

Supplementary material for:

New insights into gas-driven phase segregation in andesitic enclaves from Mt Mazama, USA

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Methodology

Samples

Small enclaves analyzed include 84C1162 (8x9x10 cm³) and 84C1163 (6 x 8 x 10 cm³), both described in Bacon (1986) and a slab cut through large enclave 84C1155 (58 x 73 x ~70 cm³). Data included in Table 1.

X-ray scanning and processing of cores

Scanning conditions for the large enclave core are provided below.

Core Name	Core diameter (mm)	Resolution (μm/voxel)	Number of scans per core	Number of projections per scan	Filter	Max accelerating voltage (kV)	Beam Current (μA)	Exposure time per projection (s)
84C1155_5mm	5	6.6	9	3142	none	63	198	1
84C1155_10mm	10	7.1	6	2000	1 mm Al	74	195	
84C1155_25mm	25	14.4	9	2000	0.5 mm Cu	91	131	
84C1163	10	7.1	1	3142	1 mm Al	75	195	1
84C1162	37	26.4	2	2000	1 mm Cu	113	135	

Table S1. XMT scanning conditions. Filters were adjusted as needed to prevent beam hardening artefacts in the data.

The multi-resolution imaging approach allows analysis of both global features and local details. Small enclave 84C1162 is the only exception; here the full sample was imaged. To prevent beam hardening artefacts, this sample was placed in a 37 mm diameter cylindrical container filled with glass beads.

The data were reconstructed using the standard proprietary Nikon software and processed in Avizo® (version 9.1). A non-local means edge-preserving filter (search window of 7 voxels,

neighborhood of 3 voxels and similarity of 0.6) was applied for noise reduction. Individual phases were identified and segmented using X-ray attenuation (greyscale), such that oxide crystals are white, pyroxenes are light grey and vesicles are dark grey to black. Plagioclase, the dominant crystal phase, and matrix glass had overlapping greyscale ranges (mid-grey). To segment phases, we applied a moment-preserving bi-level thresholding algorithm (Tsai, 1985) with thresholds determined from changes in curvature of the global greyscale histogram. We verified the consistency of our thresholding scheme within a single core by overlaying the results from adjacent scans. A separation algorithm (neighborhood of 6 to ensure that vesicles were considered connected only if they shared a full pixel face) was used to define individual vesicles when the bubble walls are too thin to be resolved at the image resolution. The separated datasets were visually assessed to ensure separation was realistic and consistent across samples. The errors associated with the volume measurements (individual vesicle and population) are described in Lin et al., 2015, and are estimated to be <0.5% for the data we present.

Thin sections

Below we provide example full thin section scans showing groundmass patches. Thin section locations and cut faces are shown in Figure 4 of the main text.

Small enclaves

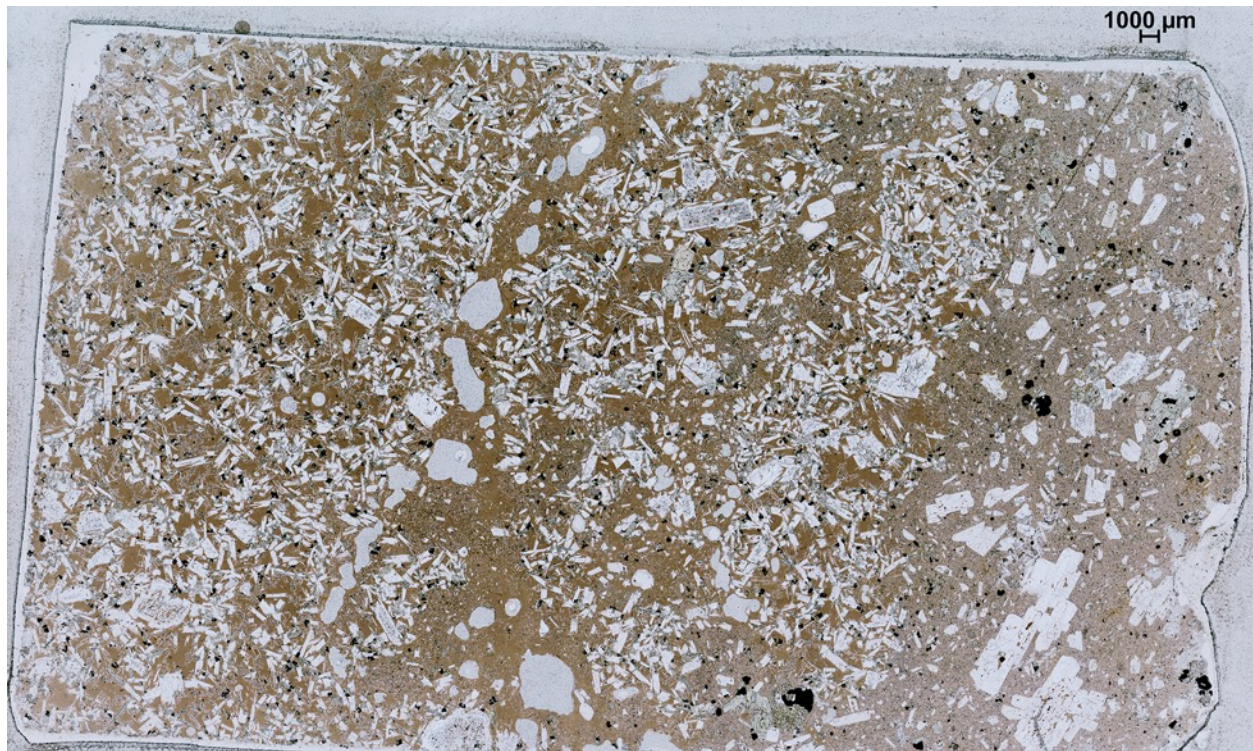


Figure S1a. Small enclave C1162. Fine-grained material to the right is host rock. Melt-filled fracture has large bubbles and is also interpreted as host.



