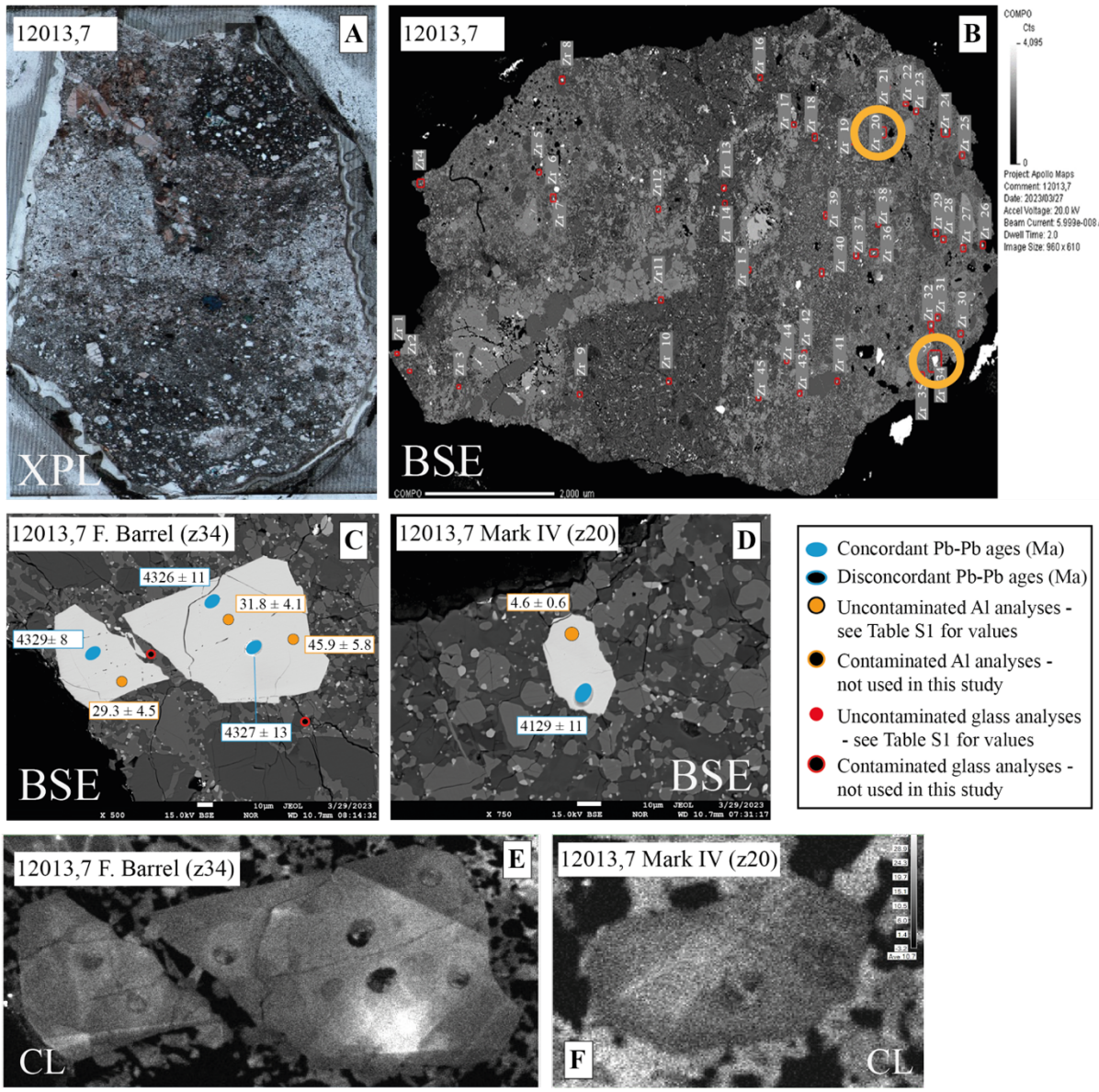


Fig. S1. Pictures for sample 12013,7. (A) Cross-polarized image of the complete thin section showing the gray and black zones; (B) BSE image of the complete thin-section showing zircon locations; (C) BSE image of zircon Faulted Barrel, with age, Al-in-zircon and AlI_{glass} shown; (D) BSE image of zircon Mark IV, with age, Al-in-zircon and AlI_{glass} shown; (E) Monochromatic CL image for Faulted Barrel; (F) Monochromatic CL image for Mark IV. For (C) and (D), Pb-Pb age (Ma; blue circles), Al-in-zircon content (ppm; orange circles), and glass analysis (red circles for uncontaminated analyses, black circles with red rims for contaminated analyses not used in this study). Uncertainties are reported as 1σ.

