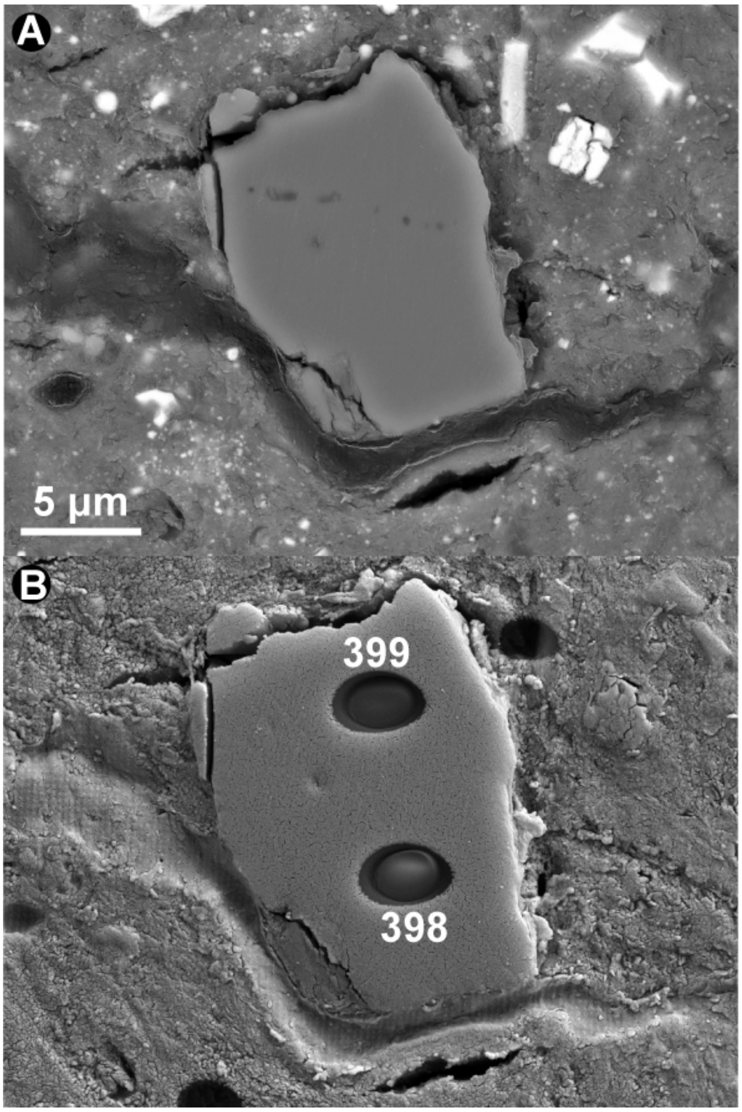


**Fig. S14. Olivine grain in Ryugu (C0002 *Ol 8*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

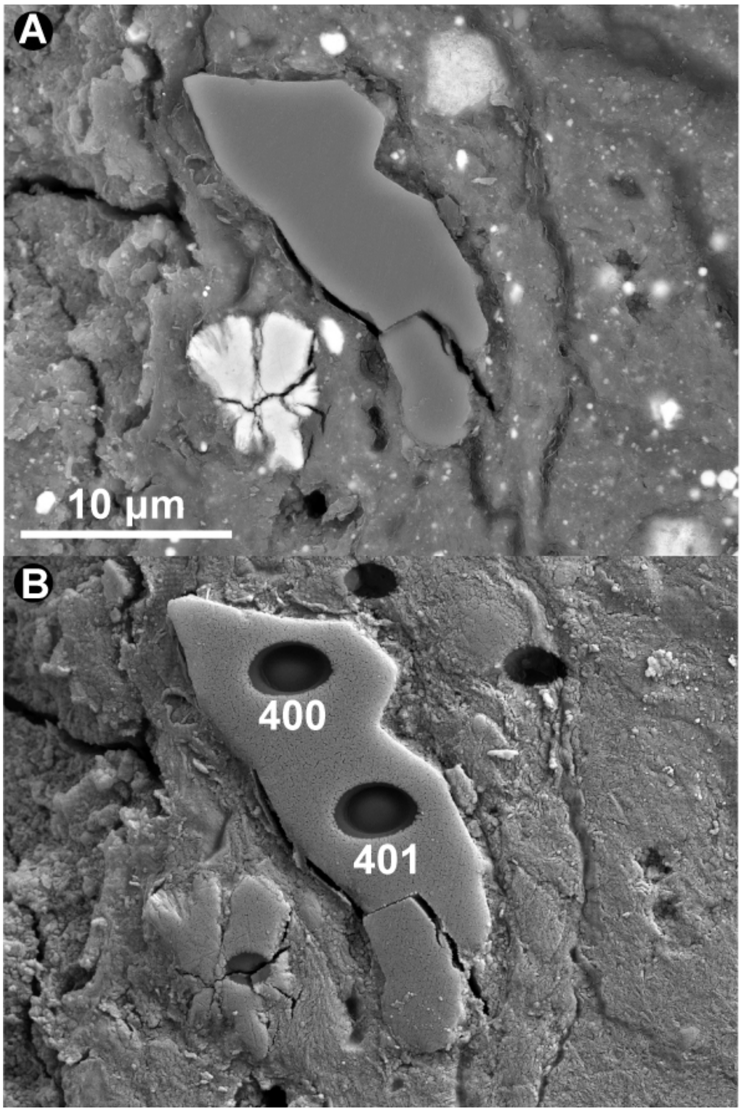


**Fig. S15. Olivine grain in Ryugu (C0002 *Ol 7*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

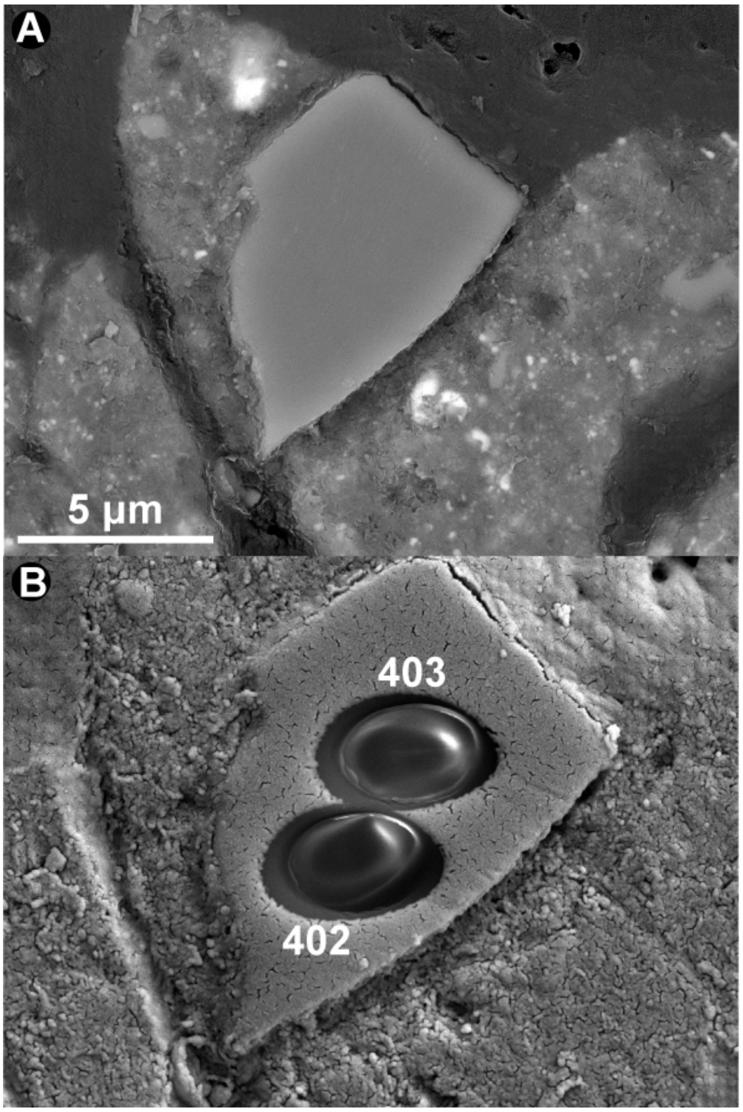


**Fig. S16. Olivine grain in Ryugu (C0002 *Ol 1-1*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

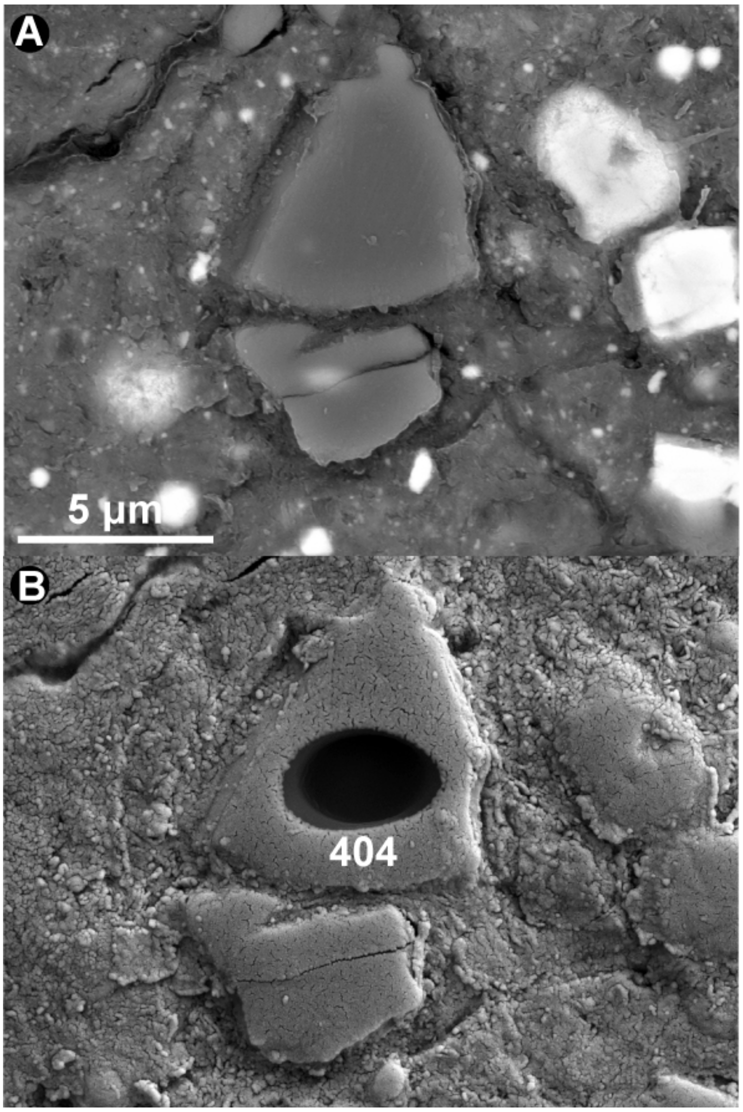

**Fig. S17. Olivine grain in Ryugu (C0002 *Ol 1-2*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

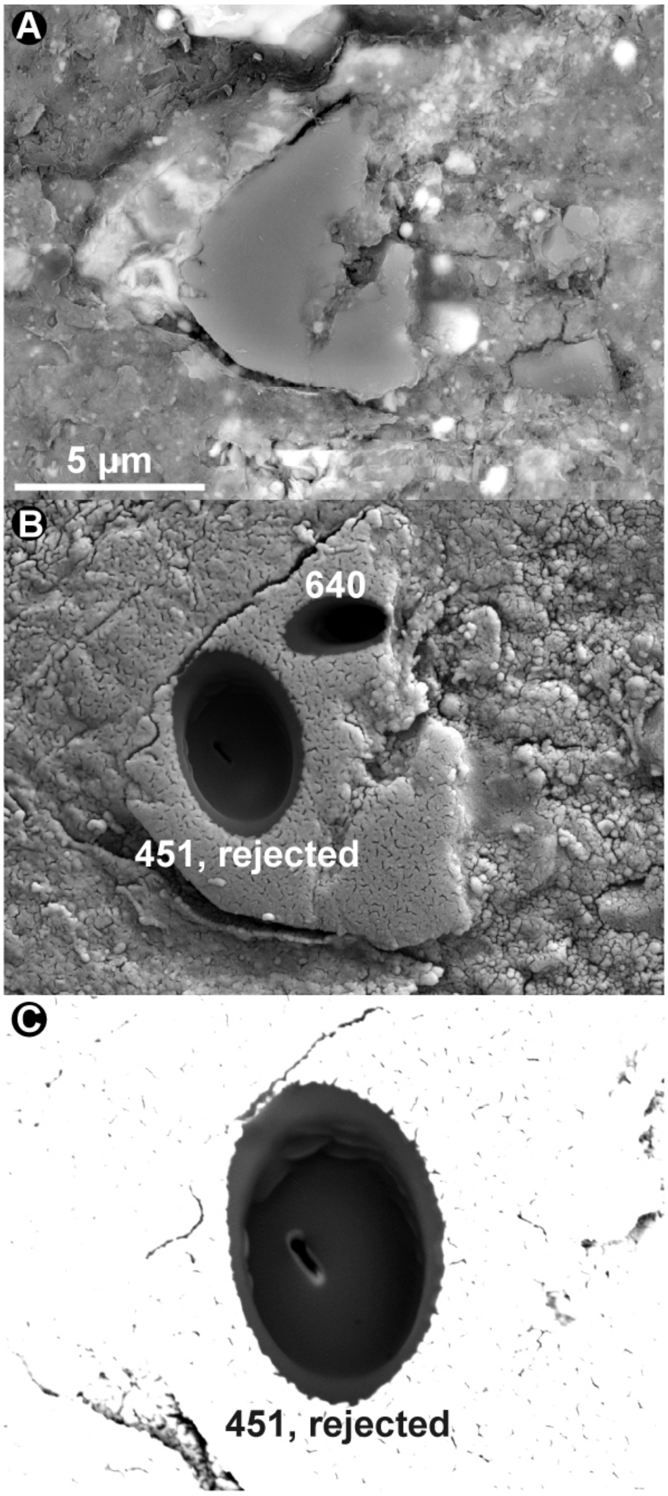


**Fig. S18. Low-Ca pyroxene grain in Ryugu (C0002 *Px 1*). (A)** BSE image taken before SIMS analysis. **(B)** SE and **(C)** BSE images after SIMS analysis. Spot #451 was rejected because that spot contains an inclusion.