Figure S1b. Small enclave C1163. Fine-grained material in the upper and lower left is host rock. Note oversized zoned plagioclase crystal in upper left that appears to be incorporated from host (same image in cross-polarized light shown in Fig. S5). Vertical stripes in image are an artefact of the stitching process.

Large enclave C1152

Rectangles show locations of higher magnification images used for textural analysis (where labeled with letters) and general investigation.

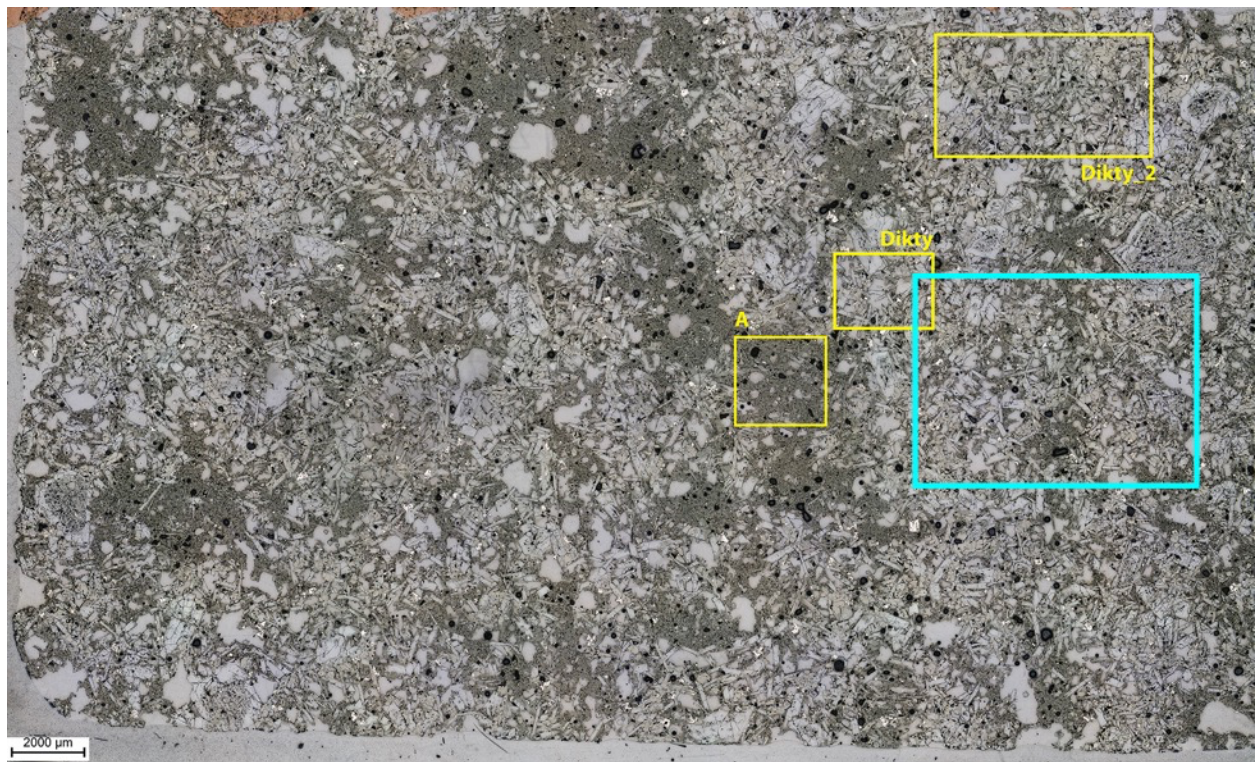


Figure S1c. Large enclave core C1152_2

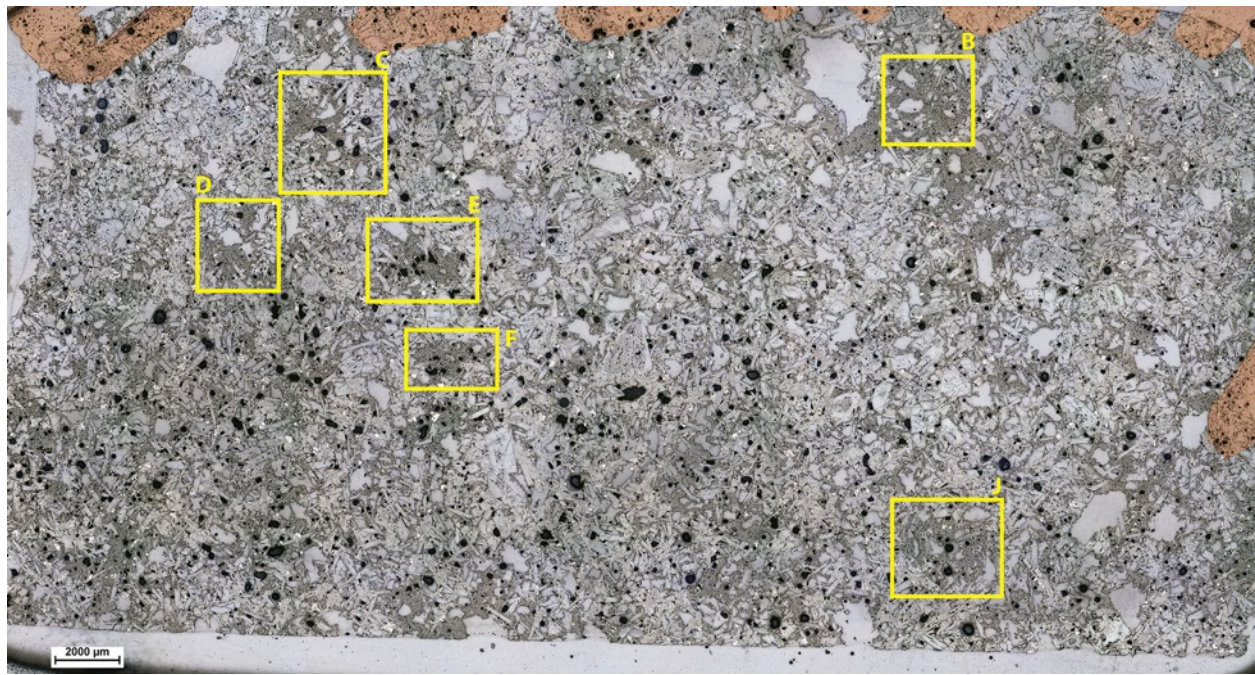


Figure S1d. Large enclave core C1152_3

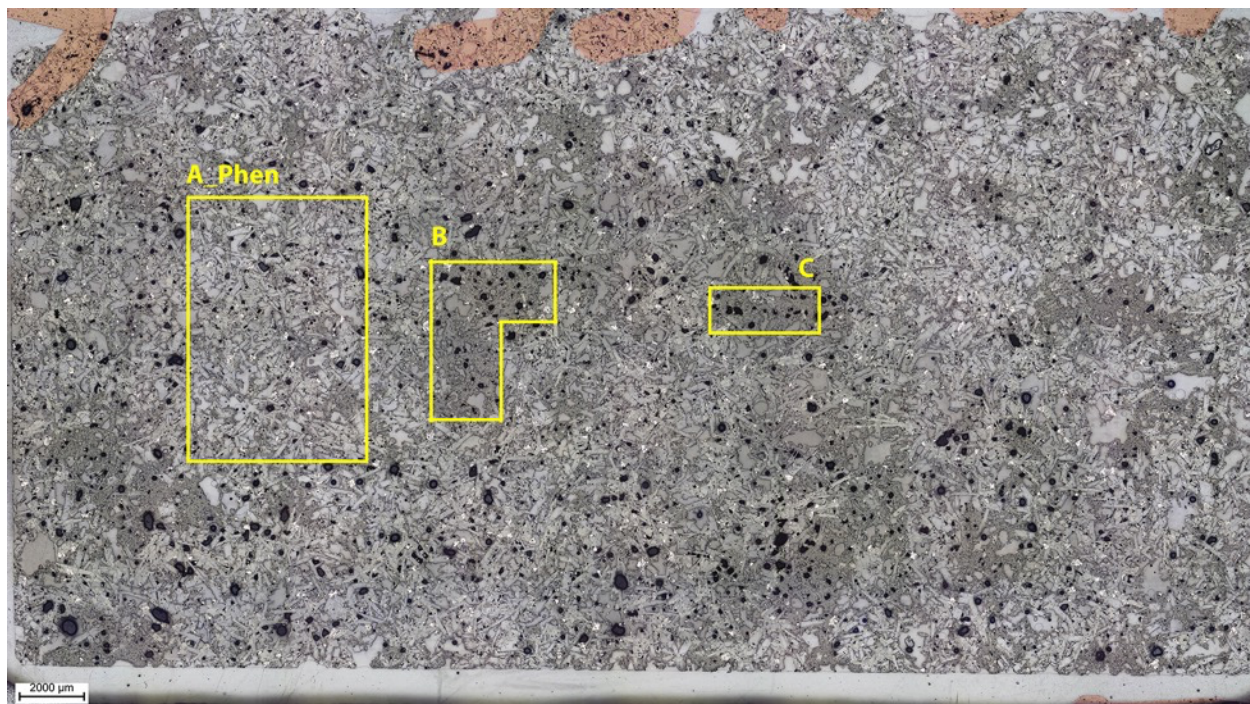


Figure S1e. Large enclave core C1152_4

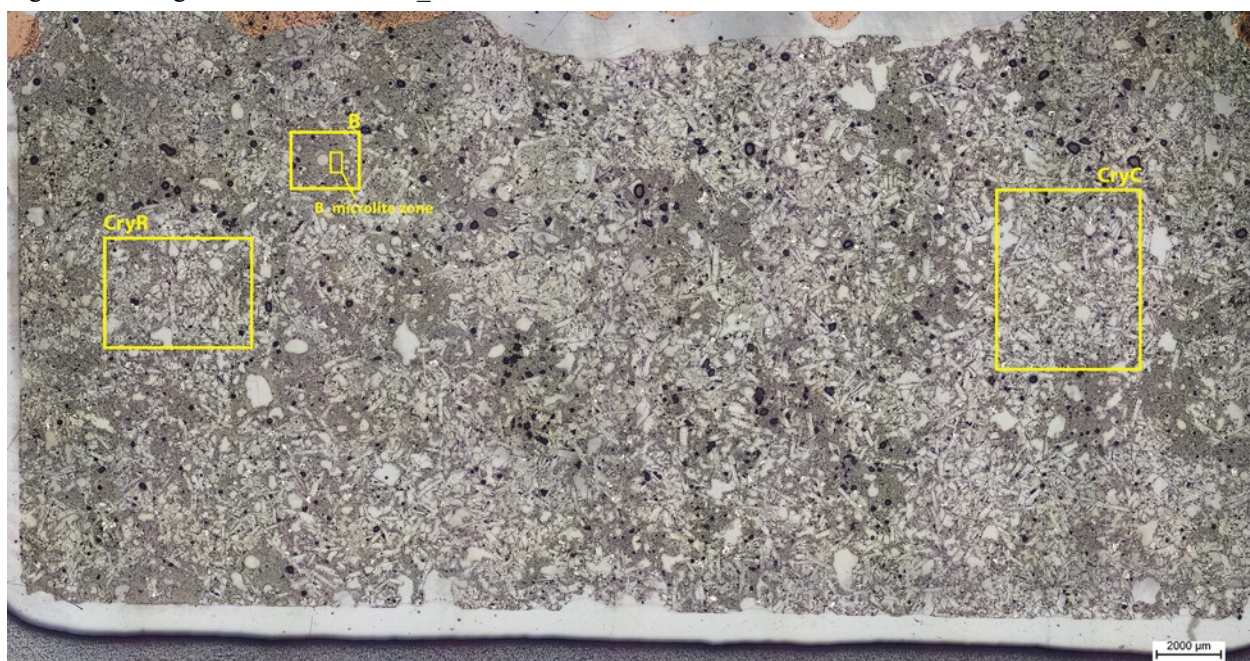


Figure S1e. Large enclave outer core C1152_5

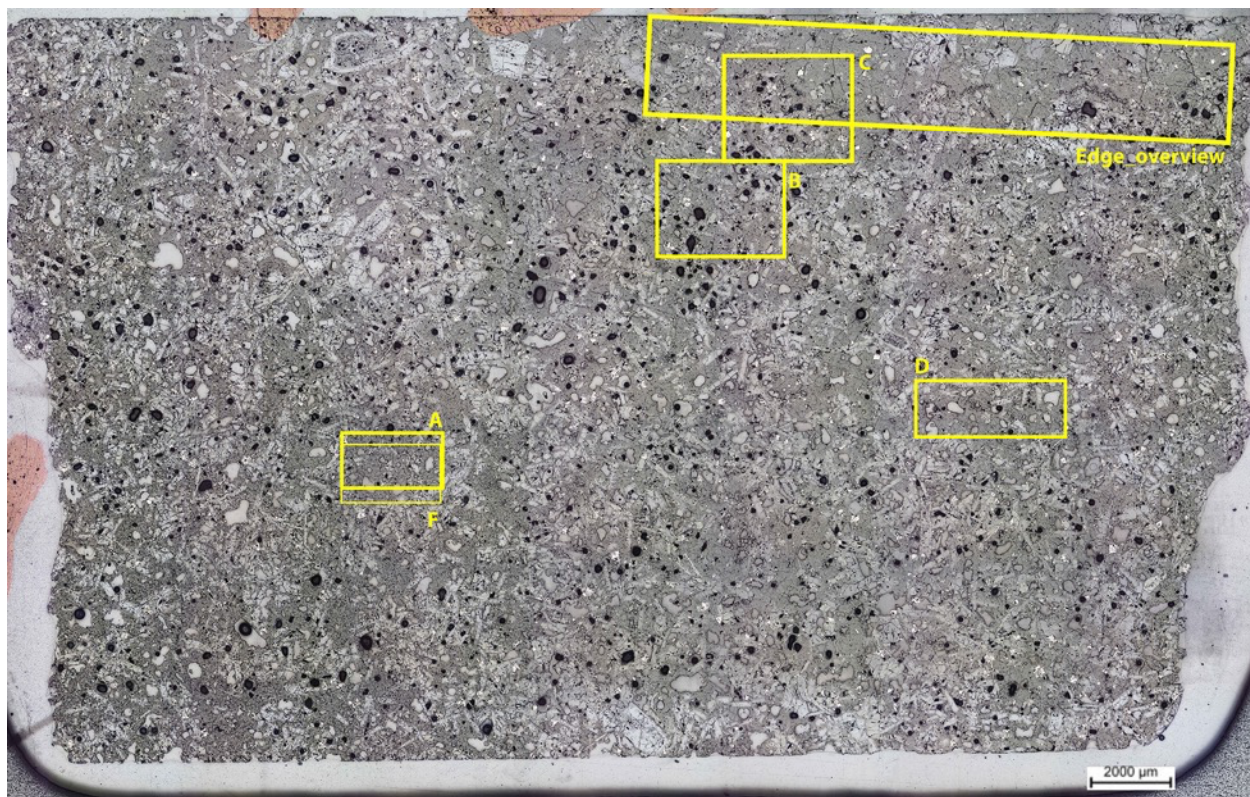


Figure S1f. Large enclave rind C1152_6

BSE imaging

Backscattered electron imaging provides improved resolution and compositional contrast. For this reason, BSE images were used for detailed examination of enclave textures and quantitative analysis of vesicles and crystals in enclave samples. Backscatter Electron (BSE) images were obtained with a Hitachi S-3500N Scanning Electron Microscope (SEM) at the University of Bristol. Imaging conditions for large enclave thin sections (linked to annotated thin section images above):