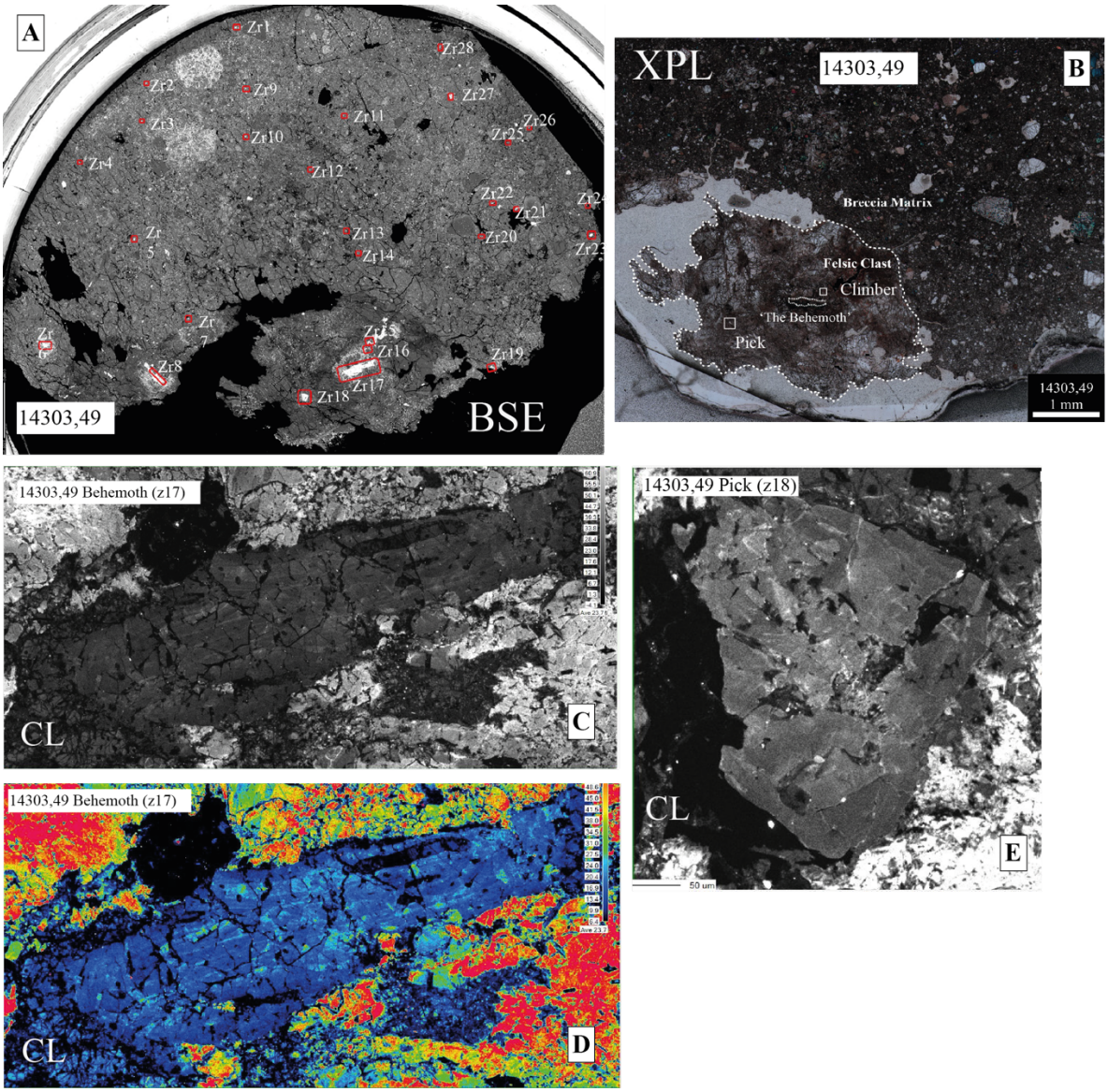


Fig. S2. Pictures for sample 14303,49. (A) BSE image of the complete thin-section showing zircon locations; (B) Cross-polarized image of the complete thin section showing matrix and felsic clast; (C) Monochromatic CL image for Behemoth; (D) Polychromatic CL image for Behemoth; (E) Monochromatic CL image for Pick.

