Supplementary Information

1. Supplementary Discussion

a. Petrogenesis from Literature

Type II Basalts Formation History. The preferred hypothesis for the formation of Type II basalts is near-surface crystal fractionation [1, 2]. Based on bulk composition and mineralogy, it has been proposed that these rocks cooled slowly within a relatively thick lava flow, allowing sufficient time and space for olivine to crystallize and fall to lower flow levels due to its higher density relative to the melt [2]. Our results cannot expand upon the near-surface crystal fractionation hypothesis. Reducing conditions should not inhibit olivine crystallization; therefore, the low oxygen fugacity suggested by our results does not, by itself, explain the absence of olivine in 75035.

Crystallization Sequence of 75035. Meyer & Boctor (1974) [3] find small, skeletal ilmenite within cristobalite, in addition to the larger laths reported by others. They interpret the texture of 75035 to suggest that pyroxene crystallizes first, with plagioclase and ilmenite joining the assemblage next. Considerable overlap of these three phases is implied. Ilmenite continues to crystallize until the appearance of SiO_2-phases [3]. A separate petrological study interprets the large ilmenite laths in 75035 as indicative of ilmenite being the liquidus phase [4]. Slight penetration of the ilmenite laths by plagioclase suggests that ilmenite continues to grow during part of the plagioclase crystallization interval. In that study, pyroxene is interpreted as the third phase to crystallize. The crystallization sequences proposed in both [3] and [4] allow for large phenocrysts of ilmenite, consistent with its relatively early crystallization from a melt-dominated environment. Therefore, magmatic conditions inferred from ilmenite laths likely reflect the overall melt system rather than local anomalies in small residual melt pockets.

b. Insights into Petrogenesis from Our Data

Minerals at Grain Boundaries of Ilmenite. Lift-outs extracted from locations VII and VIII (Fig. 1g) were specifically chosen to examine minerals at the grain boundaries of ilmenite to determine whether any information could be gained about the petrogenesis. In both samples, ilmenite was found adjacent to plagioclase and within $1\,\mu$m of an SiO_2-phase (see Figs. S1 and S2). Four-dimensional scanning transmission electron microscopy (4D-STEM) analysis of the SiO_2 region from sample VIII reveals d-spacings matching cristobalite, the expected SiO_2-phase for 75035 [1], with $P2_1/c$ crystal symmetry ($d = 1.827$ Å, 2.176 Å). Given the limited spatial context of STEM, it is difficult to determine definitively whether ilmenite was still crystallizing during the formation of cristobalite. The proximity of the SiO_2-phase to ilmenite is a neutral observation, as it could be consistent with either of the crystallization sequences proposed by Meyer & Boctor (1974) [3] and Longhi et al. (1974) [4].

Any Insights from Tomography? Supplementary Video 1 rotates the chip and highlights the ilmenite domain to reveal its 3D shape, while Supplementary Video 2 steps through each vertical slice. We find that the ilmenite region (white) appears as laths penetrating the surrounding plagioclase (darker gray) and pyroxene (lighter gray). This observation is consistent with both crystallization sequences described above, in which ilmenite crystallized early. However, it remains unclear whether ilmenite began crystallizing before or after the initial formation of plagioclase. The tomographic images do support the interpretation that pyroxene largely crystallized after both ilmenite and plagioclase.

2. Supplementary Videos

Supplementary Video 1. Rotation of the density map from X-ray attenuation of the chip from 75035-232, followed by a rotation of the selected intensity range (145–214), highlighting the ilmenite domain (dimensions of ∼1.1 mm in height and ∼1.2 mm in length, and ∼0.1 mm in width).

Supplementary Video 2. X-ray tomography video progressing through slices in 3.5 μm increments, from the bottom of the chip (slice number 320) to the top (slice number 8), spanning a total height of 1109.5 μm. Circular marks are artifacts from the measurement acquisition process.