Image Name	acquisition rate	magnification	resolution (um/px)
6_rim	80 s per image	90x	1.423
6_rim2	100s per image	300x	0.427
6_D	100s per image	300x	0.427
6_F_Phen	100s per image	100x	1.281
6_F	80s per frame	300x	0.427
6_B		300x	0.427
4_B	90s per frame	300x	0.427
4_B2	90s per frame	300x	0.427
4_C	90s per frame	300x	0.427
4_A_Phen	90s per frame	90x	1.423
5_CryC	100s per image	80x	1.601
5_CryR	100s per image	80x	1.601
5B			0.427
3B	80s per frame	300x	0.427
3F	80s per frame	350x	0.366
3C	80s per frame	350x	0.366
3D	80s per frame	350x	0.366
3E	80s per frame	350x	0.366
3J	80s per frame	350x	0.366
2A		300x	0.427
2_Dikty2	200s per frame	100x	1.281
2_Dikty	200s per frame	100x	1.281

Table S2. List of all BSE images obtained for phase analysis.

EPMA

Major element glass chemistry was measured by electron probe microanalysis (EPMA) using a JEOL JXA8530F Hyperprobe at the University of Bristol. The conditions for analysis were a 5 nA beam current, a 10 μm spot size and an accelerating voltage of 15 kV. All elements were counted on-peak, and the count times were adjusted for each element to minimize beam damage. K, Ca, Si, Na and Al were analyzed first for 10s, Fe (30s), Mn (40s), Ti and Cl (50s), and Mg(60s) . Minor elements (Ti, Mg, Mn, Cl) a rhyolite glass secondary standard, KN18, was analyzed at the start and end of each analytical session to ensure that no drift had occurred. 20-30 individual analyses were collected per sample; all data was normalized to 100%, totals below 100% are attributed to secondary hydration. Data are provided in spreadsheet format in accompanying supplement.

Plagioclase size and shape measurements

Crystal sizes are shown as cumulative plots in in Figure 12b; here we present an example of how these data were collected, provide those data from the enclave core in a different form and add shape measurements (aspect ratio, determined as long/short axis of the best-fitting ellipse) of both crystals and microlites.

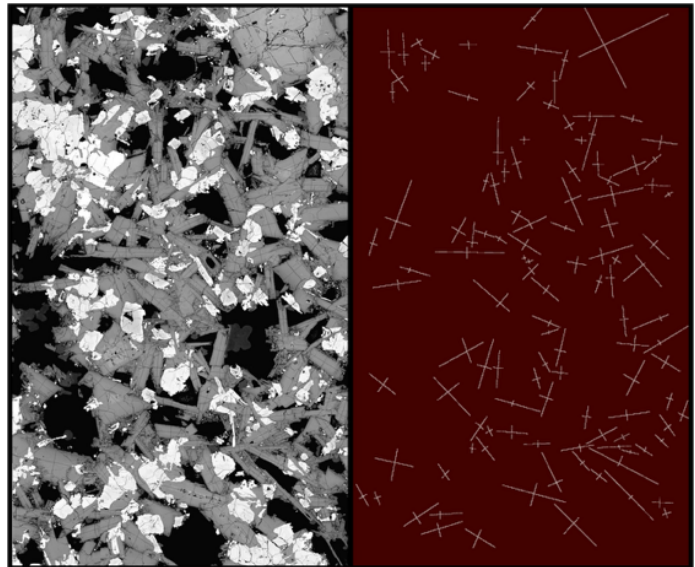


Figure S2a. Illustration of measurement process for thin section C1152_2 area dikty2 (see Fig. S1c; note that images are rotated 90° to match format of 2b).

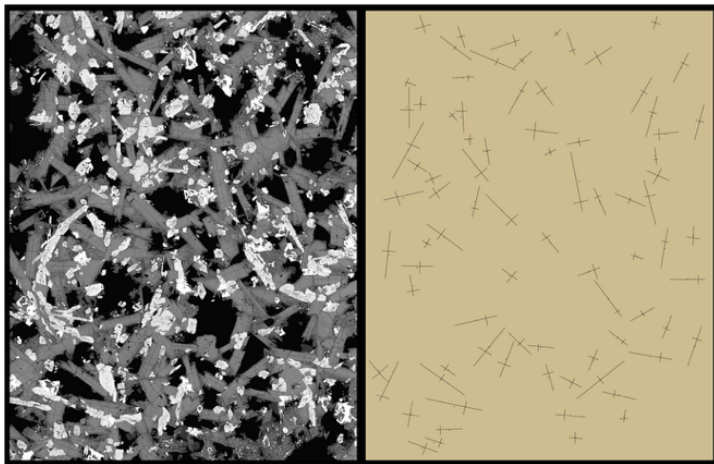


Figure S2b. Illustration of measurement process for thin section C1152_5 area CryC (see Fig. S1e).