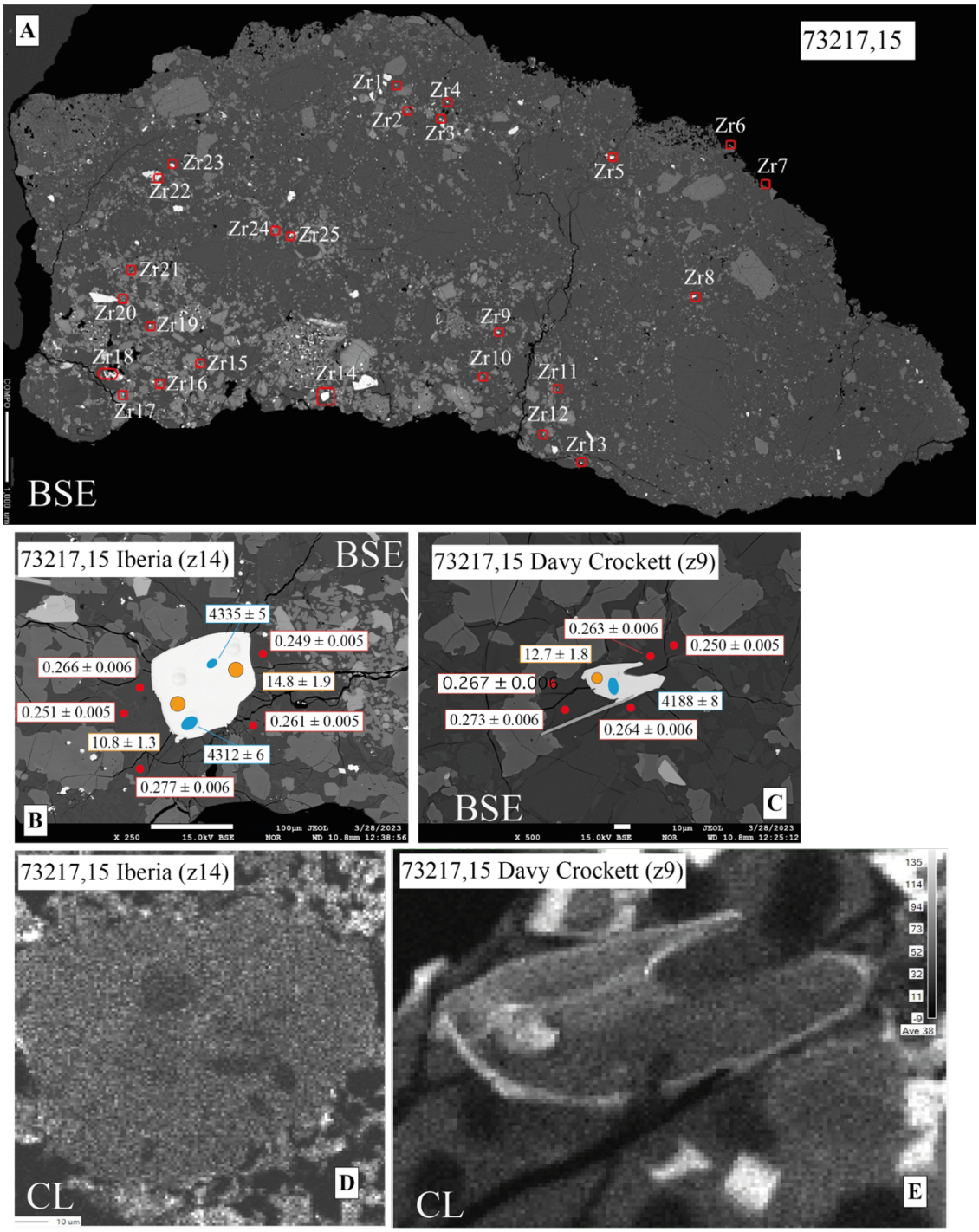


Fig. S3. Pictures for sample 73217,15. (A) BSE image of the complete thin-section showing zircon locations; (B) BSE image of zircon Iberia, with age, Al-in-zircon and AlI_{glass} shown (legend as in Fig. S1); (C) BSE image of zircon Davy Crockett, with age, Al-in-zircon and AlI_{glass} shown (Legend as in Fig. S1); (D) Monochromatic CL image for Iberia; (E) Monochromatic CL image for Davy Crockett. For (B) and (C), Pb-Pb age (Ma; blue circles), Al-in-zircon content (ppm; orange circles), and glass analysis (red circles for uncontaminated analyses, black circles with red rims for contaminated analyses not used in this study). Uncertainties are reported as 1σ.