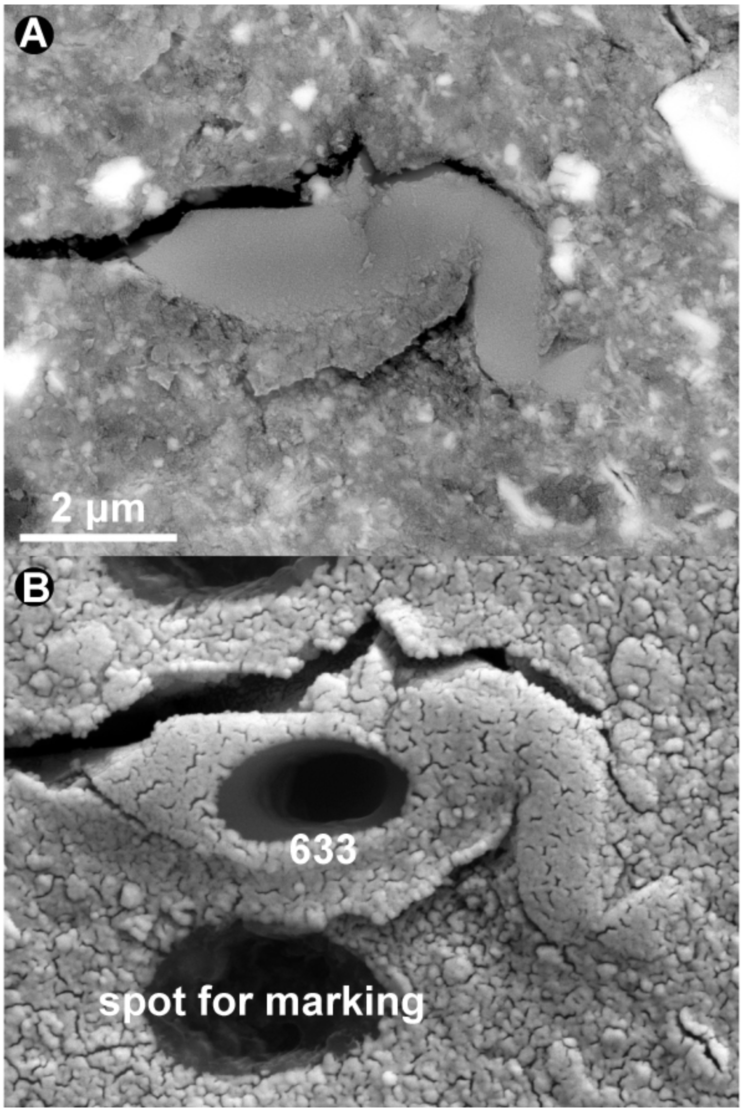


**Fig. S19. Spinel grain in Ryugu (C0002 *Sp 1*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

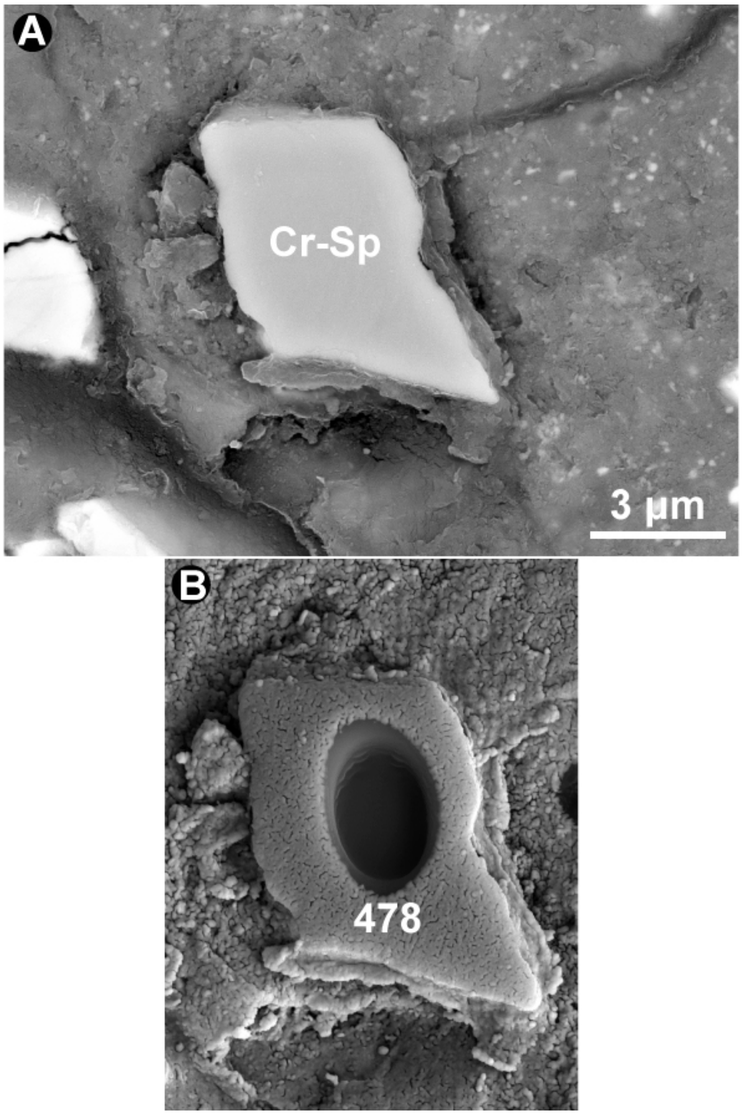


**Fig. S20. Spinel grain in Ryugu (C0002 *Cr-Sp 1*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

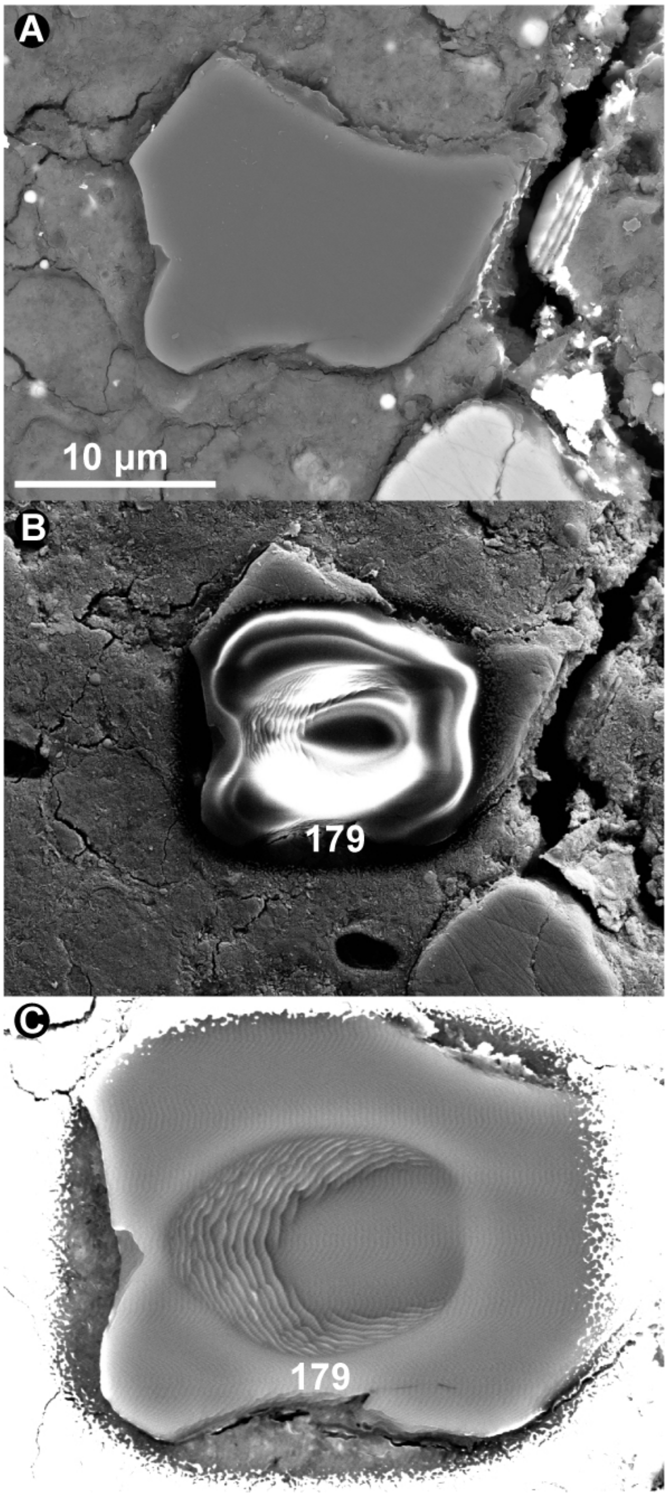


**Fig. S21. Olivine grain in Ivuna (Ivuna *Ol 3-1*). (A)** BSE image taken before SIMS analysis. **(B)** SE and **(C)** BSE images after SIMS analysis.

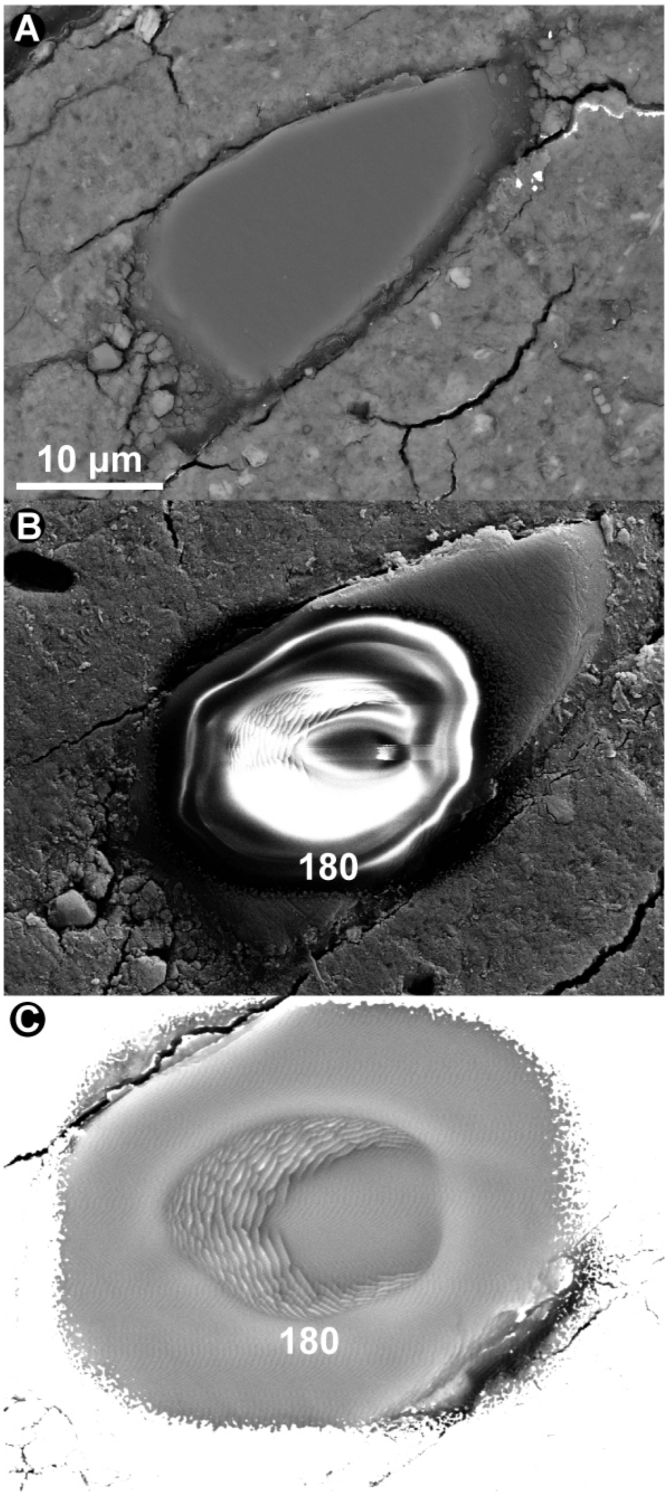


**Fig. S22. Olivine grain in Ivuna (Ivuna *Ol 4-1*). (A)** BSE image taken before SIMS analysis. **(B)** SE and **(C)** BSE images after SIMS analysis.

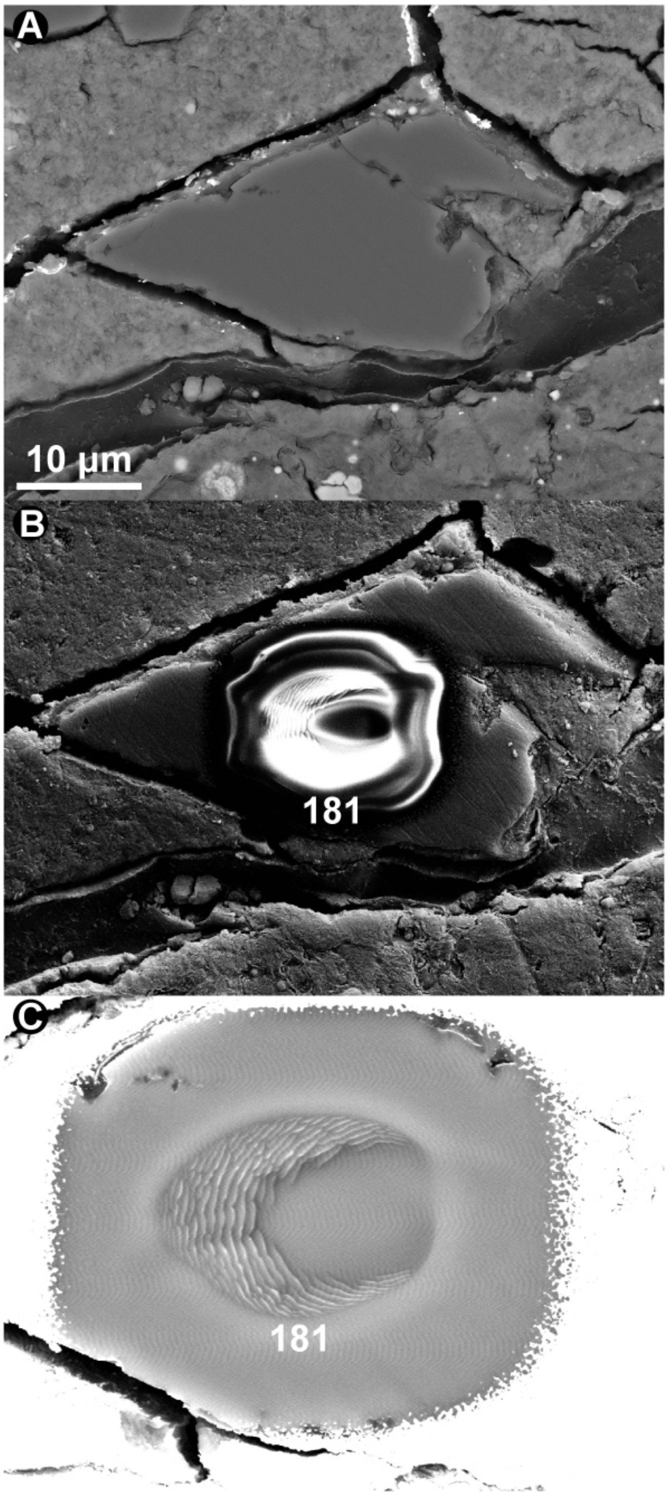


**Fig. S23. Olivine grain in Ivuna (Ivuna *Ol 6-4*). (A)** BSE image taken before SIMS analysis. **(B)** SE and **(C)** BSE images after SIMS analysis.

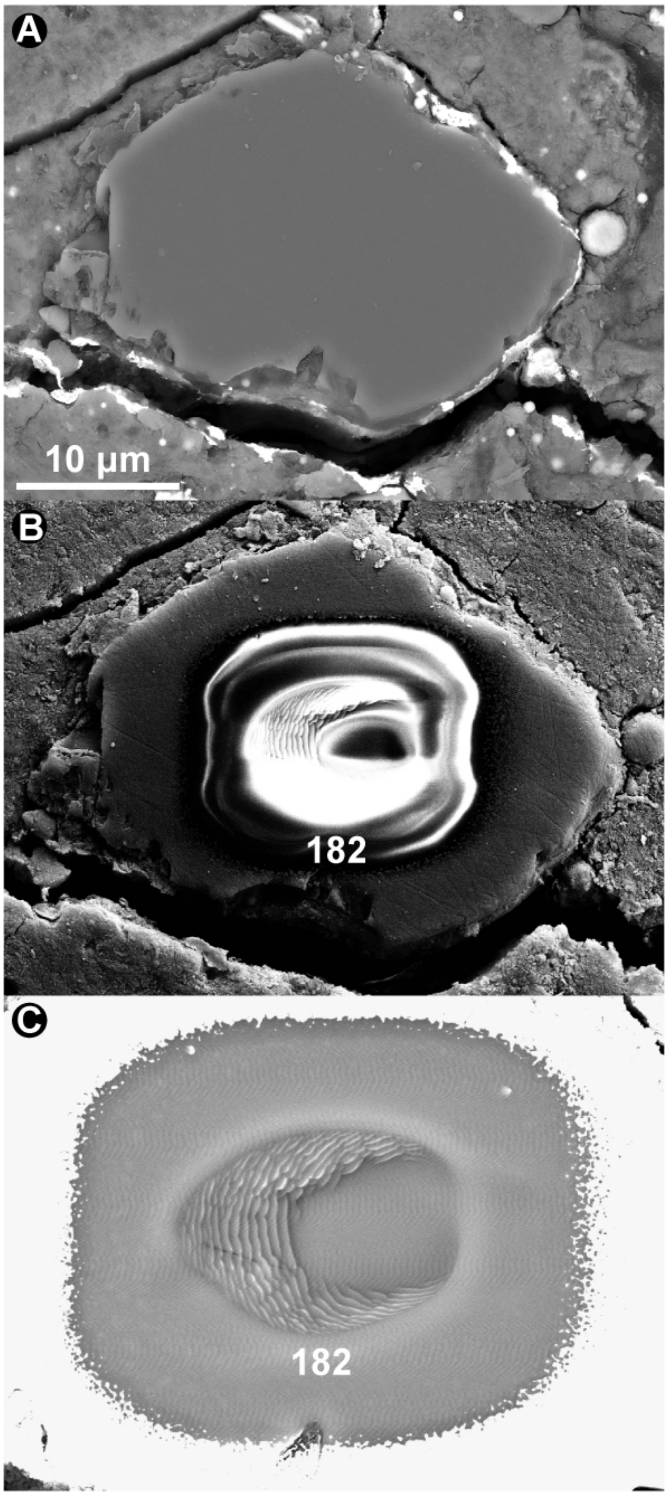


**Fig. S24. Olivine grain in Ivuna (Ivuna *Ol 25*). (A)** BSE image taken before SIMS analysis. **(B)** SE and **(C)** BSE images after SIMS analysis.