Histograms below show sizes and aspect ratios of crystals in the large enclave core (slide 2) and in a diktytaxitic zone near the core-rind boundary (slide 5). The crystal populations have similar aspect ratios, but area-based measurements of crystals in slide 5 are slightly larger.

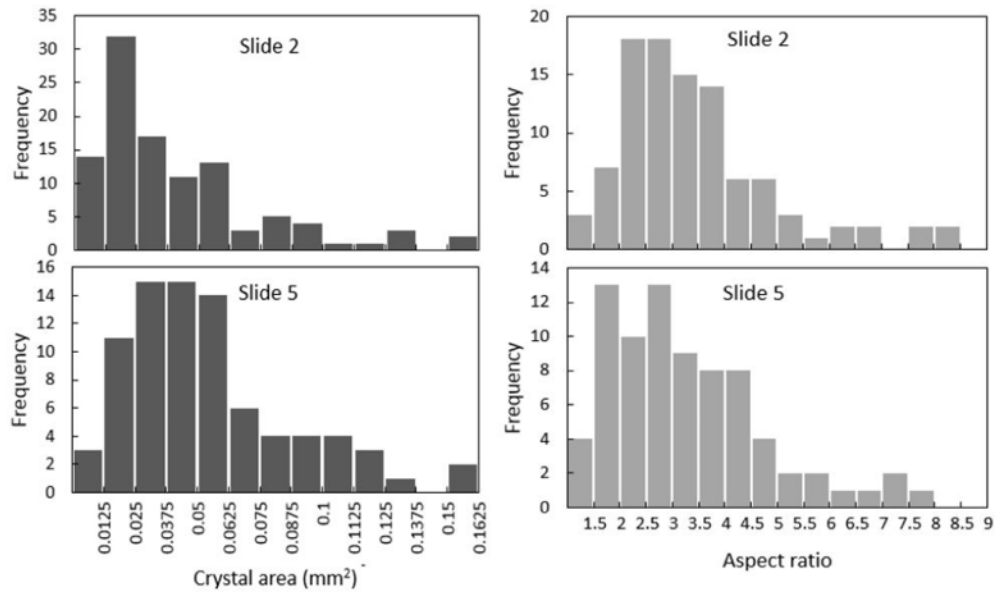


Figure S3a. Histograms showing the size (area) and shape (aspect ratio) of crystals from the large enclave core.

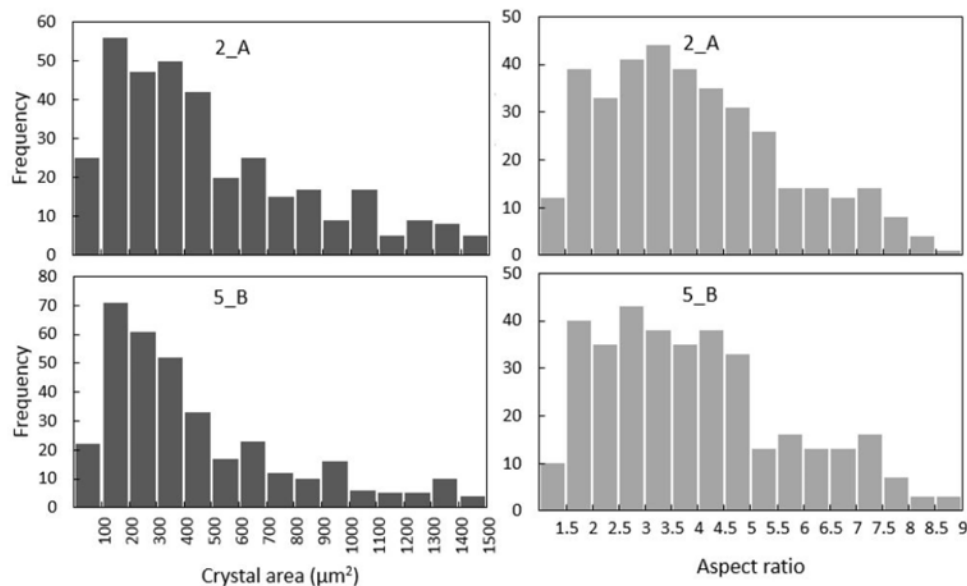


Figure S3b. Histograms showing the size (area) and shape (aspect ratio) of microlites from the large enclave core.

Plagioclase microlite size and aspect ratios were measured in groundmass patches in the same large enclave samples (slides 2 and 5). Although both populations have similar aspect ratios, the

microlites in the center are slightly larger. Microlites have larger aspect ratios than the phenocrysts, consistent with late stage microlite crystallization from cooling. The data further suggest that the increase in size toward the enclave center indicates that the edge of the enclave cooled faster, and therefore microlite growth was interrupted earlier.