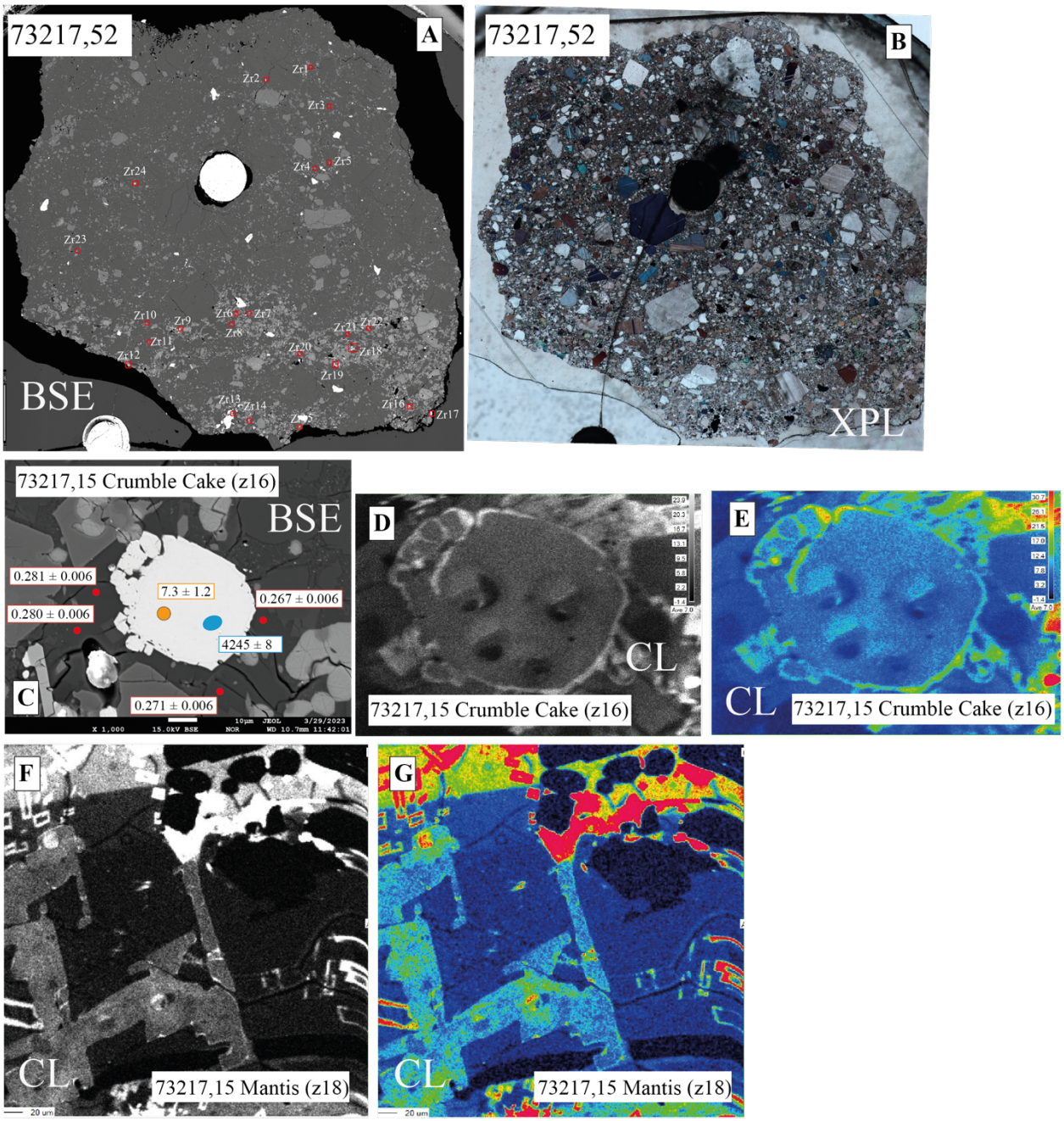


Fig. S4. Pictures for sample 73217,52. (A) BSE image of the complete thin-section showing zircon locations; (B) Cross-polarized image of the complete thin section showing the gray and black zones; (C) BSE image of zircon Crumble Cake, with age, Al-in-zircon and AlI_{glass} shown (legend as in Fig. S1); (D) Monochromatic CL image for Crumble Cake; (E) Polychromatic CL image for Crumble Cake; (F) Monochromatic CL image for Mantis; (E) Polychromatic CL image for Mantis. For (C), Pb-Pb age (Ma; blue circles), Al-in-zircon content (ppm; orange circles), and glass analysis (red circles for uncontaminated analyses, black circles with red rims for contaminated analyses not used in this study). Uncertainties are reported as 1σ.

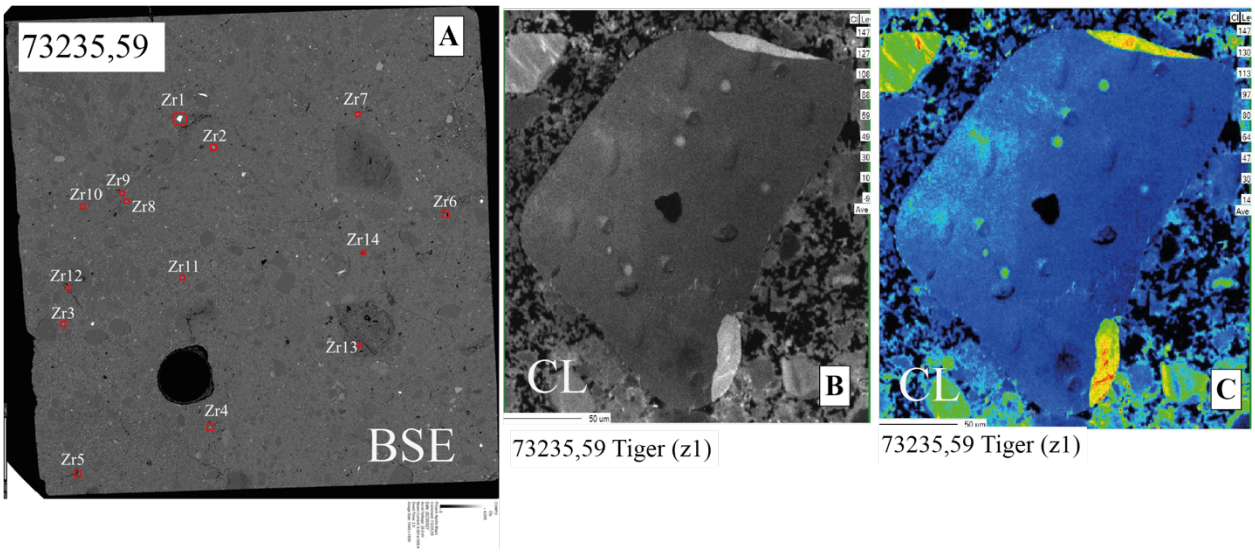


Fig. S5. Pictures for sample 73235,59. (A) BSE image of the complete thin-section showing zircon locations; (B) Monochromatic CL image for Tiger; (E) Polychromatic CL image for Tiger.

