Supplementary Information

Supplementary Note 1. Errors in GBPD analyses

Our GBPD analyses focused on the olivine–olivine–fluid triple junction with apparent dihedral angles lower than the median value + 5° and assumed a vertical grain boundary plane. Based on a simple theoretical calculation, we show that grain boundary planes at such triple junctions are dominantly subvertical with respect to the polished section. Although we cannot exactly determine the extent of grain boundary plane tilting in cross-sectional images, the apparent dihedral angles can be used to constrain the extent of tilting statistically.

Following the method of Harker and Parker (1945), we can calculate the apparent dihedral angle, Y on an arbitrary sectioning plane at the mineral–mineral–fluid triple junction in an isotropic system, with one true dihedral angle θ. This method is identical to that used to compute the theoretical cumulative frequency curve of the apparent dihedral angle, as shown in Figure 3. A schematic of the triple junction with a sectioning plane is shown in Figure S5. The unit normal of the sectioning plane is defined in angular coordinates Q and ϕ (Q, ϕ = 0°–90°), and Y is a function of θ, Q, and ϕ (Harker and Parker 1945). In Figure S6a, the contours of Y for a representative θ of 60° are shown in the $\sin^2 Q$ versus ϕ diagram. In this diagram, the area fraction of angles ≤ Y corresponds to the probability that the observed apparent dihedral angles become ≤ Y (Harker and Parker 1945). The apparent dihedral angles around θ were more likely to be observed on the polished section than the other angles. The median of the Y values closely corresponds to θ (Jurewicz and Jurewicz 1986). We noted that a Y value smaller than θ

required a smaller ϕ, and vice versa. Increasing $\sin^2 Q$ (i.e., Q) tended to cause Y values to deviate from the median (i.e., θ).

The angle between the grain boundary plane and the arbitrary sectioning plane, F (F = 0°–90°) can be calculated from their normals. F is dependent on Q and ϕ, but independent of θ (Figure S1). In Figure S6b, the contours of F are shown in the $\sin^2 Q$ versus ϕ diagram. As in the case of Y, the area fraction of angles of ≥ F should correspond to the probability that the angles become ≥ F. At $\sin^2 Q$ (i.e., Q) = 0 or ϕ = 0, the grain boundary plane is vertical (F = 90°). With increasing Q and ϕ, F tends to deviate from 90°; that is, the grain boundary plane becomes tilted. Therefore, subvertical (i.e., F close to 90°) grain boundary planes can be expected at triple junctions with Y smaller than the median, because such Y values can only be observed at low ϕ.

Combining the Y and F contours in the $\sin^2 Q$ versus ϕ diagram allows us to compute the probability of observing sub-vertical grain boundary planes at triple junctions in an arbitrary Y window on the polished section. We regarded the minimum deviation of F from 90°, which satisfies probability of more than approximately 68%, as the representative error (1s) of our GBPD analyses. In Figure S6c, the area of F ≥ 67° in our preferred Y window from 0° to 65° (i.e., median + 5°) is shown in the $\sin^2 Q$ versus ϕ diagram for θ = 60°. We found that 71% of the apparent dihedral angles fell within the range of 0° ≤ Y ≤ 65°, in which 68% of grain boundary planes formed an angle ≥ 67° with respect to the sectioning plane. Thus, we inferred a representative error of approximately 23° in our GBPD analyses. Although this value slightly increased and decreased at lower and higher θ, respectively, it was not significantly dependent on θ in the range of interest (23°–24° at θ = 50°–80°). If we do not use dihedral angle constraints (i.e., a Y window of 0°–180°), the probability of F ≥ 67° decreases to 49% and the estimated error becomes 35°.

References

Harker, D., and Parker, E.R. (1945) Grain shape and grain growth. Transactions of the American Society for Metals, 34, 156–201.

Jurewicz, S.R., and Jurewicz, A.J.G. (1986) Distribution of apparent angles on random sections with emphasis on dihedral angle measurements. Journal of Geophysical Research, 91, 9277.