3. Supplementary Figures

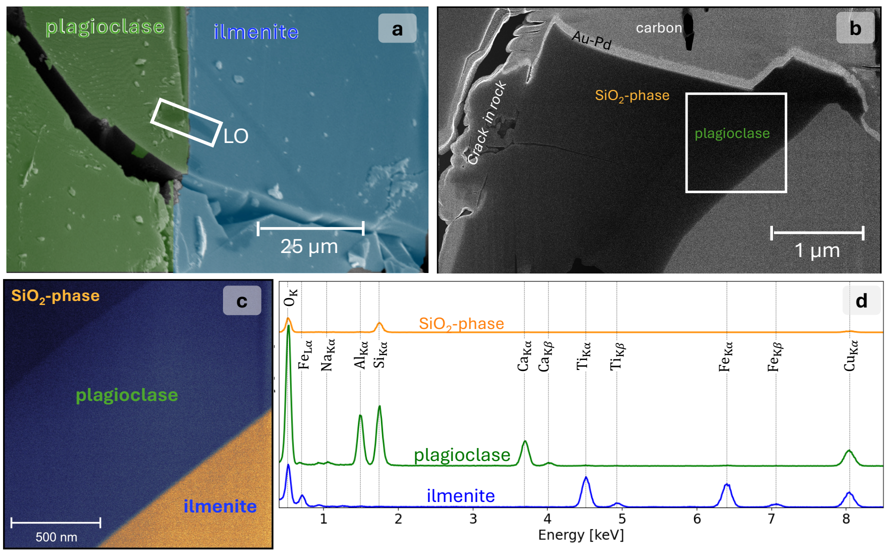

Fig. S1: Minerals at the grain boundary of ilmenite from sample VII. a, SEM image of the area where sample VII was extracted. **b,** Secondary electron image of the lift-out; the crack aligns with the one shown in (**a**), and the white box denotes the region where EDS data were acquired. **c,** HAADF image of the boxed region in (**b**), where EDS spectra were collected using the Nion UltraSTEM-200X. **d,** EDS spectra averaged over regions in (**c**) for the SiO_2-phase (orange), plagioclase (green), and ilmenite (blue).

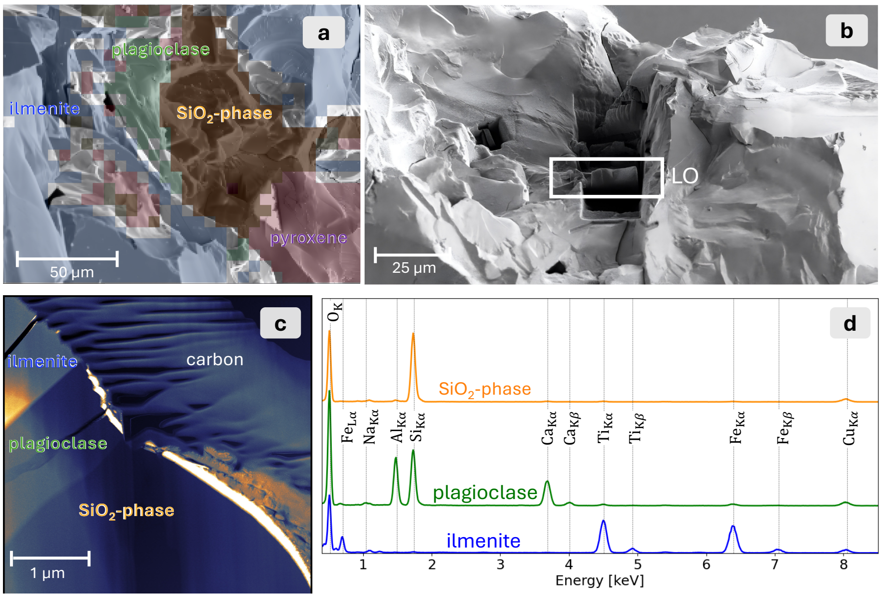

Fig. S2: Minerals at the grain boundary of ilmenite from sample VIII. a, SEM image of the sample region before lift-out, overlaid with grains identification from EDS. **b,** SEM image after FIB milling of trenches. **c,** HAADF image of the area where EDS was acquired using the JEOL F200. **d,** EDS spectra averaged over regions in (**c**) for SiO_2-phase (orange), plagioclase (green), and ilmenite (blue). Elemental quantification of the ilmenite from a thin region is used to extract the mole fraction of minor elements (see Methods), as summarized in Extended Data Table 1.

References

[1] Brown, G. M., Peckett, A., Emeleus, C. H., Phillips, R. & Pinsent, R. H. Petrology and mineralogy of Apollo 17 mare basalts. *Lunar and Planetary Science Conference Proceedings* **1**, 1–13 (1975).

[2] Rhodes, J. M. *et al.* Chemistry, classification, and petrogenesis of Apollo 17 mare basalts. *Lunar and Planetary Science Conference Proceedings* **2**, 1467–1489 (1976).

[3] Meyer, H. O. A. & Boctor, N. Z. Opaque mineralogy: Apollo 17, rock 75035. *Lunar and Planetary Science Conference Proceedings* **1**, 707–716 (1974).

[4] Longhi, J., Walker, D., Grove, T. L., Stolper, E. M. & Hays, J. F. The petrology of the Apollo 17 mare basalts. *Lunar and Planetary Science Conference Proceedings* **1**, 447–469 (1974).