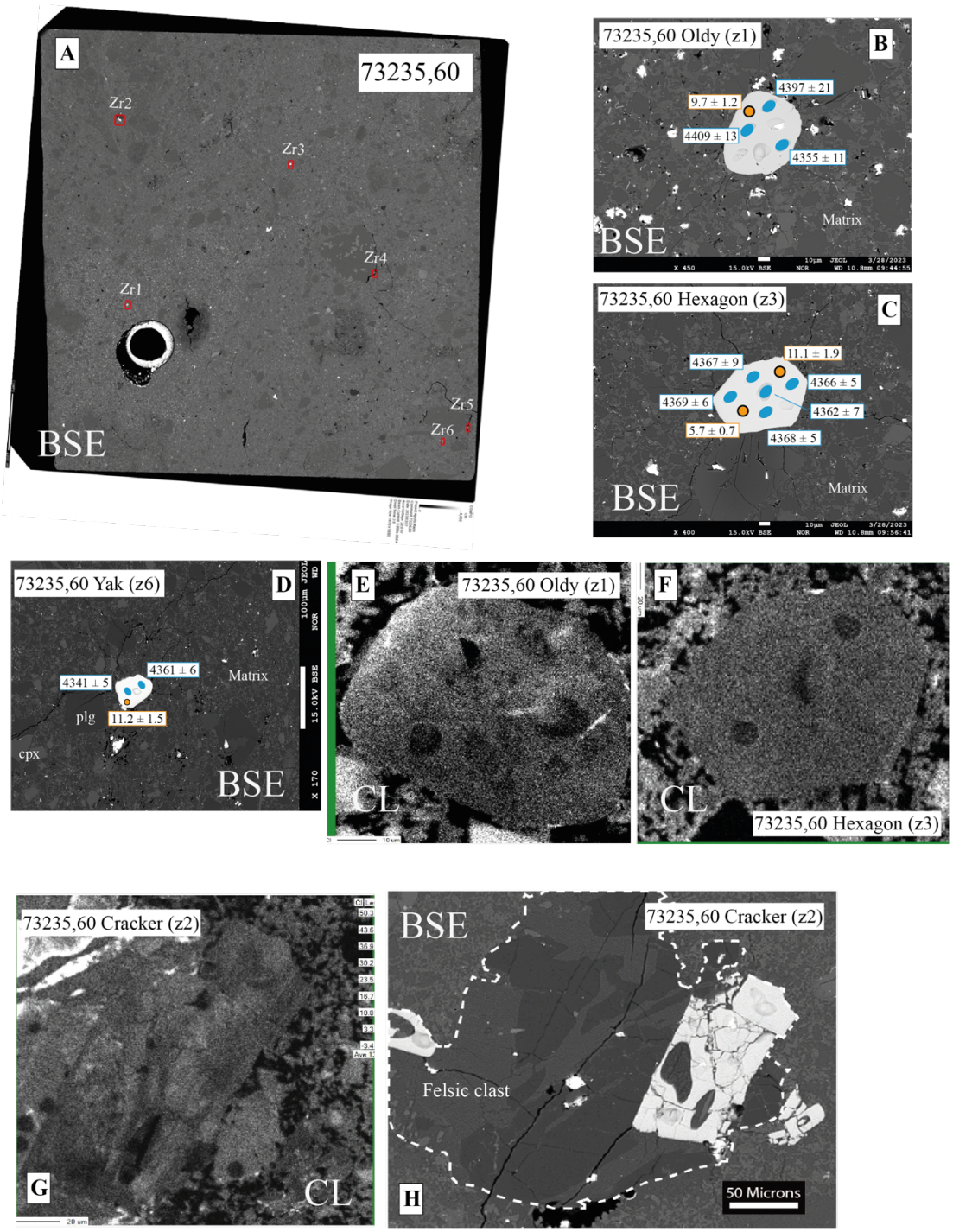


Fig. S6. Pictures for sample 73235,60. (A) BSE image of the complete thin-section showing zircon locations; (B) BSE image of zircon Oldy, with age, Al-in-zircon and AlI_{glass} shown (legend as in Fig. S1); (C) BSE image of zircon Hexagon, with age, Al-in-zircon and AlI_{glass} shown (legend as in Fig. S1); (D) BSE image of zircon Yak, with age, Al-in-zircon and AlI_{glass} shown (legend as in Fig. S1); (E) Monochromatic CL image for Oldy; (F) Monochromatic CL image for Hexagon; (F) Monochromatic CL image for Cracker; (E) BSE view of Cracker in the felsic clast. For (B), (C) and (D), Pb-Pb age (Ma; blue circles), Al-in-zircon content (ppm; orange circles), and glass analysis (red circles for uncontaminated analyses, black circles with red rims for contaminated analyses not used in this study). Uncertainties are reported as 1σ.