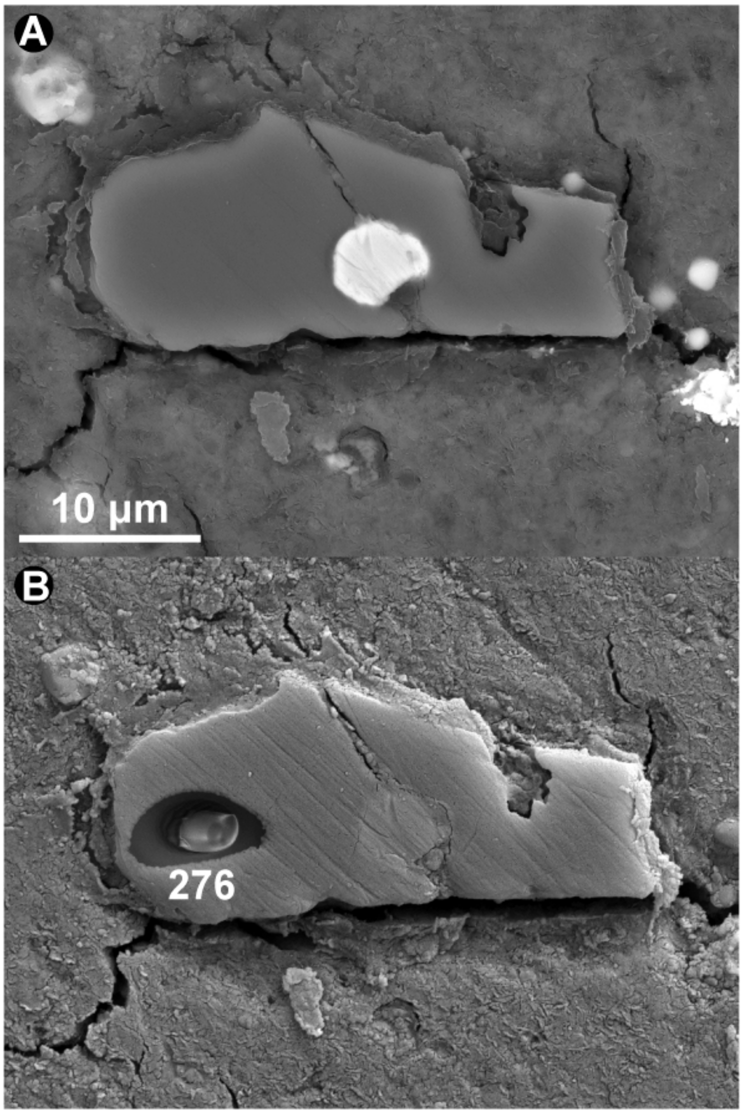


**Fig. S25. Olivine grain in Ivuna (Ivuna *Ol 2*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

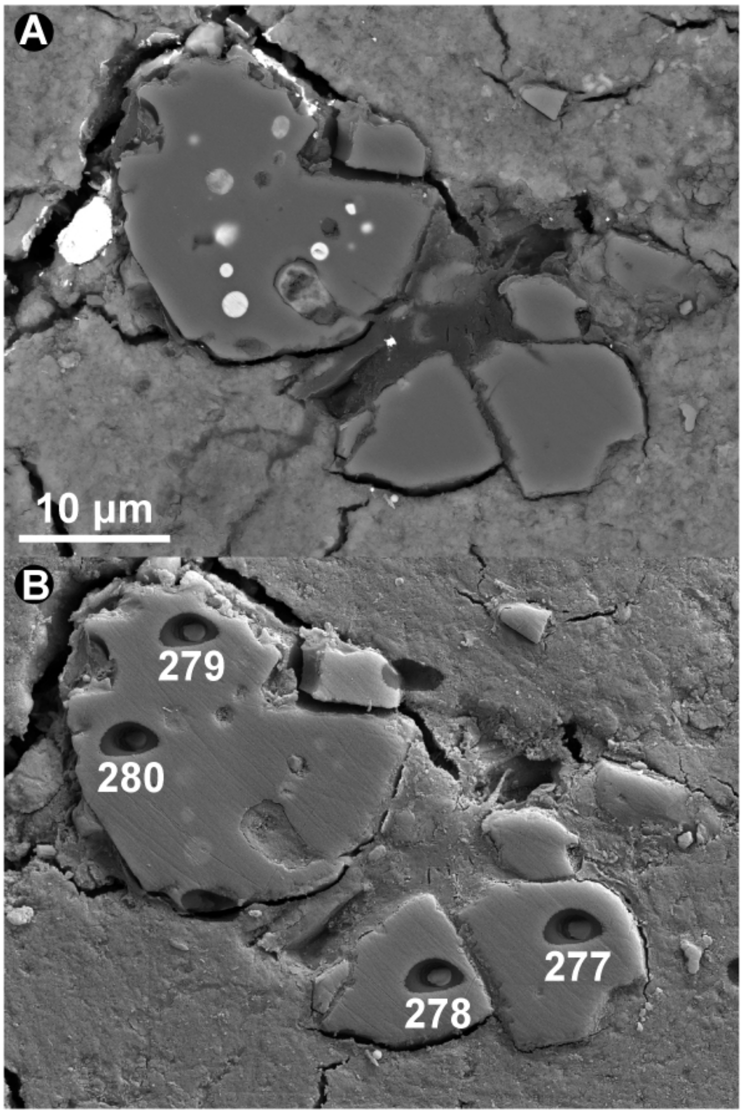


**Fig. S26. Olivine grains in Ivuna (Ivuna *Ol 6-1, 6-2, 6-3*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

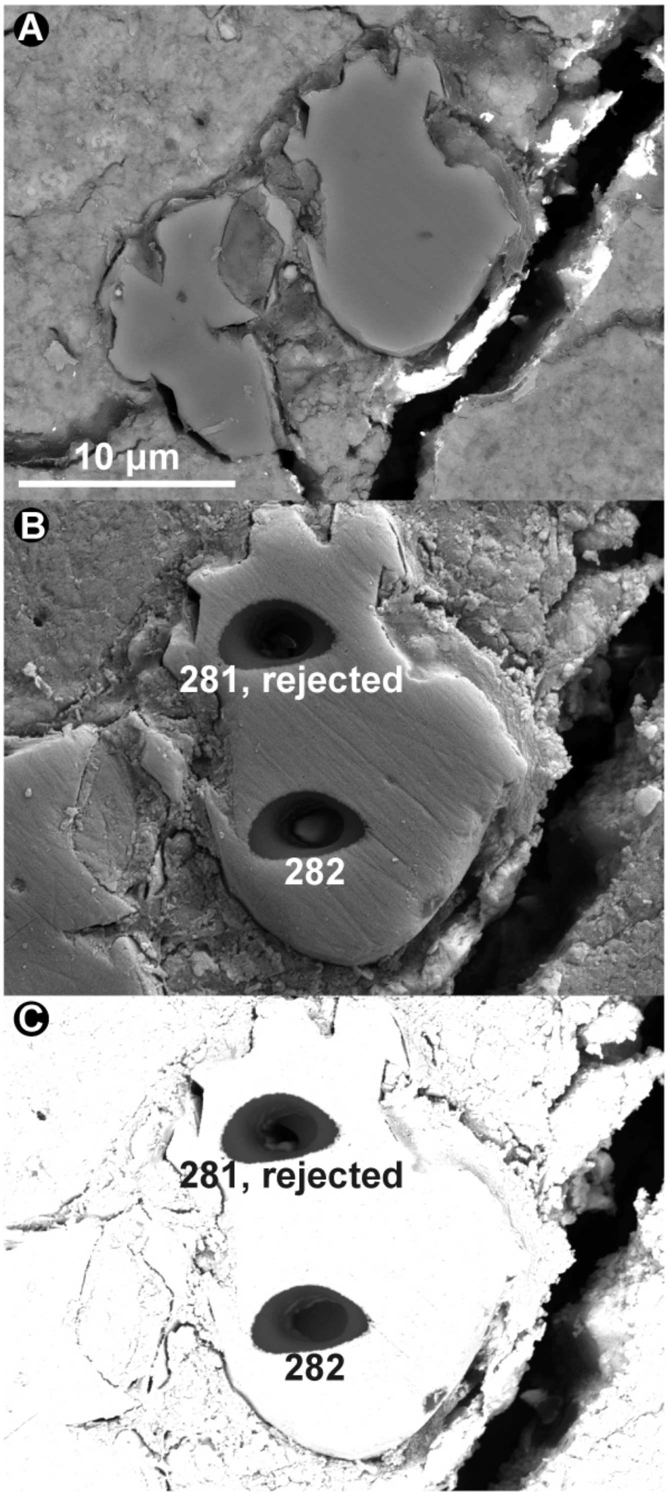


**Fig. S27. Olivine grain in Ivuna (Ivuna *Ol 6-5*). (A)** BSE image taken before SIMS analysis. **(B)** SE and **(C)** BSE images after SIMS analysis. Spot #281 was rejected because that spot contains an inclusion.