We used the program ShapeCalc (Mangler et al., 2022) to estimate the best fit shape for each crystal population (Fig. S4). The results are presented as Zingg diagrams, which plot the ratio of the short (S) to intermediate (I) axis on the abscissa and the ratio of the intermediate (I) to long (L) axis on the ordinate. These estimates confirm the extreme shapes inferred from 2D shape measurements and show that the average shapes of both framework crystals and microlites lie on the spectrum between prismatic and acicular (short axis $S < \text{intermediate axis } I \ll \text{long axis } L$). In this projection, cubes plot near $x = 1$ and $y = 1$ ($S = I = L$), thin prisms plot near $x = 1$, $y = 0$ ($S = I \ll L$), flat plates plot near $x = 0$ and $y = 1$ ($S \ll I = L$); crystals that plot near $x = 0$ and $y = 0$ have $S \ll I \ll L$. The data show that all plagioclase crystals are highly acicular and have best-fit axis ratios of $\sim 1:3:20$. The shapes of plagioclase microlites are similar, although with slightly larger intermediate axes ($1:3.5:20$). Shape estimates show high variability for $I:L$, consistent with the low probability of intersecting the maximum long axis. Values of $S:I$ are more limited.

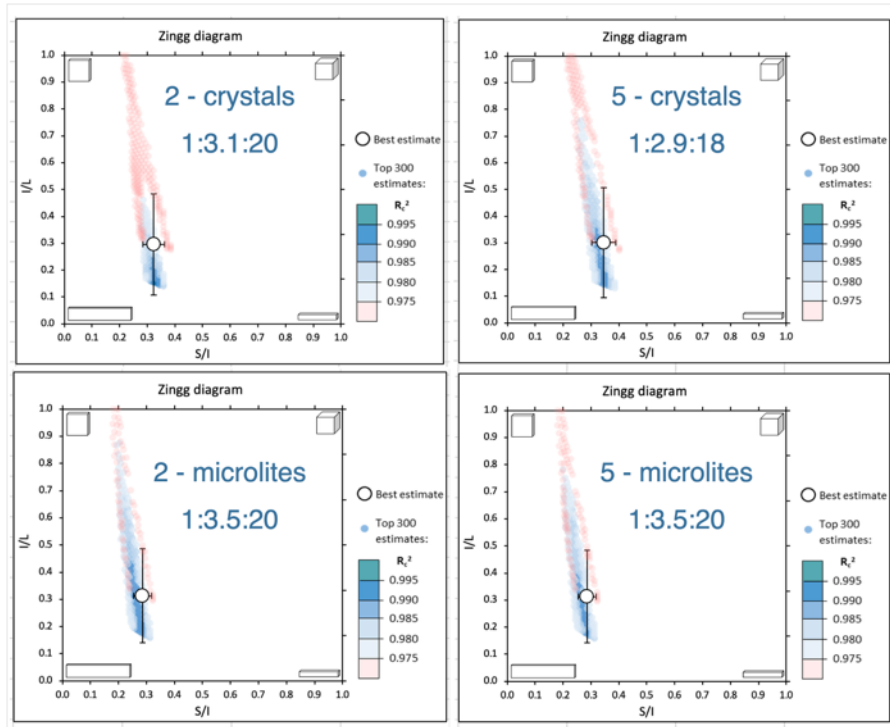


Figure S4. Zingg diagrams for the same crystals measured in Figure S3. Zingg diagrams were calculated using the program ShapeCalc (Mangler et al., 2022) and are labeled by slide (2 or 5), plagioclase type (crystal or microlite). Also shown are the best fit axis ratios short S : intermediate I : long L .

Incorporation of host crystals

Enclaves contain outsized phenocrysts incorporated from the host magma, as illustrated by the oversized plagioclase crystal in Figure S5. This plagioclase is complexly zoned with numerous reaction rims that indicate a complex crystallization history.