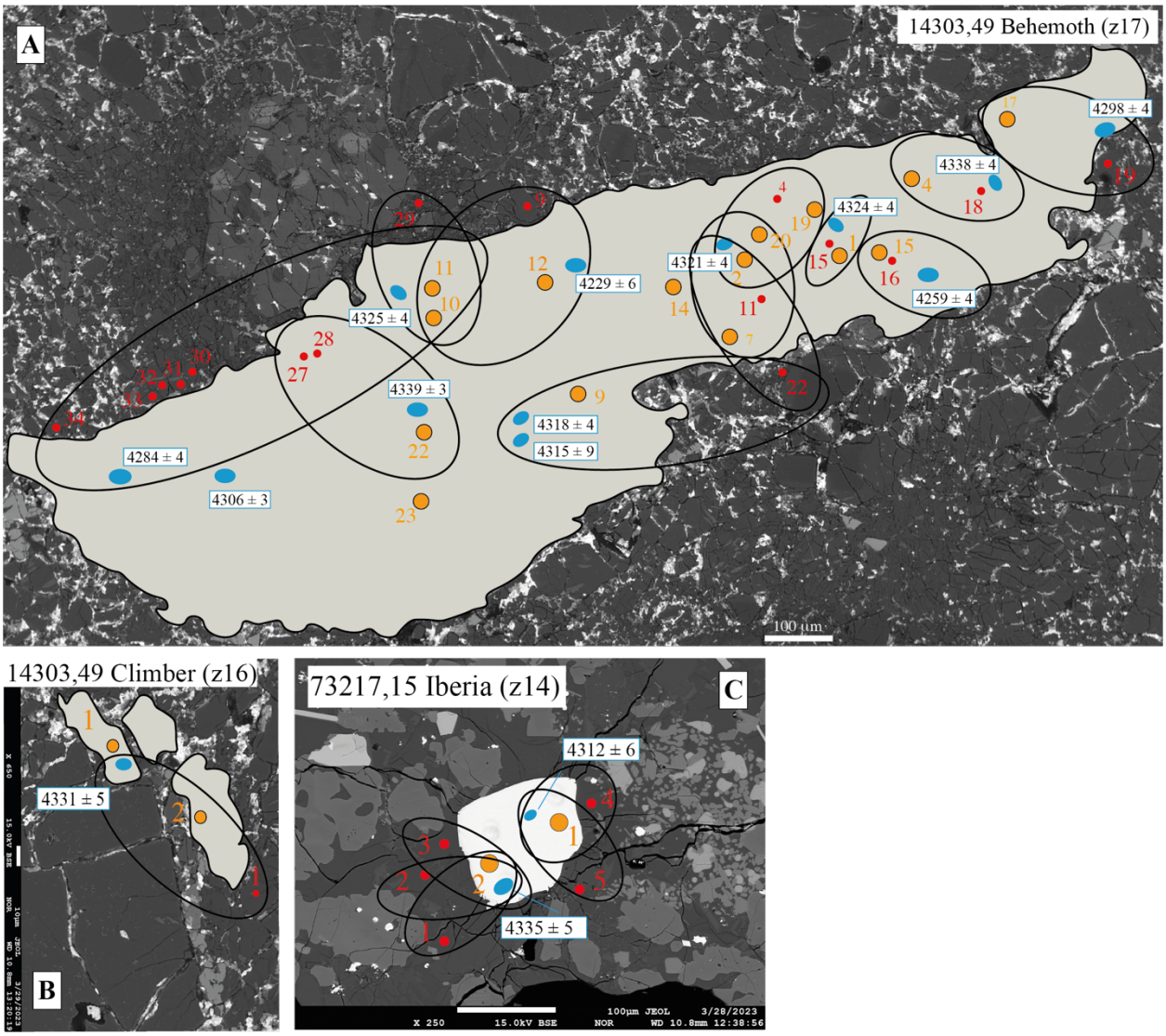


Fig. S7. Glass/Al-in zircon correlation. (A) zircon "Behemoth"; (B) zircon "Climber"; (C) zircon "Iberia". Blue ellipses are Pb-Pb ages (Ma), Orange spot are Al-in-zircon analyses and red spots are AlI_{glass} analyses. Uncertainties are reported as 1σ.

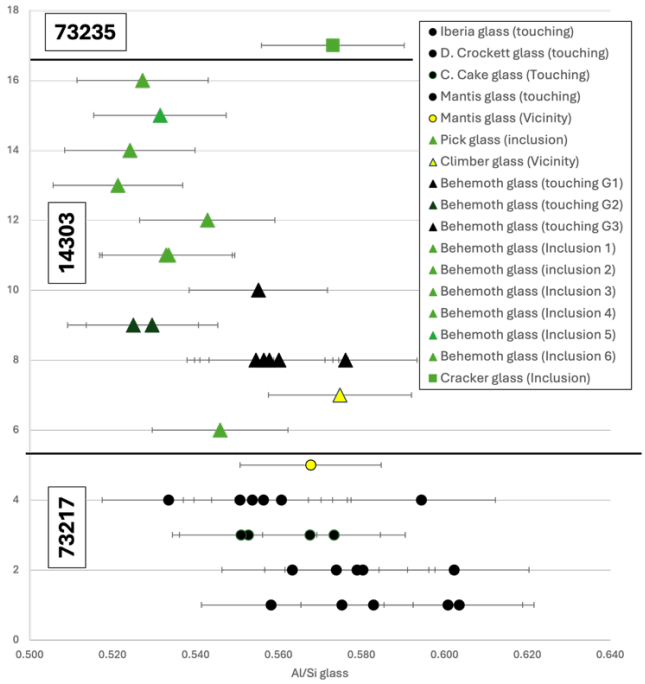


Fig. S8. Glasses analyses for all zircons in all samples. Expressed as Al/Si glass which is equivalent AlI_{glass}. Green = inclusion, black = touching, yellow = distal. Triangles = zircons in 14303,49, circles = zircons in 73217, square = zircons in 73235. Uncertainties are reported as 1σ.