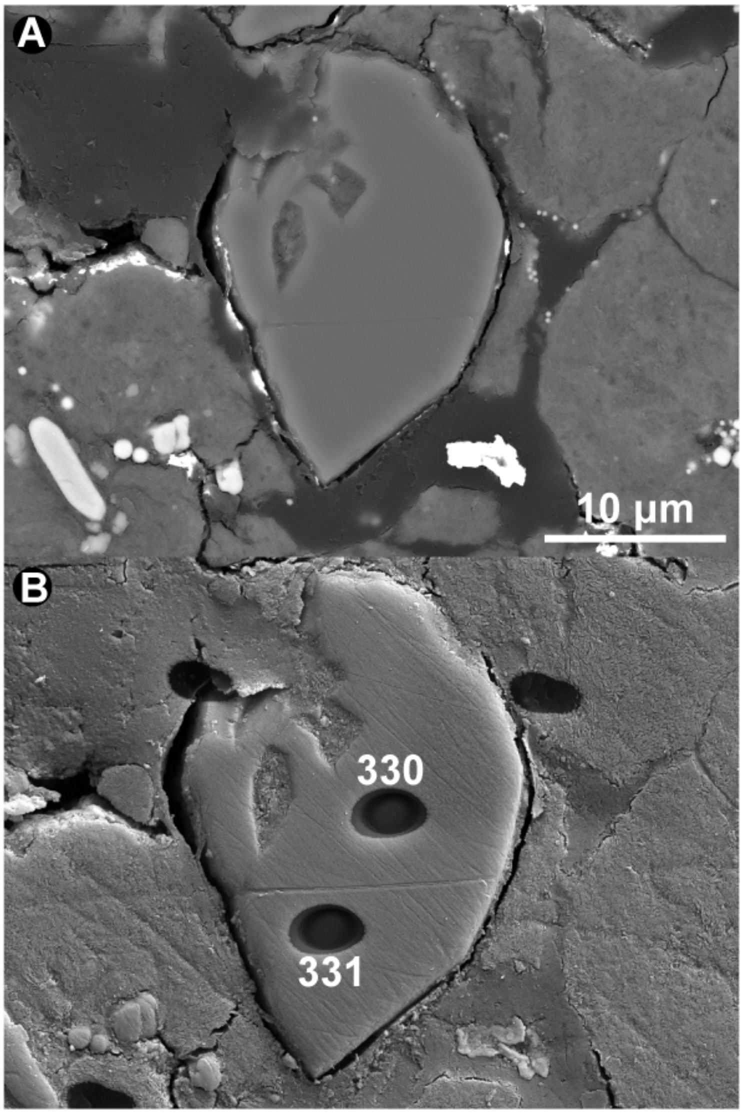

**Fig. S28. Olivine grain in Ivuna (Ivuna *Ol 17*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

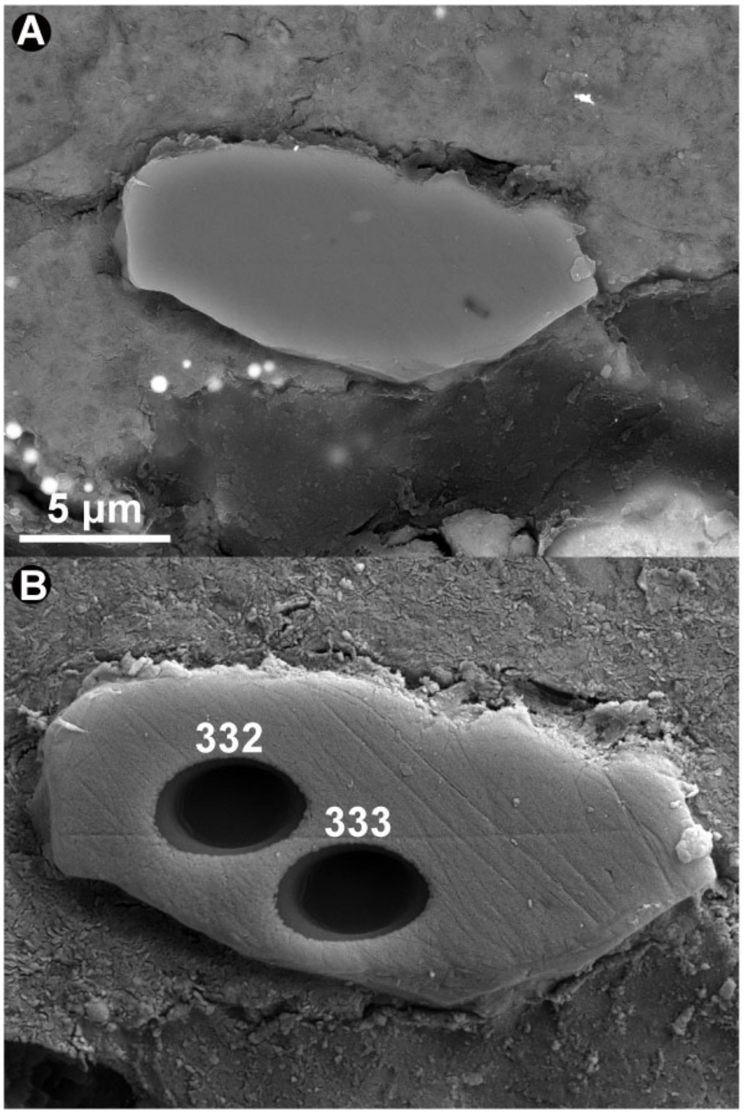


**Fig. S29. Olivine grain in Ivuna (Ivuna *Ol 3-2*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

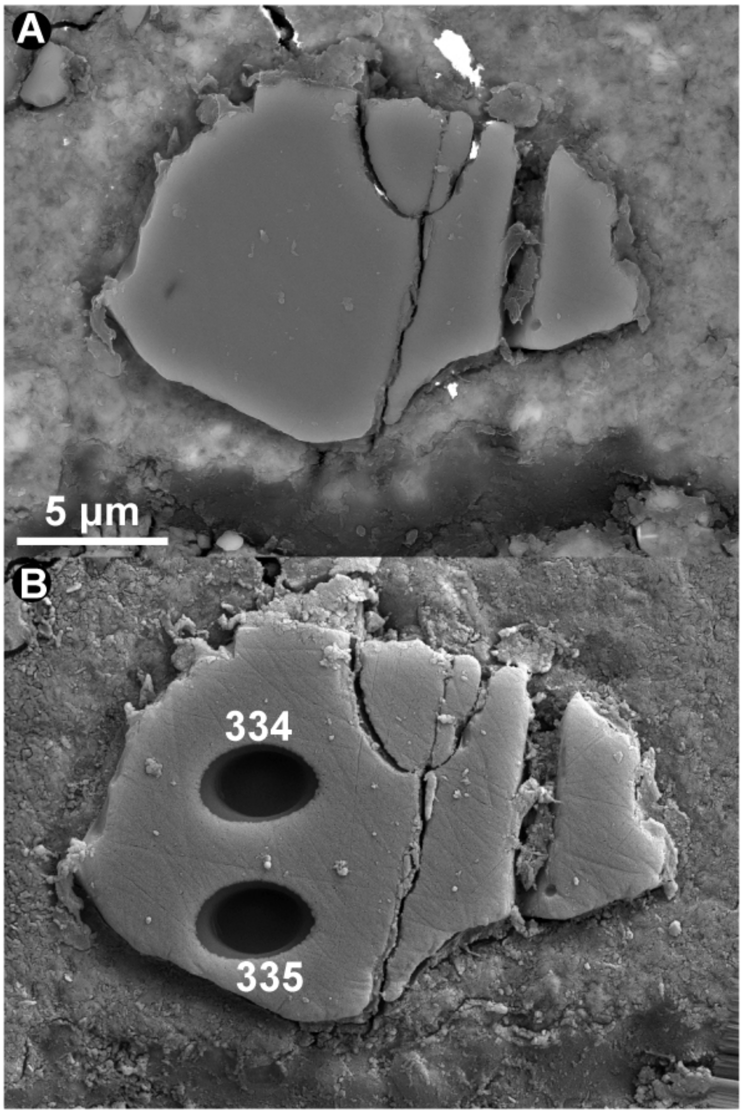


**Fig. S30. Olivine grain in Ivuna (Ivuna *Ol 4-2*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

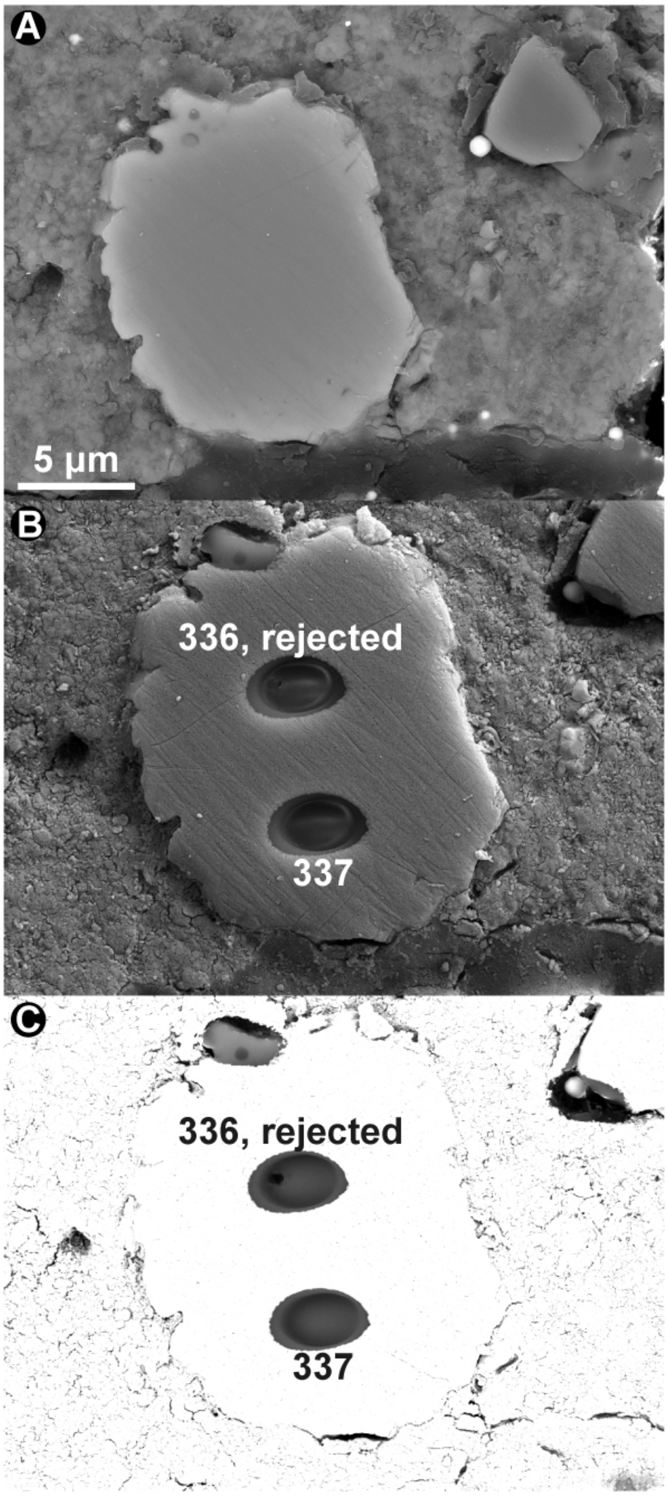


**Fig. S31. Olivine grain in Ivuna (Ivuna *Ol 20*). (A)** BSE image taken before SIMS analysis. **(B)** SE and **(C)** BSE images after SIMS analysis. Spot #336 was rejected because that spot contains an inclusion.

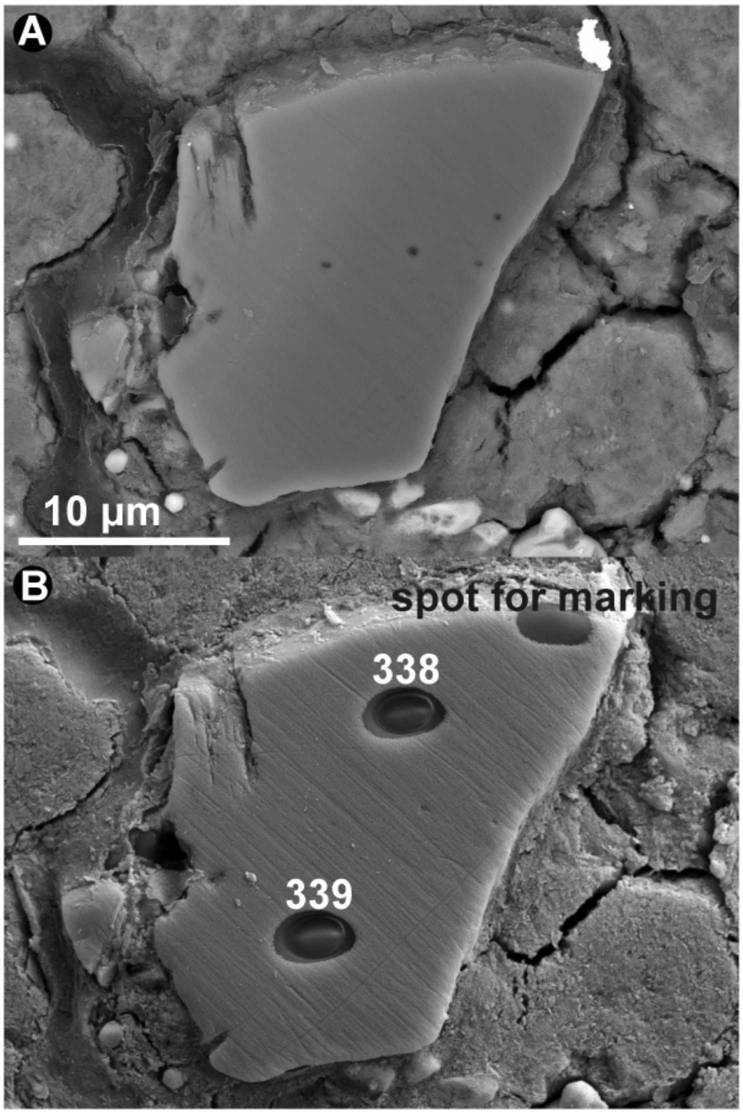


**Fig. S32. Olivine grain in Ivuna (Ivuna *Ol 19*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

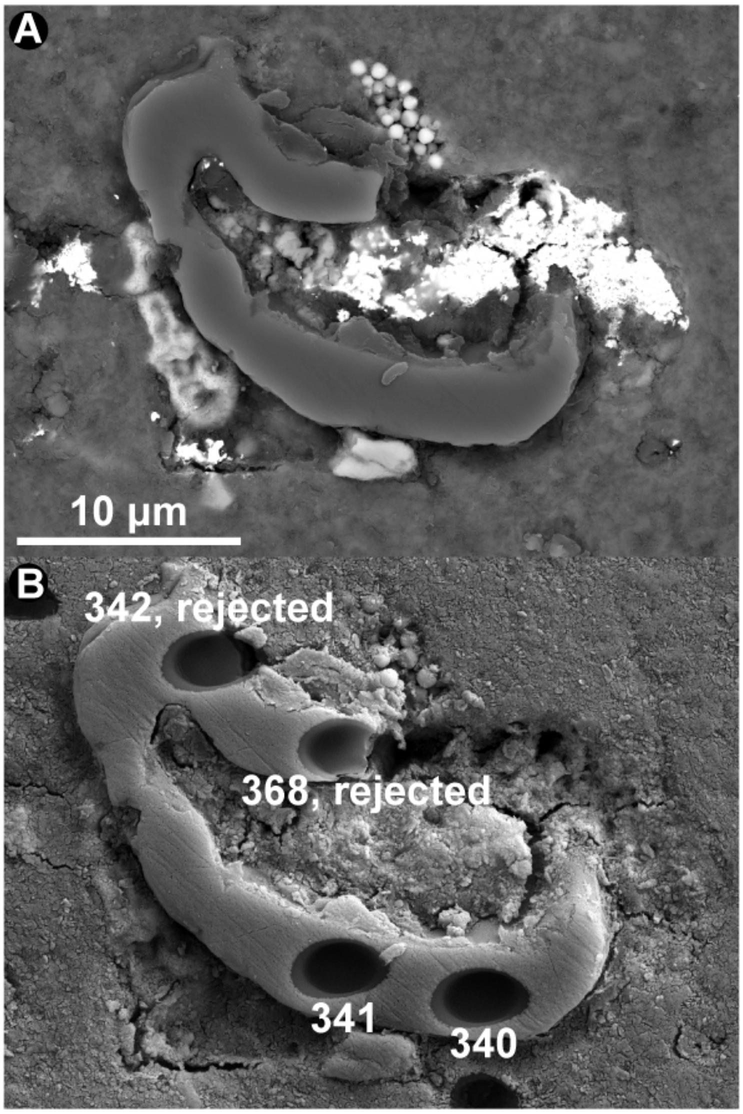


**Fig. S33. Olivine grain in Ivuna (Ivuna *Ol 26*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis. Spots #342 and #368 were rejected because those spots contain matrix minerals.

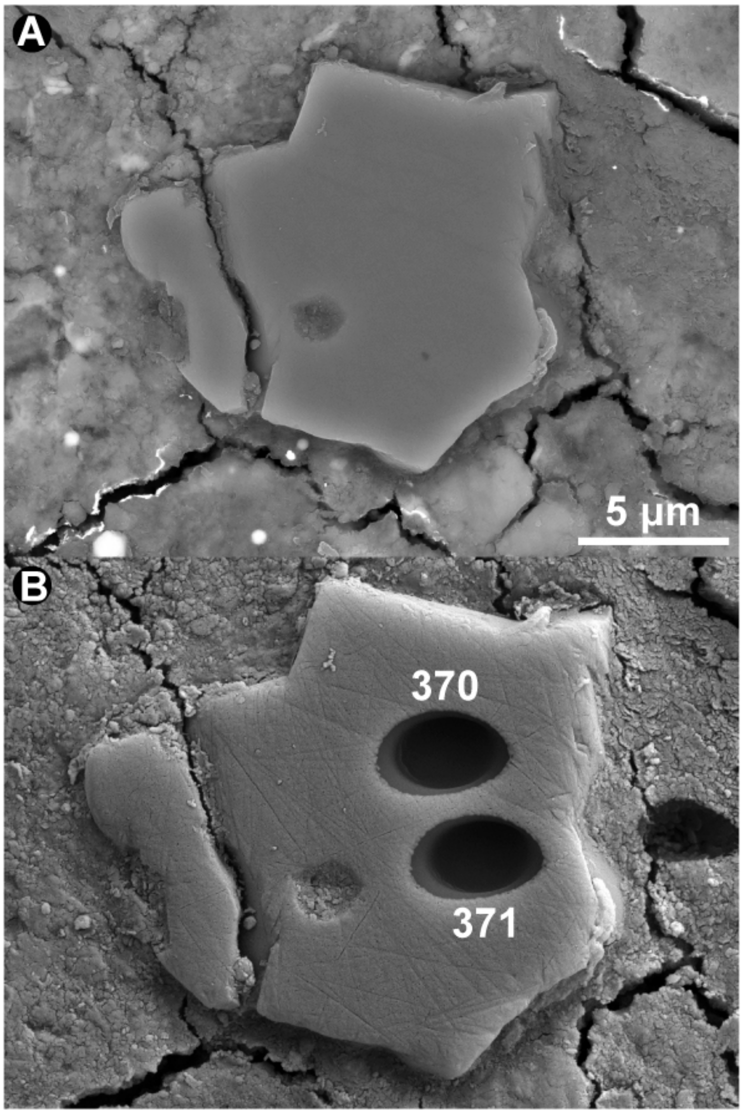


**Fig. S34. Olivine grain in Ivuna (Ivuna *Ol 24*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

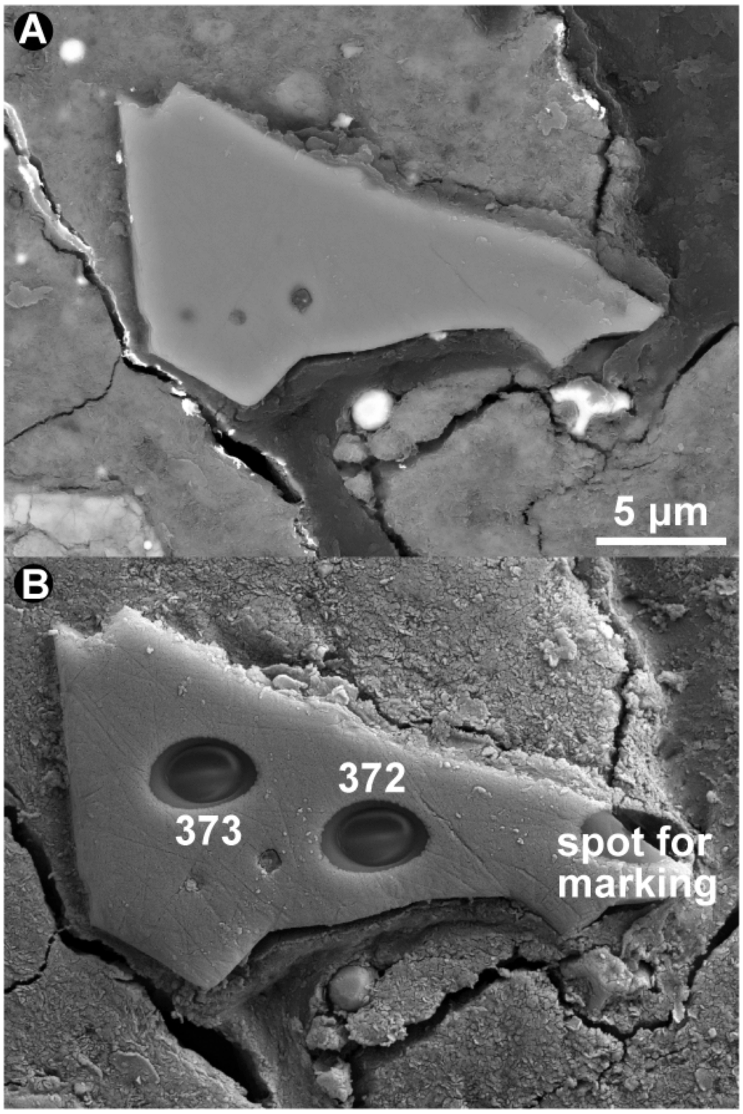


**Fig. S35. Olivine grain in Ivuna (Ivuna *Ol 23*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

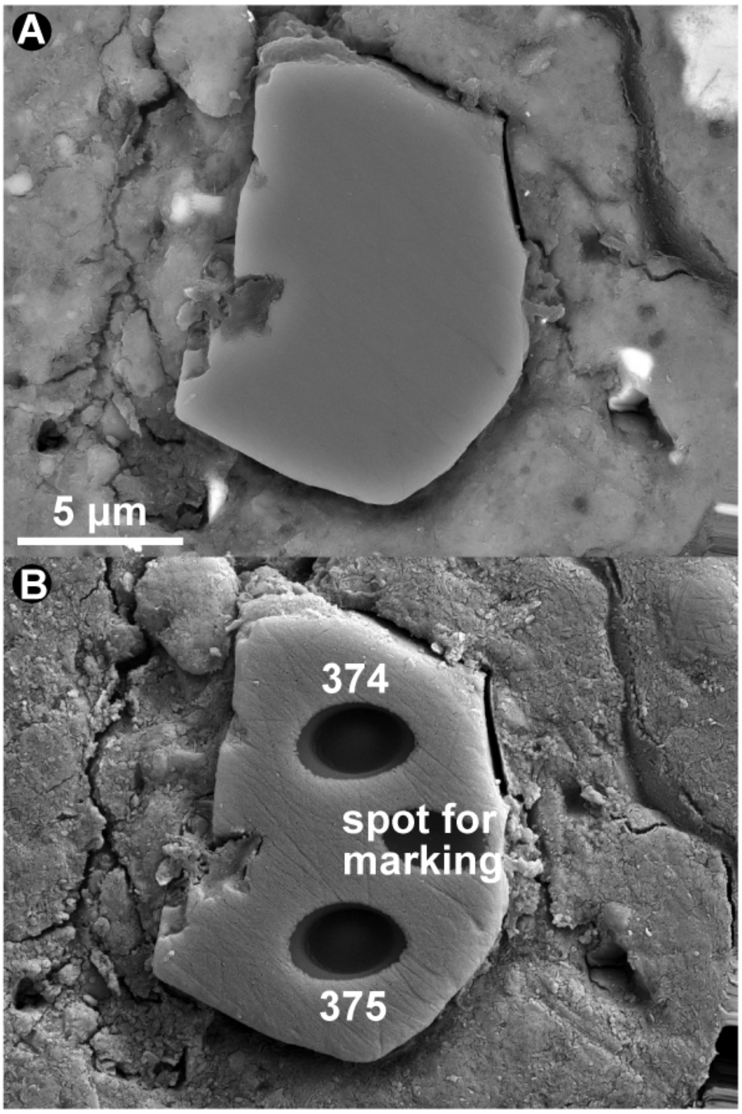


**Fig. S36. Olivine grain in Ivuna (Ivuna *Ol 27*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

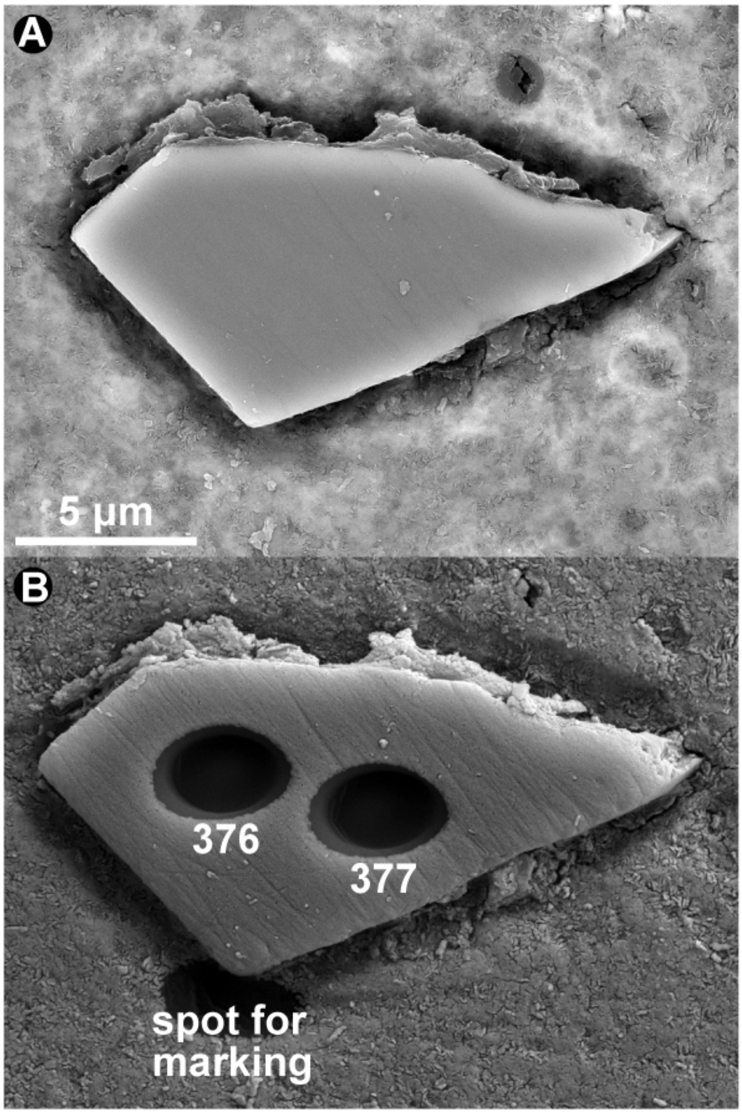


**Fig. S37. Olivine grain in Ivuna (Ivuna *Ol 11*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

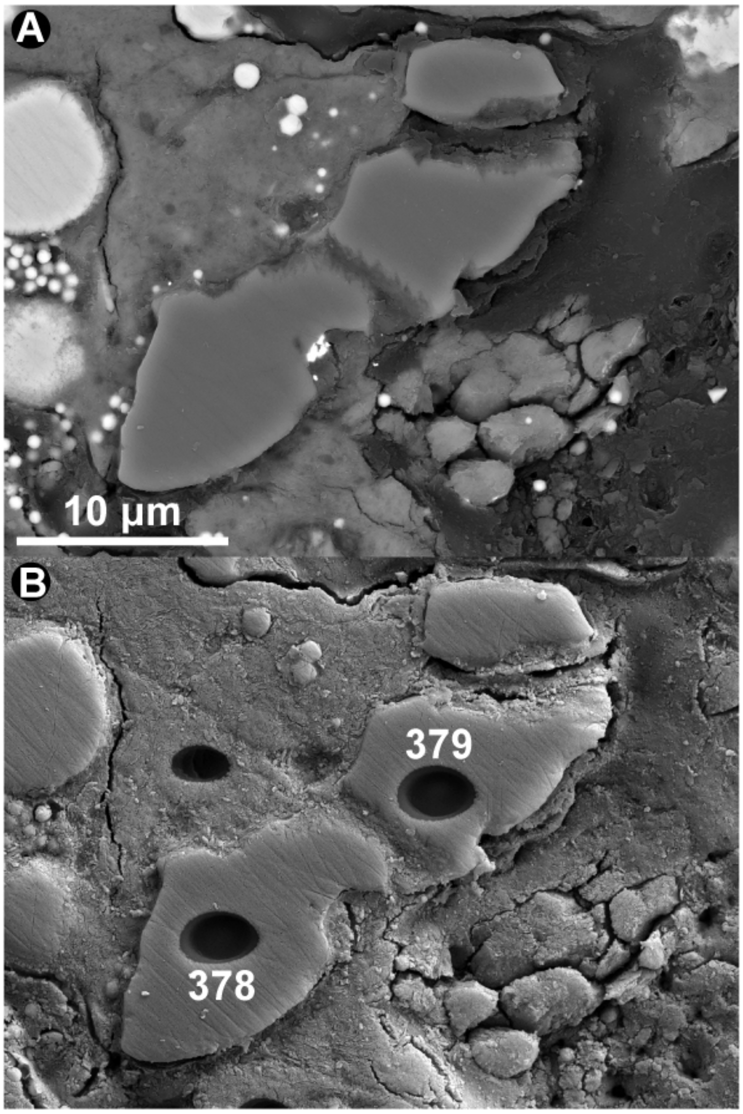


**Fig. S38. Olivine grain in Ivuna (Ivuna *Ol 10*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

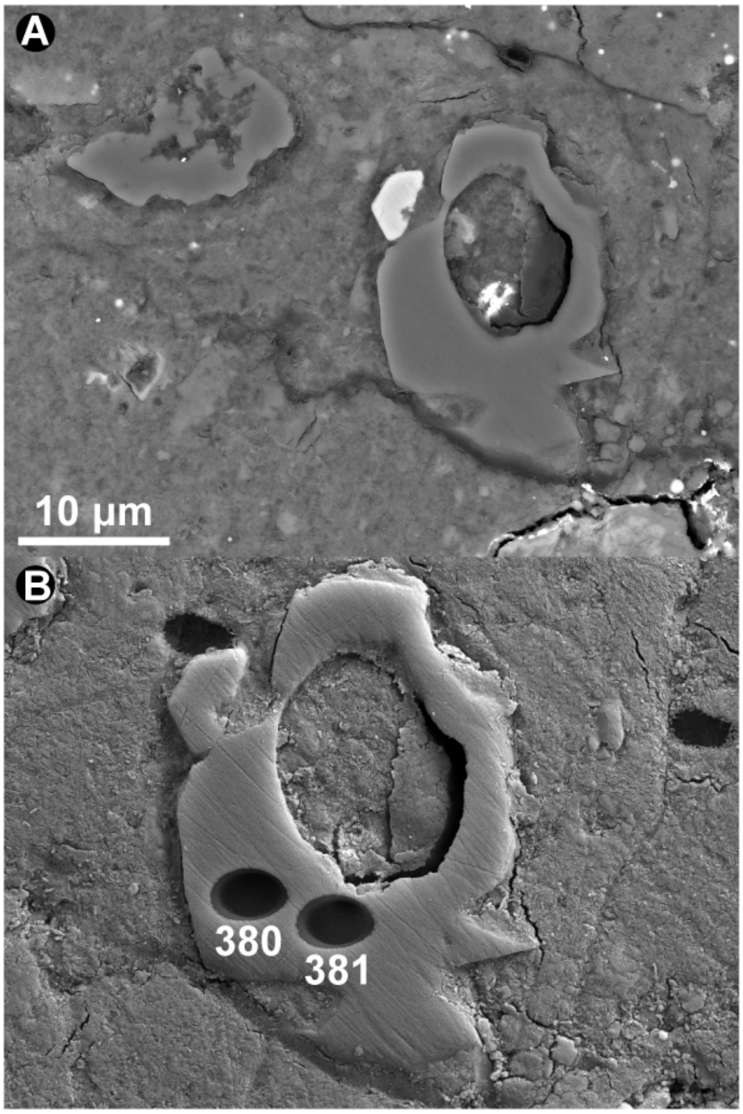


**Fig. S39. Olivine grain in Ivuna (Ivuna *Ol 12*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

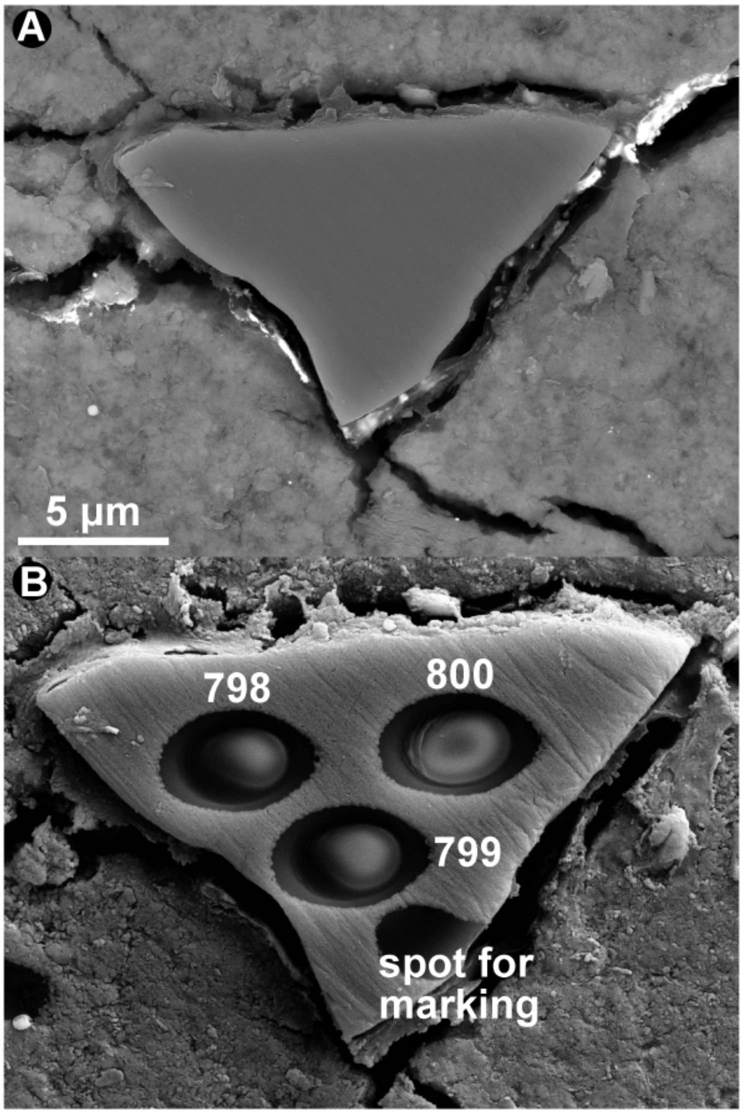


**Fig. S40. Olivine grain in Ivuna (Ivuna *Ol 6-6*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

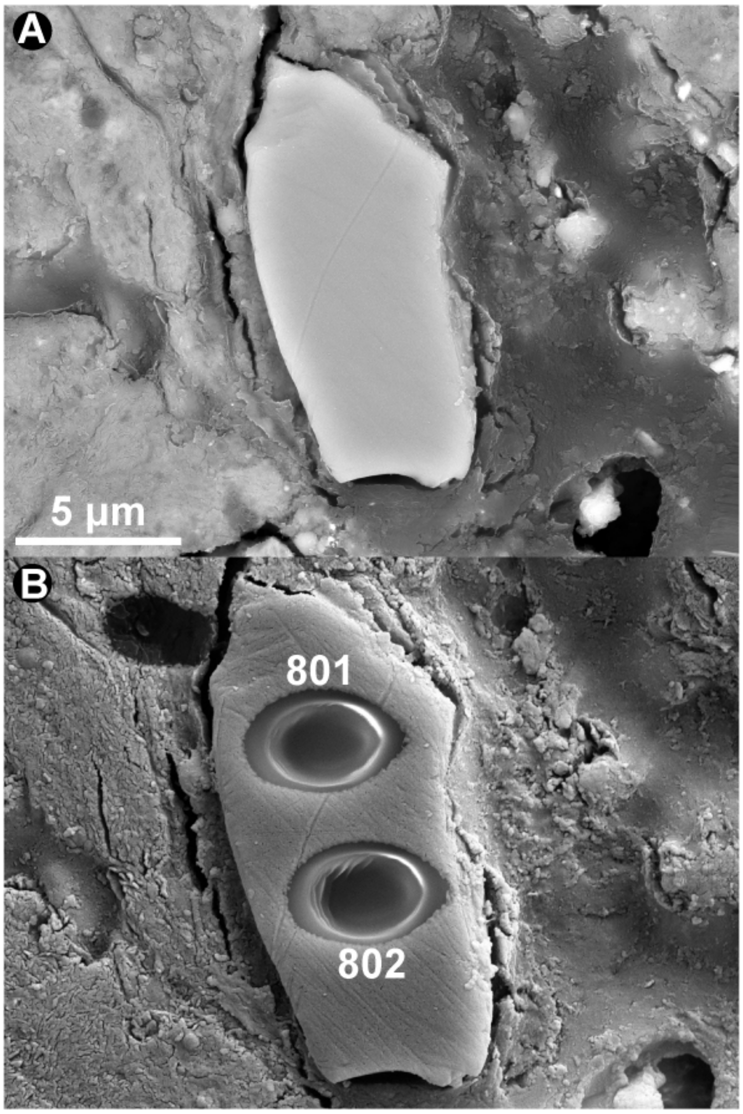