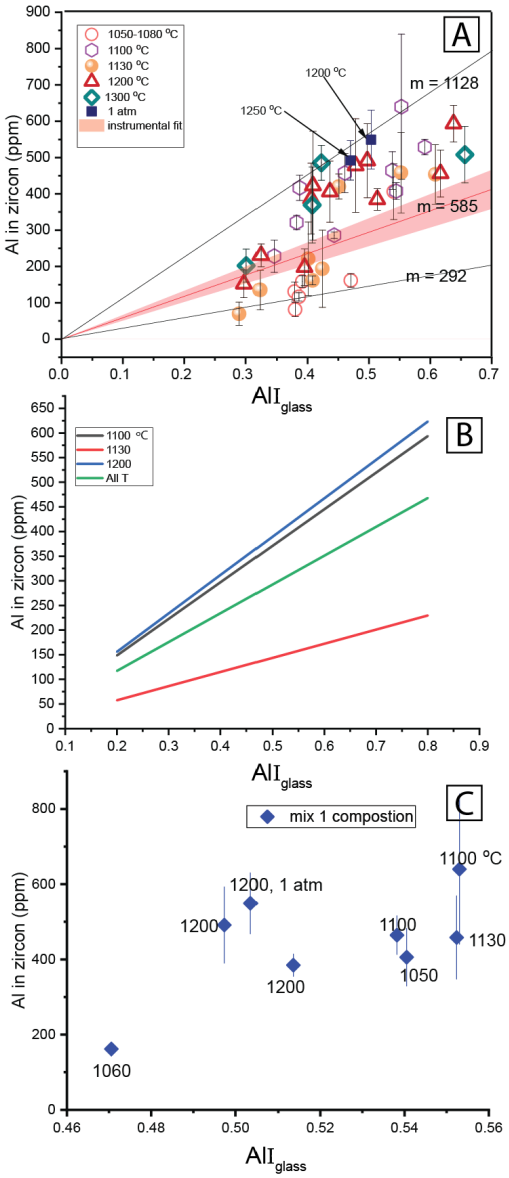


Fig. S9. Al-in-Zircon experimental results. (A). For a given experiment, the ppm Al in zircon (errors are 1 s.d.) correlated with the melt composition parameter $[Al_2O_3]^{1/2}/SiO_2 = AlI_{glass}$ The fitting takes into consideration errors associated with the measurements using the instrumental fitting technique in the Origin ® 2023b software package, where the bands reflect the 95% confidence on the slope estimate. All plotted data can be found in the Data S7. The results summarize a total of 299 zircon analyses on 40 experimental samples. The fit is forced through the origin, such that as the Al content in the melt → 0 so does the Al content in the zircon. Our preferred slope for this fit is m = 585 (See Data S6 for the coefficient on the fit used for eq. (4)), and slopes that bound 95% of the experimental results are also shown for comparison. (B) The data do not show strong evidence for a T dependence; for example, we show isothermal fits for Al-in-zircon vs melt composition parameter AlI_{glass}. Also provided in Data S6 are fits isothermal experimental datasets. (C) As a further exploration of the effect of T, mix composition 1 was easiest to grow under diverse T conditions, and a comparison of Al in zircon (ppm) vs. AlI_{glass} shows no correlation with T.

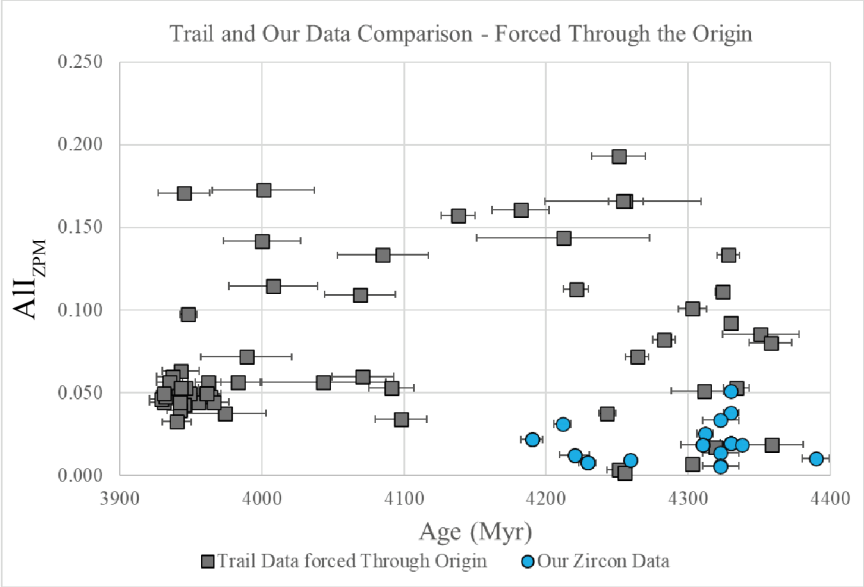


Fig. S10. Our lunar zircon AlI_{zpm} compared to AlI_{zpm} of lunar zircons calculated from Al-in-zircon data presented by Trail et al.[30]. The zircon parent magmas (blue circles) are all relatively low in Al, with their AlI_{zpm} similar to the low Al population (gray squares) of Apollo 14 zircons presented by Trail et al.[30]. Uncertainties are reported as 1σ.