**Fig. S41. Olivine grain in Ivuna (Ivuna *Ol 8-1*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

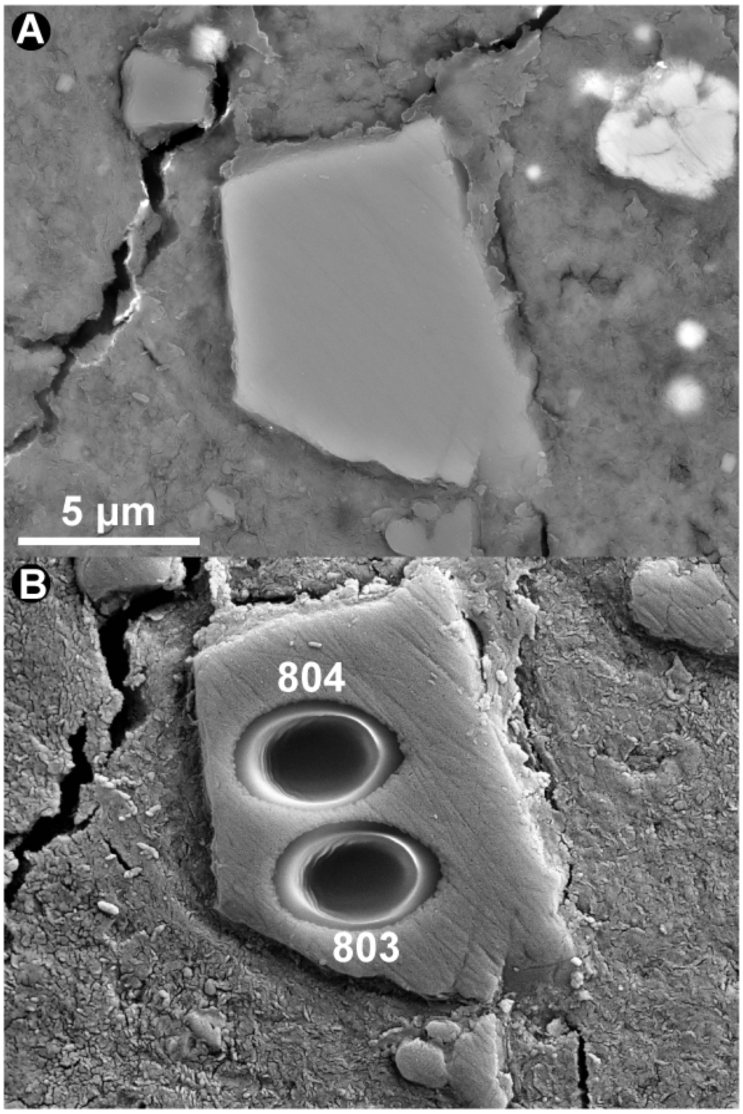


**Fig. S42. Olivine grain in Ivuna (Ivuna *Ol 8-2*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

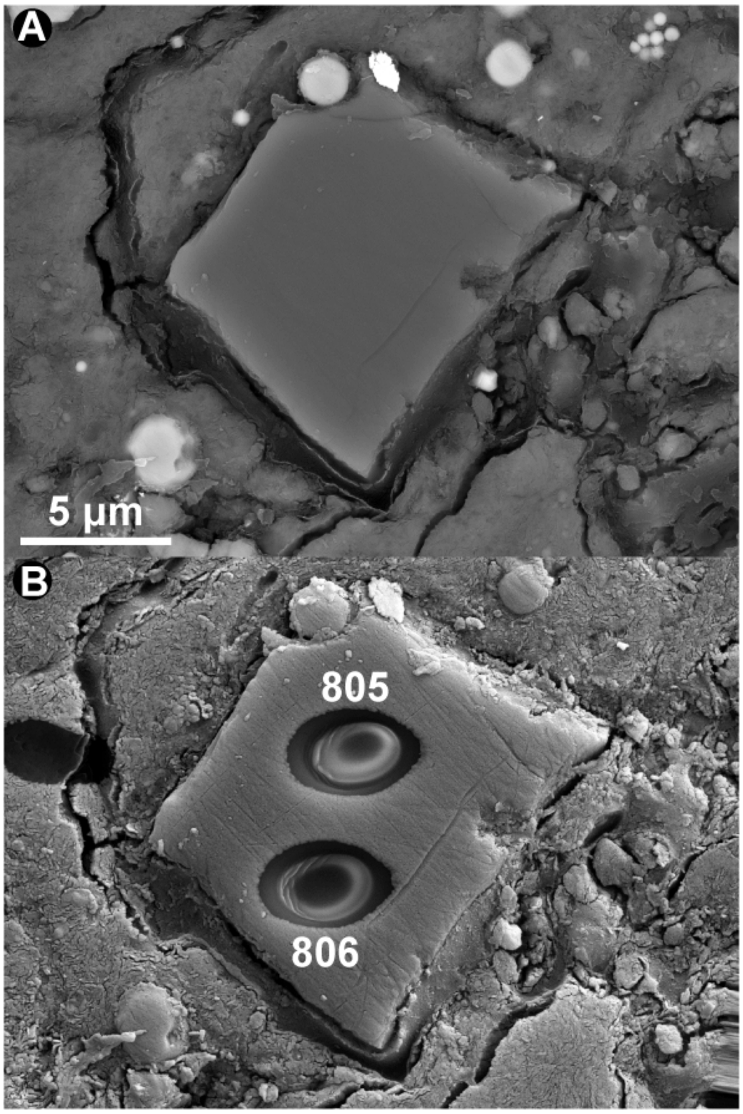


**Fig. S43. Olivine grain in Ivuna (Ivuna *Ol 8-3*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

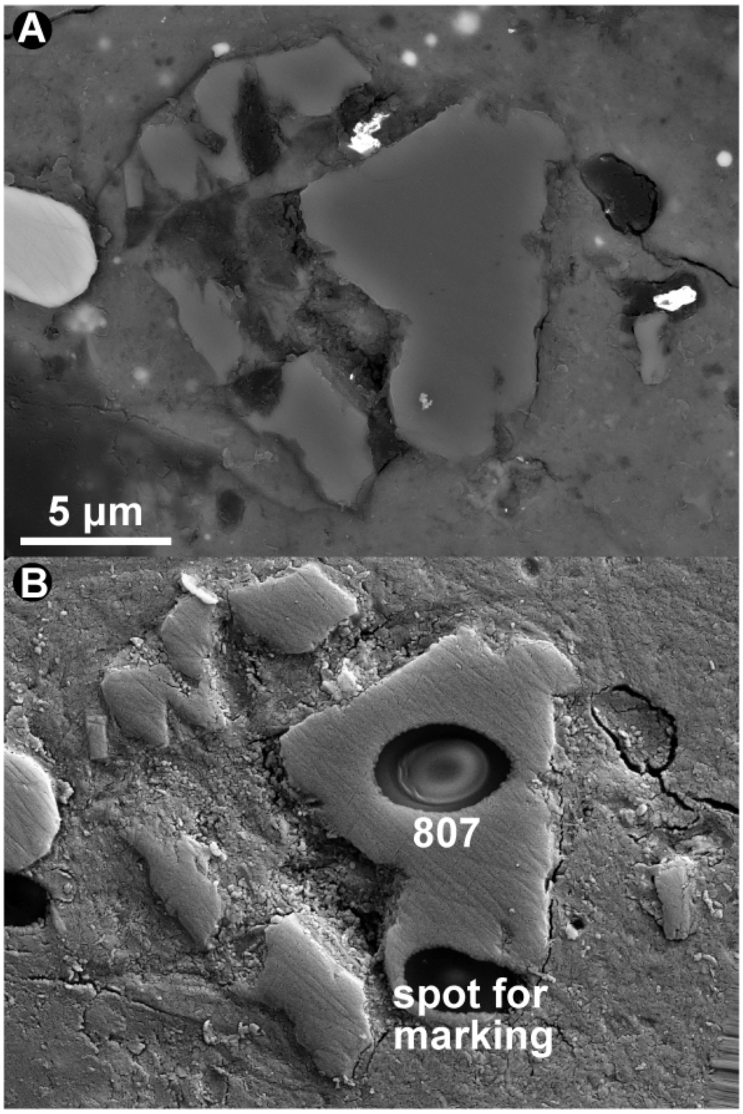


**Fig. S44. Olivine grain in Ivuna (Ivuna *Ol 9*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

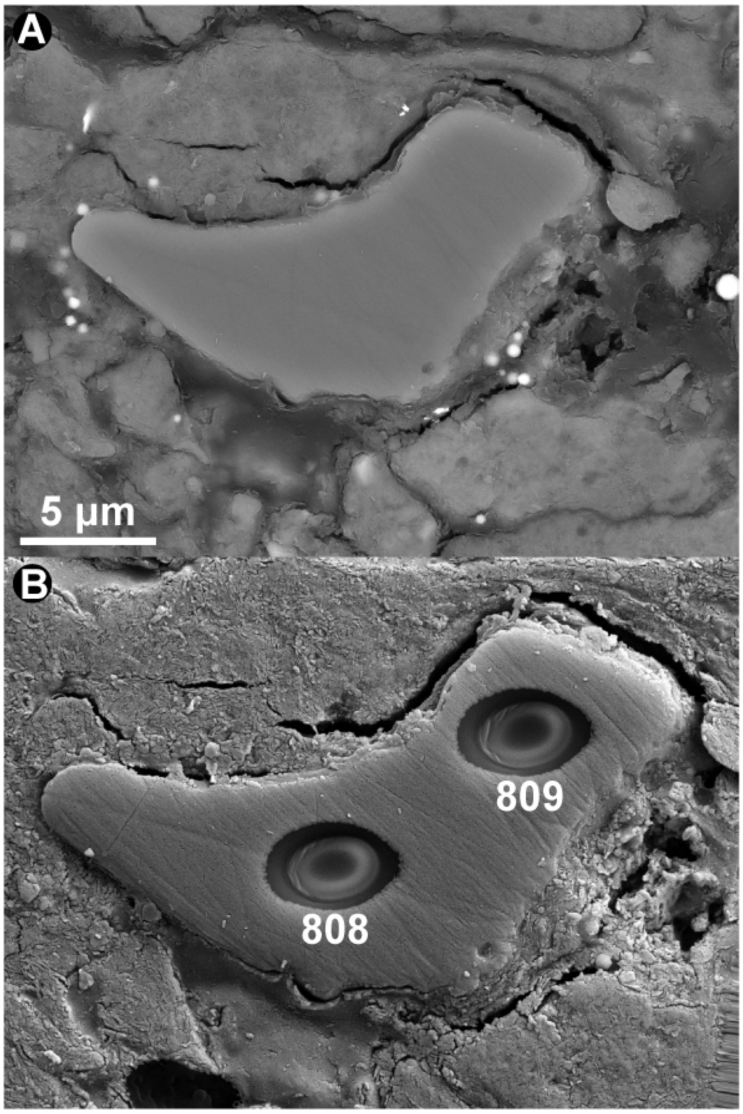


**Fig. S45. Olivine grain in Ivuna (Ivuna *Ol 13*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

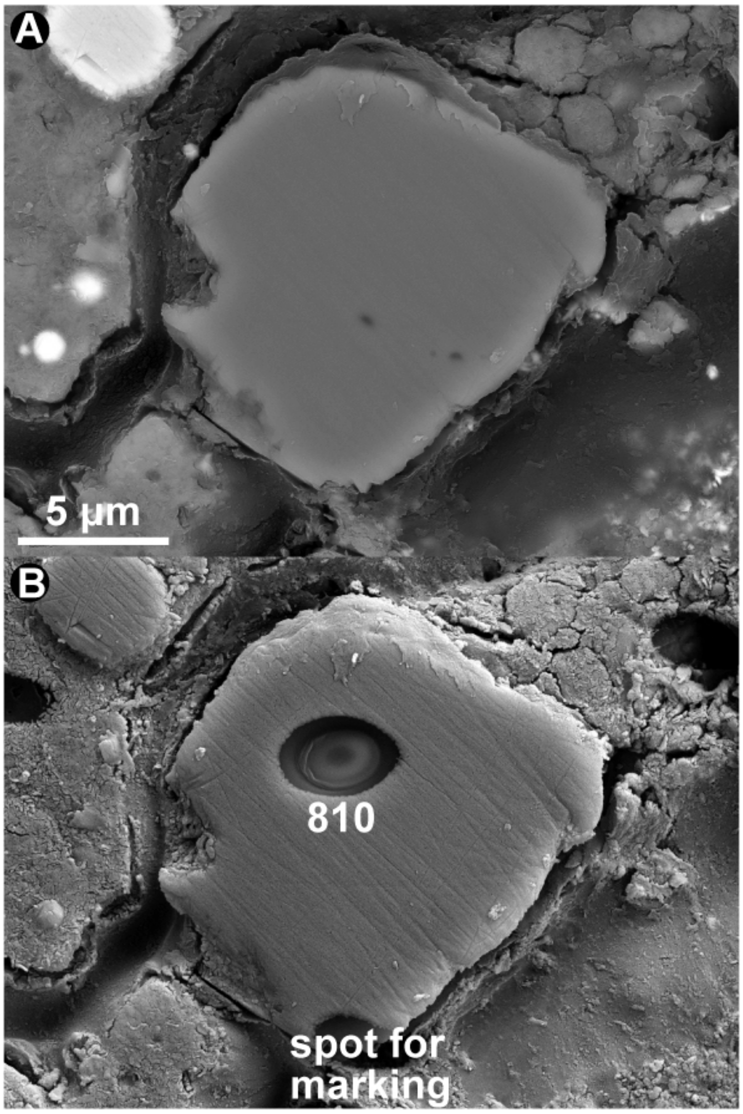


**Fig. S46. Olivine grain in Ivuna (Ivuna *Ol 14*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

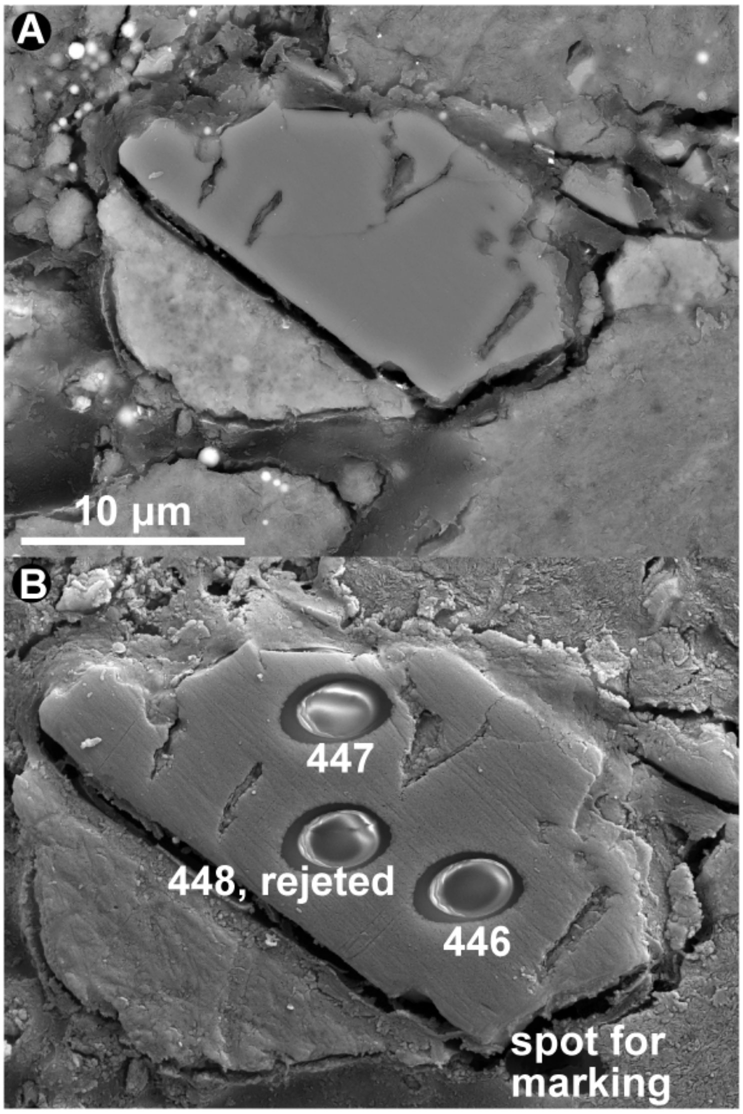


**Fig. S47. Low-Ca pyroxene grain in Ivuna (Ivuna *Px 1*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis. Spot #448 was rejected because that spot contains a crack.

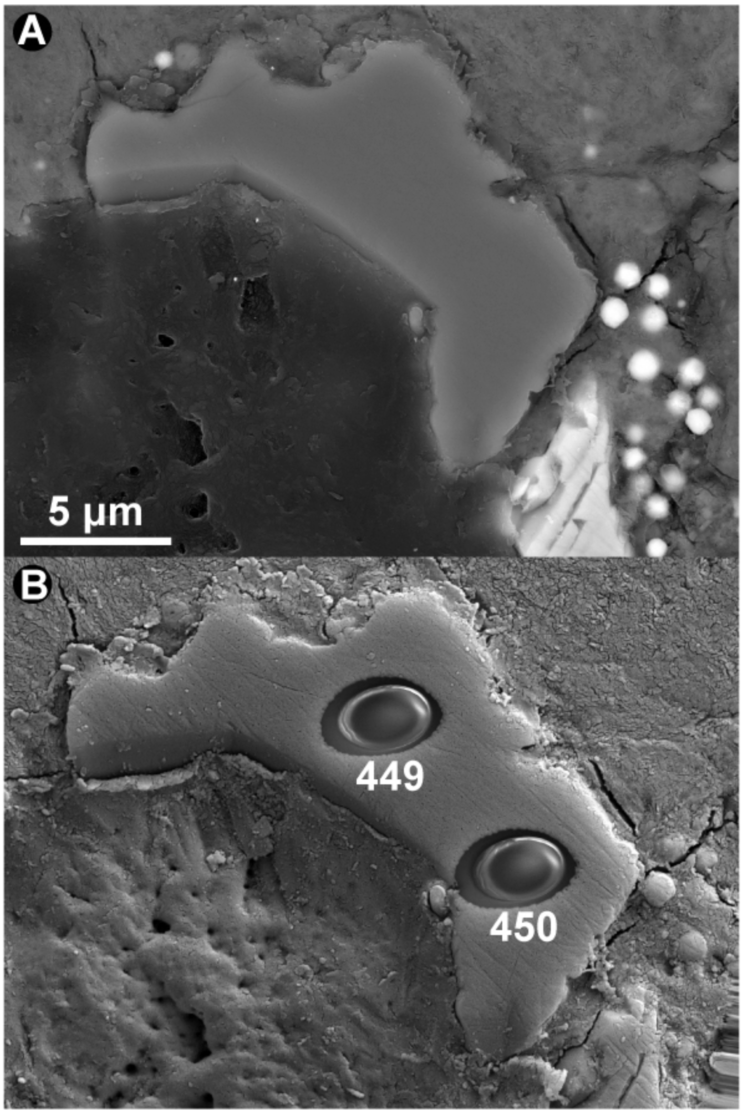

**Fig. S48. Low-Ca pyroxene grain in Ivuna (Ivuna *Px 2*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

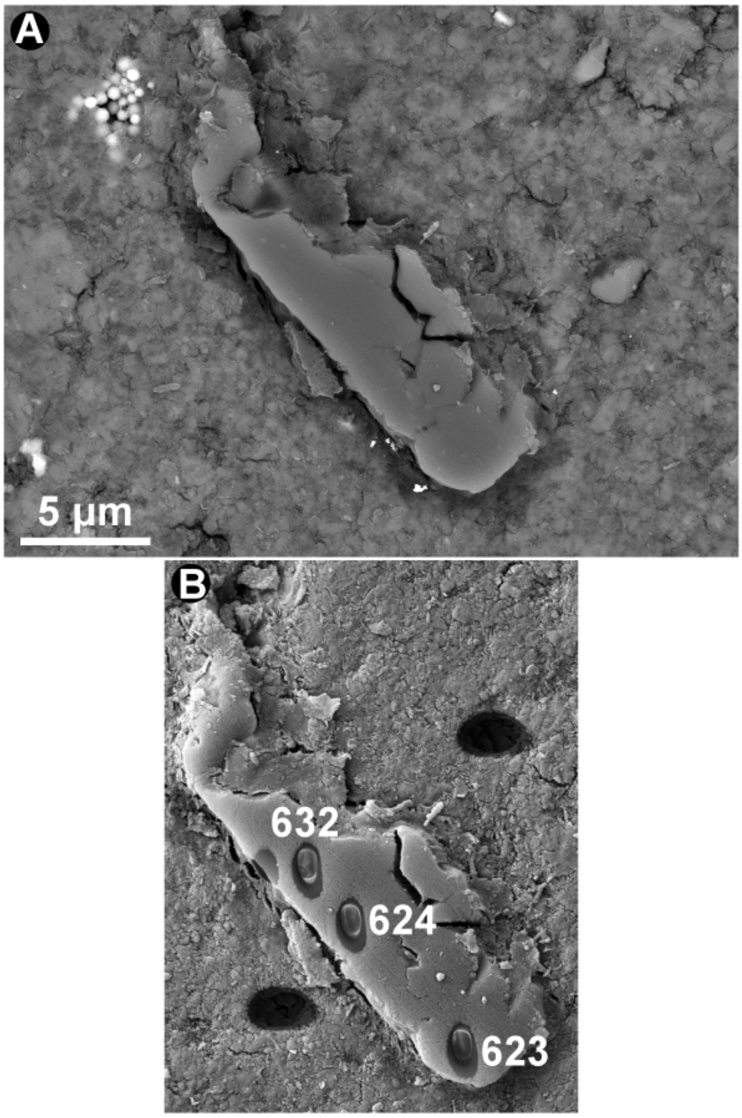


**Fig. S49. Spinel grain in Ivuna (Ivuna *Sp 1*). (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis.

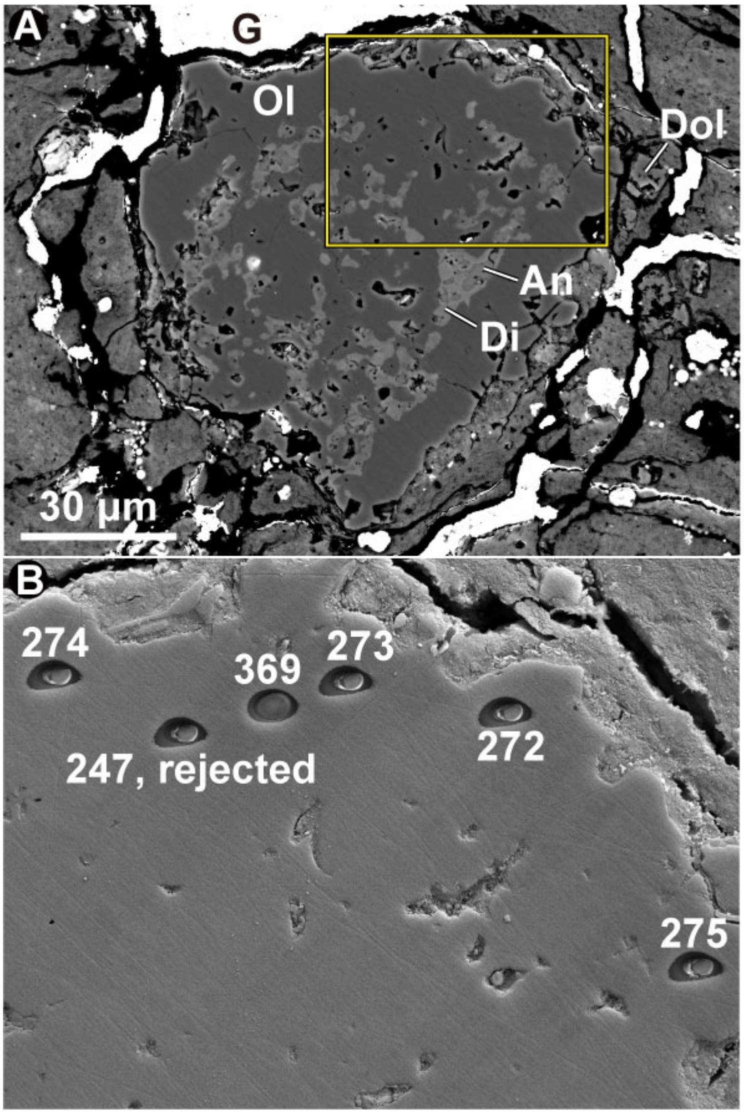


**Fig. S50. Amoeboid olivine aggregate in Ivuna. (A)** BSE image taken before SIMS analysis. **(B)** SE image after SIMS analysis for the area indicated by yellow box in (A). Spot #247 (and the whole analytical session including #247) was rejected because the standard analysis was unstable.

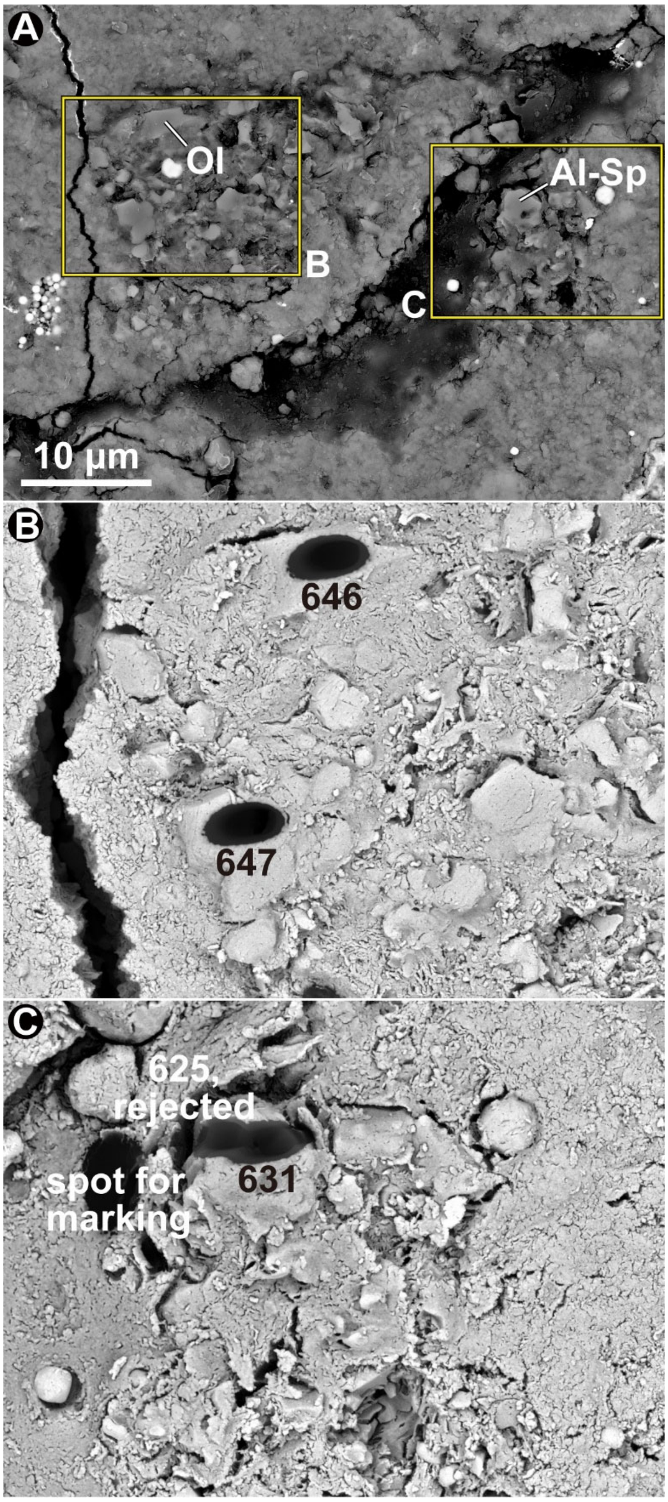


**Fig. S51. Spinel-olivine inclusion in Ivuna. (A)** BSE image taken before SIMS analysis. **(B, C)** SE images after SIMS analysis for the areas indicated by yellow boxes in (A). Spot #625 was rejected because that spot contains resin.

**Table S1. Representative chemical compositions of olivine, low-Ca pyroxene, and spinel in Ryugu and Ivuna.**

| | Ryugu | | | | Ivuna | | | |
|---|---|---|---|---|---|---|---|---|
| wt% | Ol | Px | Al-Sp | Cr-Sp | Ol | Ol | Px | Al-Sp |
| MgO | 55.05 | 38.42 | 28.06 | 6.24 | 54.08 | 27.20 | 38.68 | 26.60 |
| $Al_2O_3$ | bdl | bdl | 69.69 | 22.94 | bdl | bdl | bdl | 66.82 |
| $SiO_2$ | 42.02 | 58.70 | 0.55 | 0.32 | 41.19 | 34.91 | 58.19 | bdl |
| CaO | bdl | 0.44 | bdl | bdl | 0.16 | 0.38 | 0.58 | bdl |
| $TiO_2$ | bdl | bdl | bdl | 0.65 | bdl | bdl | 0.13 | 0.63 |
| $V_2O_5$ | bdl | bdl | 0.36 | 0.66 | bdl | bdl | bdl | bdl |
| $Cr_2O_3$ | 0.31 | 0.56 | 0.30 | 39.19 | 0.56 | 0.31 | 0.50 | 2.16 |
| MnO | 0.51 | 0.16 | bdl | bdl | 1.35 | 0.44 | bdl | 0.42 |
| FeO | 1.95 | 2.32 | 1.55 | 28.46 | 2.25 | 35.15 | 1.36 | 2.08 |
| Total | 99.85 | 100.61 | 100.51 | 98.47 | 99.58 | 98.40 | 99.45 | 98.70 |

| Cations | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mg | 1.95 | 0.97 | 0.99 | 0.30 | 1.93 | 1.15 | 0.98 | 0.97 |
| Al | bdl | bdl | 1.95 | 0.88 | bdl | bdl | bdl | 1.93 |
| Si | 1.00 | 0.99 | 0.01 | 0.01 | 0.99 | 0.99 | 0.99 | bdl |
| Ca | bdl | 0.01 | bdl | bdl | 0.00 | 0.01 | 0.01 | bdl |
| Ti | bdl | bdl | bdl | 0.02 | bdl | bdl | 0.00 | 0.01 |
| V | bdl | bdl | 0.01 | 0.01 | bdl | bdl | bdl | bdl |
| Cr | 0.01 | 0.01 | 0.01 | 1.01 | 0.01 | 0.01 | 0.01 | 0.04 |
| Mn | 0.01 | 0.00 | bdl | bdl | 0.03 | 0.01 | bdl | 0.01 |
| Fe | 0.04 | 0.03 | 0.03 | 0.78 | 0.05 | 0.83 | 0.02 | 0.04 |
| Total | 3.00 | 2.01 | 3.00 | 3.01 | 3.01 | 3.01 | 2.01 | 3.00 |
| per oxygen | 4 | 3 | 4 | 4 | 4 | 4 | 3 | 4 |

Al-Sp: Mg-Al spinel, Cr-Sp: Cr-spinel, Ol: olivine, Px: low-Ca pyroxene.
bdl = below detection limit.

**Table S2. Oxygen-isotope (‰) and chemical (wt%) compositions of olivine, low-Ca pyroxene, and spinel in Ryugu.**

| grain ID | grain# | spot# | $\delta^{17}O$ | 2σ | $\delta^{18}O$ | 2σ | $\Delta^{17}O$ | 2σ | Mg# | CaO | $Cr_2O_3$ | MnO | FeO |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Olivine* | | | | | | | | | | | | | |
| *FCEMEM analysis (~30 pA)* | | | | | | | | | | | | | |
| *Ol 5-1* | 1 | 393 | -47.7 | 1.5 | -46.4 | 0.8 | -23.5 | 1.5 | 98.7 | 0.09 | 0.30 | 0.53 | 1.34 |
| | 1 | 394 | -47.2 | 1.4 | -45.7 | 0.8 | -23.5 | 1.4 | 98.4 | 0.08 | 0.35 | 0.50 | 1.58 |
| | 1 | 395 | -47.8 | 1.4 | -45.4 | 0.8 | -24.2 | 1.6 | 98.1 | 0.10 | 0.31 | 0.51 | 1.95 |
| Average | | | -47.6 | 1.4 | -45.8 | 0.8 | -23.7 | 1.5 | 98.4 | 0.09 | 0.32 | 0.51 | 1.62 |
| *Ol 5-2* | 2 | 396 | -8.2 | 1.4 | -5.5 | 0.8 | -5.4 | 1.4 | 91.0 | 0.21 | 0.31 | 0.14 | 8.28 |
| | 2 | 397 | -5.4 | 1.5 | -4.0 | 0.8 | -3.3 | 1.5 | 83.0 | 0.21 | 0.21 | 0.21 | 19.12 |
| Average | | | -6.8 | 1.4 | -4.7 | 0.8 | -4.4 | 1.5 | 87.0 | 0.21 | 0.26 | 0.18 | 13.70 |
| *Ol 8* | 3 | 398 | -6.7 | 1.5 | -3.7 | 0.8 | -4.8 | 1.5 | 97.9 | 0.20 | 0.55 | 0.16 | 1.91 |
| | 3 | 399 | -6.8 | 1.4 | -4.5 | 0.8 | -4.4 | 1.5 | 98.1 | 0.21 | 0.57 | 0.17 | 1.87 |
| Average | | | -6.8 | 1.5 | -4.1 | 0.8 | -4.6 | 1.5 | 98.0 | 0.21 | 0.56 | 0.17 | 1.89 |
| *Ol 7* | 4 | 400 | -48.0 | 1.6 | -45.0 | 0.8 | -24.5 | 1.6 | 98.6 | bdl | 0.39 | 0.15 | 1.37 |
| | 4 | 401 | -46.1 | 1.5 | -46.7 | 0.8 | -21.8 | 1.5 | 98.7 | bdl | 0.32 | 0.19 | 1.29 |
| Average | | | -47.0 | 1.5 | -45.9 | 0.8 | -23.2 | 1.5 | 98.7 | | 0.36 | 0.17 | 1.33 |
| *Ol 1-1* | 5 | 402 | -7.1 | 1.7 | -4.3 | 0.8 | -4.9 | 1.8 | 90.9 | 0.15 | 0.20 | 0.53 | 7.99 |
| | 5 | 403 | -9.1 | 1.5 | -5.5 | 0.8 | -6.2 | 1.6 | 91.0 | 0.12 | 0.23 | 0.56 | 7.91 |
| Average | | | -8.1 | 1.6 | -4.9 | 0.8 | -5.5 | 1.7 | 90.9 | 0.14 | 0.22 | 0.55 | 7.95 |
| *Ol 1-2* | 6 | 404 | -47.6 | 1.6 | -45.5 | 0.8 | -23.9 | 1.7 | 98.7 | 0.08 | 0.32 | 0.22 | 1.26 |
| *Low-Ca pyroxene* | | | | | | | | | | | | | |
| *FCEMEM analysis (~3 pA)* | | | | | | | | | | | | | |
| *Px 1* | 1 | 640 | -7.3 | 3.4 | -5.7 | 2.4 | -4.3 | 3.4 | 96.7 | 0.44 | 0.56 | 0.16 | 2.32 |
| *Mg-Al spinel* | | | | | | | | | | | | | |
| *FCEMEM analysis (~3 pA)* | | | | | | | | | | | | | |
| *Sp 1* | 1 | 633 | -46.2 | 2.7 | -44.9 | 1.9 | -22.9 | 3.0 | 97.0 | bdl | 0.30 | bdl | 1.55 |
| *Cr-spinel* | | | | | | | | | | | | | |
| *FCEMEM analysis (~30 pA)* | | | | | | | | | | | | | |
| *Cr-Sp 1** | 1 | 478 | -1.4 | 1.4 | 0.7 | 1.0 | -1.8 | 1.4 | 28.1 | bdl | 39.19 | bdl | 28.46 |

Mg# = [Mg/(Mg+Fe)] × 100 in mol%

bdl = below detection limit.

Counting detection limits (3 sigma) for CaO and MnO are 0.06 wt% and 0.09 wt%, respectively.

*Cr#, [Cr/(Cr+Al)] × 100 in mol%, is 53.4.