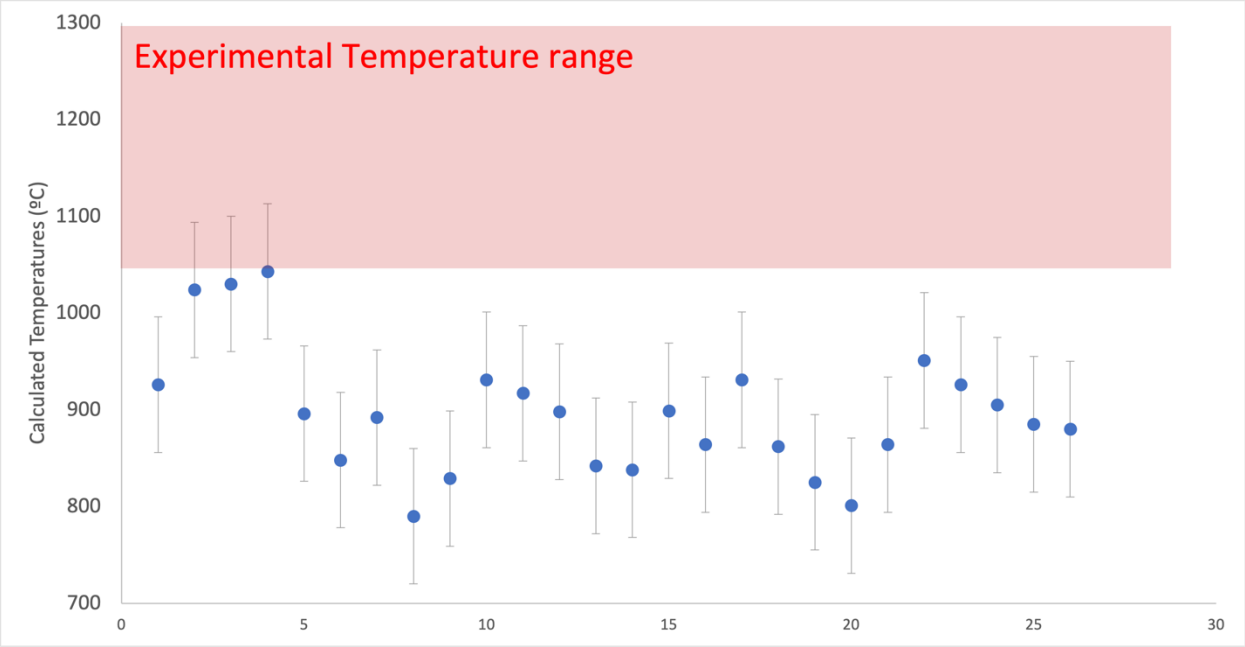
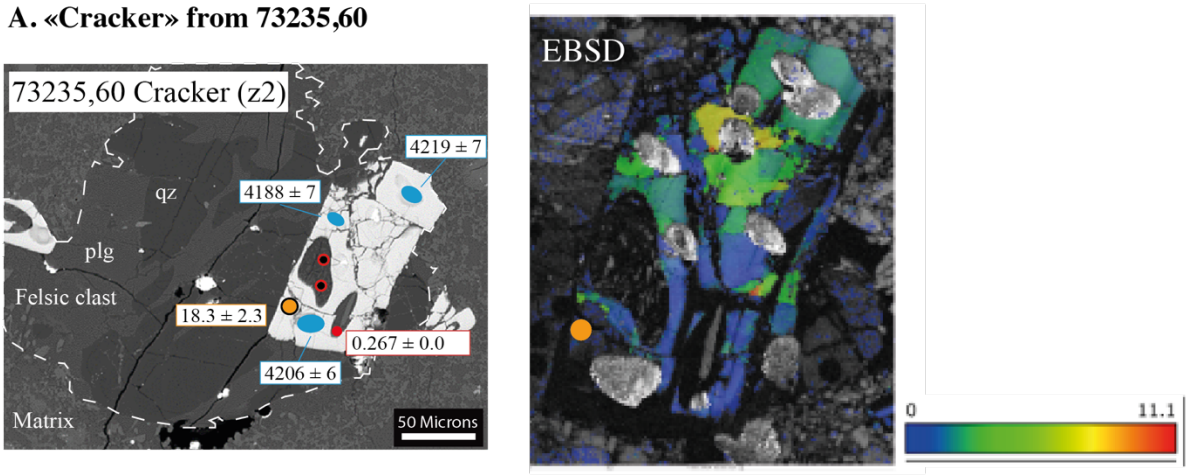


Fig S11 Experimental temperature range (1050°C to 1300°C) compared to calculated Ti-in-zircon thermometry-derived formation temperatures of lunar zircons. The average temperature difference is approximately 150°C, supporting the relevance of our calibration despite some zircon temperatures falling below the experimental range. Significant differences in zircon-melt equilibrium are not expected within this discrepancy. Calculated Ti-in-zircon temperature data can be found in Data S2. Uncertainties are reported as 1σ.

A. «Cracker» from 73235,60



B. «Hexagon» from 73235,60

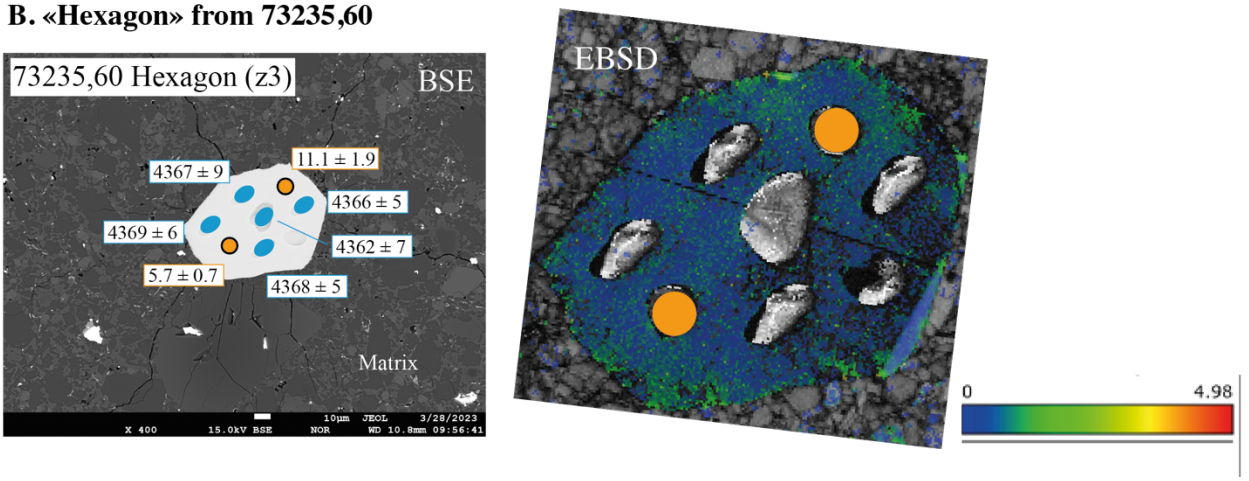


Fig. S12 Example of BSE and EBSD images for zircons with Al analyze spots. Zircons show very limited deformation at the site of Al analyses (orange spots), with misorientation of less than 6°. EBSD pictures from this study. Additional EBSD images are available in Ref. 13, 22 and 36. Pb-Pb age (Ma; blue circles), Al-in-zircon content (ppm; orange circles), and glass analysis (red circles for uncontaminated analyses, black circles with red rims for contaminated analyses not used in this study). Uncertainties are reported as 1σ.