**Table S3. Oxygen-isotope (‰) and chemical (wt%) compositions of olivine, low-Ca pyroxene, and spinel in Ivuna.**

| grain ID | grain# | spot# | $\delta^{17}O$ | 2σ | $\delta^{18}O$ | 2σ | $\Delta^{17}O$ | 2σ | Mg# | CaO | $Cr_2O_3$ | MnO | FeO |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Olivine* | | | | | | | | | | | | | |
| *3FC analysis (~1 nA)* | | | | | | | | | | | | | |
| *Ol 3-1* | 1 | 179 | -7.5 | 0.6 | -4.2 | 0.3 | -5.3 | 0.6 | 98.5 | 0.20 | 0.47 | 0.13 | 1.58 |
| *Ol 4-1* | 2 | 180 | -7.6 | 0.6 | -4.3 | 0.3 | -5.4 | 0.6 | 98.5 | 0.16 | 0.49 | 0.13 | 1.55 |
| *Ol 6-4* | 3 | 181 | -10.3 | 0.6 | -7.1 | 0.4 | -6.6 | 0.6 | 98.6 | 0.32 | 0.34 | bdl | 1.43 |
| *Ol 25* | 4 | 182 | -7.5 | 0.6 | -4.8 | 0.3 | -5.0 | 0.6 | 98.4 | 0.40 | 0.27 | 0.13 | 1.67 |
| *FCEMEM analysis (~30 pA)* | | | | | | | | | | | | | |
| *AOA* | | 272 | -47.6 | 1.8 | -46.4 | 0.8 | -23.4 | 1.9 | 99.1 | 0.10 | 0.26 | 0.27 | 0.90 |
| *AOA* | | 273 | -47.7 | 1.8 | -46.5 | 0.8 | -23.5 | 1.9 | 99.2 | 0.08 | 0.25 | 0.23 | 0.86 |
| *AOA* | | 274 | -47.9 | 1.8 | -46.5 | 0.8 | -23.7 | 1.9 | 99.1 | 0.08 | 0.37 | 0.32 | 0.91 |
| *AOA* | | 275 | -47.5 | 1.8 | -45.6 | 0.8 | -23.8 | 1.9 | 99.0 | 0.10 | 0.35 | 0.45 | 0.99 |
| *AOA* | | 369 | -47.1 | 2.0 | -45.4 | 1.1 | -23.5 | 2.0 | 99.2 | 0.17 | 0.21 | 0.23 | 0.86 |
| Average | | | -47.6 | 1.8 | -46.1 | 0.9 | -23.6 | 1.9 | 99.1 | 0.11 | 0.29 | 0.30 | 0.90 |
| *Ol 2* | 5 | 276 | -9.4 | 1.8 | -7.0 | 0.8 | -5.7 | 1.9 | 96.3 | 0.41 | 0.26 | 0.23 | 3.71 |
| *Ol 6-3* | 6 | 277 | -7.6 | 1.8 | -6.4 | 0.8 | -4.3 | 1.9 | 98.4 | 0.19 | 0.38 | 0.17 | 1.62 |
| *Ol 6-2* | 7 | 278 | -8.2 | 1.8 | -5.3 | 0.8 | -5.4 | 1.9 | 98.4 | 0.21 | 0.47 | 0.13 | 1.67 |
| *Ol 6-1* | 8 | 279 | -10.9 | 1.8 | -7.7 | 0.8 | -6.9 | 1.9 | 98.4 | 0.19 | 0.44 | 0.11 | 1.67 |
| | 8 | 280 | -8.7 | 1.8 | -6.2 | 0.8 | -5.5 | 1.9 | 98.3 | 0.20 | 0.48 | 0.15 | 1.74 |
| Average | | | -9.8 | 1.8 | -6.9 | 0.8 | -6.2 | 1.9 | 98.4 | 0.20 | 0.46 | 0.13 | 1.71 |
| *Ol 6-5* | 9 | 282 | -47.0 | 1.8 | -46.0 | 0.8 | -23.1 | 1.9 | 98.7 | 0.07 | 0.30 | 0.63 | 1.28 |
| *Ol 17* | 10 | 330 | -8.1 | 1.8 | -4.4 | 1.4 | -5.8 | 2.0 | 98.3 | 0.22 | 0.55 | 0.15 | 1.73 |
| | 10 | 331 | -7.4 | 1.8 | -3.7 | 1.4 | -5.5 | 2.0 | 98.2 | 0.24 | 0.54 | 0.15 | 1.76 |
| Average | | | -7.8 | 1.8 | -4.1 | 1.4 | -5.6 | 2.0 | 98.2 | 0.23 | 0.55 | 0.15 | 1.75 |
| *Ol 3-2* | 11 | 332 | -48.7 | 1.8 | -49.2 | 1.4 | -23.1 | 2.0 | 98.8 | 0.10 | 0.35 | 0.87 | 1.26 |
| | 11 | 333 | -49.0 | 1.8 | -49.6 | 1.4 | -23.2 | 2.0 | 98.7 | 0.06 | 0.33 | 0.82 | 1.27 |
| Average | | | -48.8 | 1.8 | -49.4 | 1.4 | -23.1 | 2.0 | 98.8 | 0.08 | 0.34 | 0.85 | 1.27 |
| *Ol 4-2* | 12 | 334 | -11.6 | 1.8 | -10.7 | 1.4 | -6.0 | 2.0 | 98.5 | 0.25 | 0.31 | 0.13 | 1.54 |
| | 12 | 335 | -11.4 | 1.8 | -9.2 | 1.4 | -6.6 | 2.0 | 98.5 | 0.20 | 0.37 | 0.12 | 1.50 |
| Average | | | -11.5 | 1.8 | -10.0 | 1.4 | -6.3 | 2.0 | 98.5 | 0.23 | 0.34 | 0.13 | 1.52 |
| *Ol 20* | 13 | 337 | -9.4 | 1.8 | -6.2 | 1.4 | -6.1 | 2.0 | 79.8 | 0.12 | 0.29 | 0.62 | 18.71 |
| *Ol 19* | 14 | 338 | 1.4 | 1.8 | 3.8 | 1.4 | -0.6 | 2.0 | 84.8 | 0.23 | 0.33 | 0.19 | 14.12 |
| | 14 | 339 | 2.8 | 1.8 | 4.1 | 1.4 | 0.7 | 2.0 | 89.7 | 0.22 | 0.29 | 0.19 | 9.70 |
| Average | | | 2.1 | 1.8 | 3.9 | 1.4 | 0.0 | 2.0 | 87.3 | 0.23 | 0.31 | 0.19 | 11.91 |
| *Ol 26* | 15 | 340 | -49.8 | 1.8 | -49.5 | 1.4 | -24.1 | 2.0 | 98.6 | bdl | 0.16 | 0.58 | 1.40 |
| | 15 | 341 | -49.4 | 1.8 | -49.5 | 1.4 | -23.7 | 2.0 | | | | | |
| Average | | | -49.6 | 1.8 | -49.5 | 1.4 | -23.9 | 2.0 | | | | | |
| *Ol 24* | 16 | 370 | -47.0 | 2.0 | -45.9 | 1.1 | -23.1 | 2.0 | 98.8 | 0.07 | 0.32 | 0.19 | 1.23 |
| | 16 | 371 | -48.0 | 2.0 | -47.0 | 1.1 | -23.5 | 2.0 | | | | | |
| Average | | | -47.5 | 2.0 | -46.4 | 1.1 | -23.3 | 2.0 | | | | | |
| *Ol 23* | 17 | 372 | -1.4 | 2.0 | 1.7 | 1.1 | -2.3 | 2.0 | 76.1 | 0.19 | 0.37 | 0.19 | 21.31 |
| | 17 | 373 | -1.6 | 2.0 | 2.1 | 1.1 | -2.7 | 2.0 | 76.6 | 0.16 | 0.36 | 0.18 | 21.20 |
| Average | | | -1.5 | 2.0 | 1.9 | 1.1 | -2.5 | 2.0 | 76.4 | 0.18 | 0.37 | 0.19 | 21.26 |
| *Ol 27* | 18 | 374 | -5.5 | 2.0 | -2.7 | 1.1 | -4.1 | 2.0 | 98.3 | 0.20 | 0.45 | 0.10 | 1.71 |
| | 18 | 375 | -4.1 | 2.0 | -1.5 | 1.1 | -3.3 | 2.0 | 98.3 | 0.19 | 0.41 | 0.10 | 1.70 |
| Average | | | -4.8 | 2.0 | -2.1 | 1.1 | -3.7 | 2.0 | 98.3 | 0.20 | 0.43 | 0.10 | 1.71 |

**Table S3.** (*continued*)

| grain# | | spot# | $\delta^{17}O$ | 2σ | $\delta^{18}O$ | 2σ | $\Delta^{17}O$ | 2σ | Mg# | CaO | $Cr_2O_3$ | MnO | FeO |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Ol 11* | 19 | 376 | -8.1 | 2.0 | -5.5 | 1.1 | -5.3 | 2.0 | 98.2 | 0.23 | 0.54 | 0.20 | 1.84 |
| | 19 | 377 | -9.1 | 2.0 | -6.9 | 1.1 | -5.5 | 2.0 | | | | | |
| Average | | | -8.6 | 2.0 | -6.2 | 1.1 | -5.4 | 2.0 | | | | | |
| *Ol 10* | 20 | 378 | -8.3 | 2.0 | -4.9 | 1.1 | -5.7 | 2.0 | 98.3 | 0.16 | 0.53 | 0.25 | 1.71 |
| | 20 | 379 | -7.6 | 2.0 | -5.8 | 1.1 | -4.6 | 2.0 | 98.2 | 0.17 | 0.51 | 0.11 | 1.77 |
| Average | | | -7.9 | 2.0 | -5.4 | 1.1 | -5.1 | 2.0 | 98.3 | 0.17 | 0.52 | 0.18 | 1.74 |
| *Ol 12* | 21 | 380 | -48.6 | 2.0 | -47.8 | 1.1 | -23.7 | 2.0 | 98.7 | bdl | 0.42 | 0.86 | 1.31 |
| | 21 | 381 | -49.2 | 2.0 | -48.8 | 1.1 | -23.8 | 2.0 | 98.8 | bdl | 0.47 | 0.87 | 1.18 |
| Average | | | -48.9 | 2.0 | -48.3 | 1.1 | -23.8 | 2.0 | 98.8 | | 0.45 | 0.87 | 1.25 |
| *Ol 6-6* | 22 | 798 | -3.0 | 1.4 | 0.3 | 0.9 | -3.1 | 1.4 | 98.0 | 0.17 | 0.55 | 0.13 | 1.98 |
| | 22 | 799 | -1.3 | 1.3 | -0.9 | 0.9 | -0.9 | 1.3 | 98.2 | 0.19 | 0.61 | 0.13 | 1.84 |
| | 22 | 800 | -2.4 | 1.5 | 0.2 | 0.9 | -2.5 | 1.5 | 98.2 | 0.22 | 0.56 | 0.13 | 1.87 |
| Average | | | -2.2 | 1.4 | -0.1 | 0.9 | -2.2 | 1.4 | 98.1 | 0.19 | 0.57 | 0.13 | 1.90 |
| *Ol 8-1* | 23 | 801 | -0.3 | 1.3 | 2.2 | 0.9 | -1.5 | 1.3 | 79.9 | 0.20 | 0.33 | 0.22 | 18.88 |
| | 23 | 802 | -2.3 | 1.4 | 1.6 | 0.9 | -3.2 | 1.4 | 79.5 | 0.15 | 0.37 | 0.25 | 18.55 |
| Average | | | -1.3 | 1.3 | 1.9 | 0.9 | -2.3 | 1.4 | 79.7 | 0.18 | 0.35 | 0.24 | 18.72 |
| *Ol 8-2* | 24 | 803 | -1.4 | 1.3 | 0.4 | 0.9 | -1.6 | 1.3 | 57.4 | 0.39 | 0.29 | 0.40 | 35.13 |
| | 24 | 804 | -0.5 | 1.0 | 1.2 | 0.9 | -1.2 | 1.2 | 58.0 | 0.38 | 0.31 | 0.44 | 35.15 |
| Average | | | -1.0 | 1.2 | 0.8 | 0.9 | -1.4 | 1.3 | 57.7 | 0.39 | 0.30 | 0.42 | 35.14 |
| *Ol 8-3* | 25 | 805 | -9.7 | 1.3 | -5.8 | 0.6 | -6.7 | 1.3 | 97.9 | 0.24 | 0.39 | bdl | 2.07 |
| | 25 | 806 | -8.1 | 1.3 | -5.5 | 0.6 | -5.2 | 1.3 | 97.9 | 0.21 | 0.33 | 0.18 | 2.04 |
| Average | | | -8.9 | 1.3 | -5.7 | 0.6 | -6.0 | 1.3 | 97.9 | 0.23 | 0.36 | | 2.06 |
| *Ol 9* | 26 | 807 | -47.3 | 1.2 | -46.2 | 0.6 | -23.3 | 1.2 | 98.0 | 0.16 | 0.48 | 0.35 | 1.97 |
| *Ol 13* | 27 | 808 | -48.7 | 1.3 | -49.1 | 0.6 | -23.2 | 1.3 | 97.7 | 0.16 | 0.56 | 1.35 | 2.25 |
| | 27 | 809 | -48.2 | 1.5 | -47.9 | 0.6 | -23.3 | 1.5 | 97.8 | 0.14 | 0.56 | 1.27 | 2.19 |
| Average | | | -48.5 | 1.4 | -48.5 | 0.6 | -23.3 | 1.4 | 97.8 | 0.15 | 0.56 | 1.31 | 2.22 |
| *Ol 14* | 28 | 810 | -5.1 | 1.2 | -3.8 | 0.6 | -3.1 | 1.3 | 98.3 | 0.23 | 0.60 | 0.16 | 1.71 |
| *FCEMEM analysis (~3 pA)* | | | | | | | | | | | | | |
| *Sp-Ol incl.* | | 646 | -47.0 | 3.1 | -45.7 | 1.3 | -23.2 | 3.2 | 98.6 | bdl | 0.31 | 0.78 | 1.52 |
| | | 647 | -47.4 | 3.2 | -45.4 | 1.3 | -23.8 | 3.2 | 98.4 | bdl | 0.38 | 0.17 | 1.62 |
| Average | | | -47.2 | 3.1 | -45.5 | 1.3 | -23.5 | 3.2 | 98.5 | | 0.35 | 0.48 | 1.57 |
| *Low-Ca pyroxene* | | | | | | | | | | | | | |
| *FCEMEM analysis (~30 pA)* | | | | | | | | | | | | | |
| *Px1* | 1 | 446 | -7.4 | 1.5 | -4.2 | 1.0 | -5.3 | 1.5 | 98.1 | 0.59 | 0.50 | bdl | 1.36 |
| | 1 | 447 | -7.6 | 1.2 | -4.1 | 1.0 | -5.5 | 1.3 | 97.9 | 0.65 | 0.66 | 0.18 | 1.46 |
| Average | | | -7.5 | 1.3 | -4.1 | 1.0 | -5.4 | 1.4 | 98.0 | 0.62 | 0.58 | | 1.41 |
| *Px2* | 2 | 449 | -4.5 | 1.3 | -2.6 | 1.0 | -3.1 | 1.3 | 97.8 | 2.77 | 0.70 | 0.15 | 1.46 |
| | 2 | 450 | -5.9 | 1.3 | -3.1 | 1.0 | -4.3 | 1.3 | 97.6 | 2.78 | 0.67 | 0.13 | 1.57 |
| Average | | | -5.2 | 1.3 | -2.8 | 1.0 | -3.7 | 1.3 | 97.7 | 2.78 | 0.69 | 0.14 | 1.52 |
| *Spinel* | | | | | | | | | | | | | |
| *FCEMEM analysis (~3 pA)* | | | | | | | | | | | | | |
| *Sp-Ol incl.* | | 631 | -48.9 | 3.1 | -46.2 | 1.9 | -24.9 | 3.2 | 97.1 | 0.56 | 3.52 | bdl | 1.43 |
| *Sp1* | 1 | 623 | -47.0 | 3.0 | -44.1 | 1.9 | -24.1 | 3.1 | 95.3 | bdl | 3.25 | 0.43 | 2.36 |
| *Sp1* | 1 | 624 | -44.9 | 3.1 | -43.8 | 1.9 | -22.2 | 3.1 | 95.8 | bdl | 2.22 | 0.42 | 2.08 |
| *Sp1* | 1 | 632 | -45.9 | 3.0 | -42.7 | 1.9 | -23.7 | 3.0 | 95.5 | bdl | 2.26 | 0.37 | 2.26 |
| Average | | | -46.0 | 3.1 | -43.6 | 1.9 | -23.3 | 3.1 | 95.5 | | 2.58 | 0.41 | 2.23 |

AOA: amoeboid olivine aggregate, Sp-Ol incl.: spinel-olivine inclusion

Mg# = [Mg/(Mg+Fe)] × 100 in mol%

bdl = below detection limit.

Counting detection limits (3 sigma) for CaO and MnO are 0.06 wt% and 0.09 wt%, respectively.

**Data S1. (separate file)**
Oxygen-isotope data with SIMS.