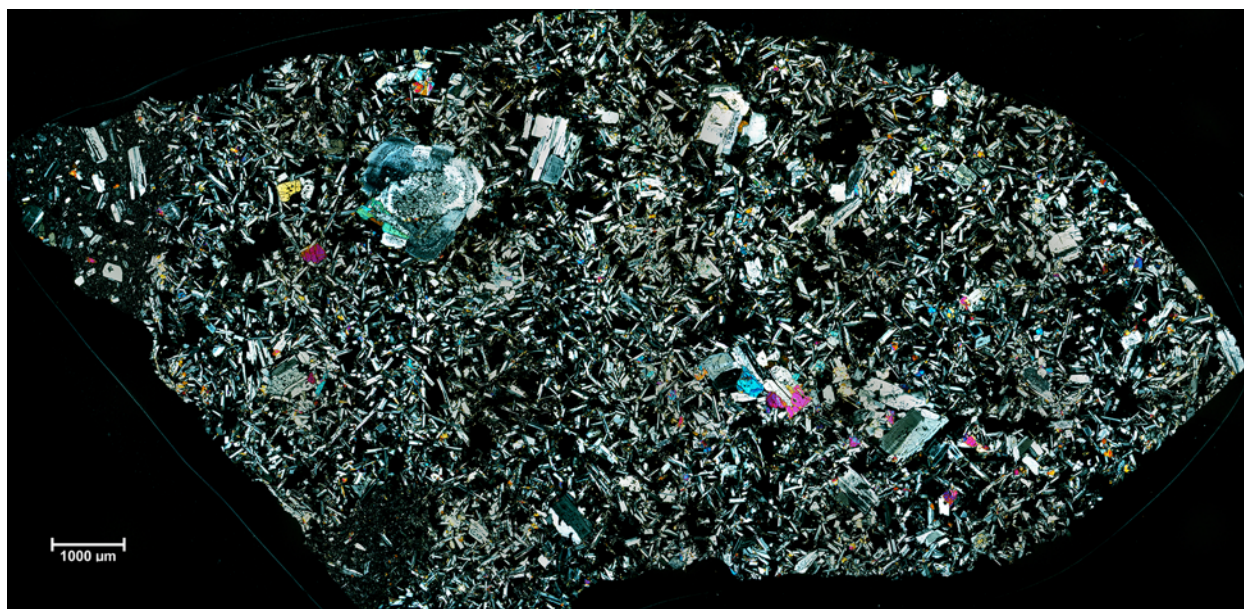


Figure S5. Full thin section BSE scan of small enclave C1163 in cross-polarized light (see Fig. 4 for corresponding sample slice, Fig. 5 for mapped groundmass patches and Fig. S1b for same section in plane polarized light). Note large inherited plagioclase crystal and other large plagioclase and crystal clots that appear to be from the host magma.

Si-phase composition

The Si element maps shown in Figure 8 highlight the presence of a prominent Si phase within the dikytaxitic vugs of the large enclave. To identify that phase, we compare Si and Al element maps (Fig. S6). Here we have used Fiji (ImageJ) to highlight the Si phase. Thresholding of the Al element map allows us to identify low-Al phases (dark red; bright red are voids) that include both low-Al pyroxenes and the Si-phases occupying the voids (Fig. S6, note in particular the turquoise arrows). The presence of a small amount of Al in the Si-phase is consistent with cristobalite, whose open structure allows some amount of Al substitution for Si.

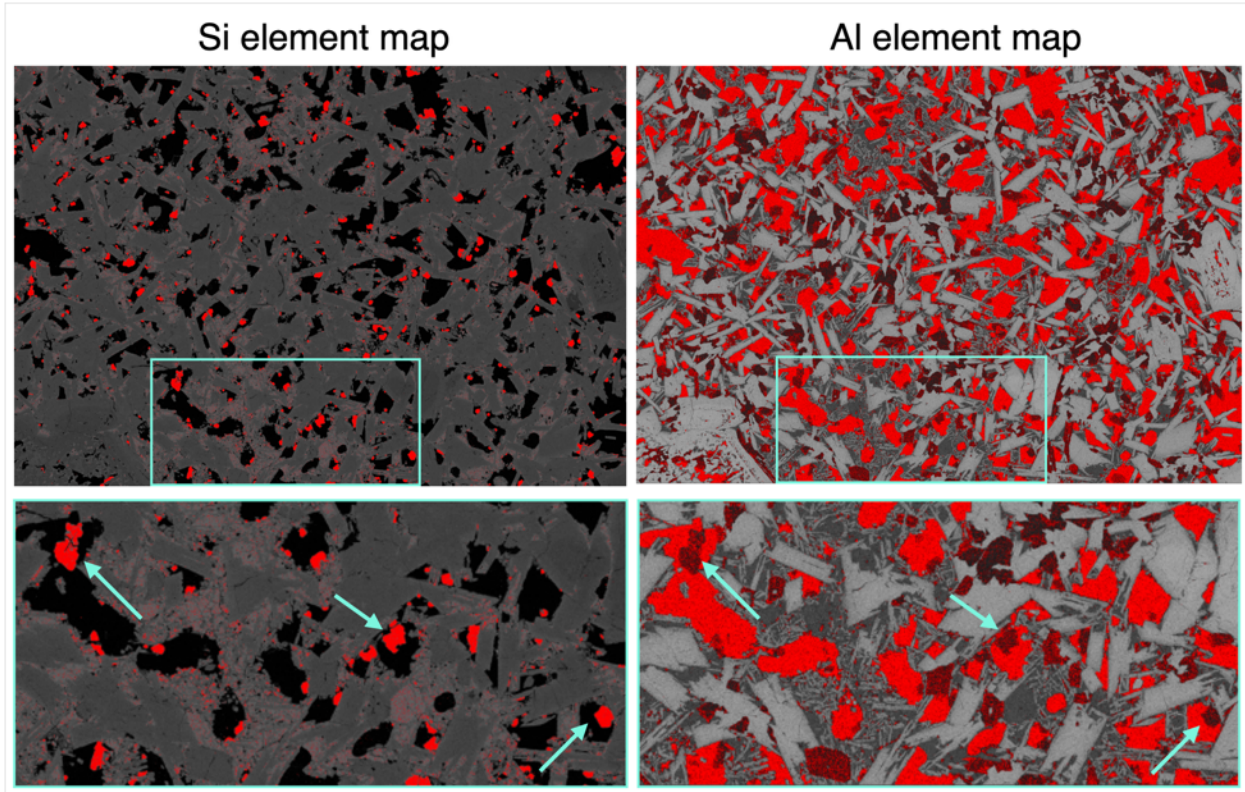


Figure S6. Comparison of Si and Al element maps demonstrating the presence of a small amount of Al in the void-occupying Si phases. Turquoise boxes in upper images show location of enlarged lower images; turquoise arrows point to example Si phases.

Vesicle shape measurements

We use form factor as a measure of vesicle shape. The 3D form factor is defined as $F_{3D} = S_{equiv}/S$, where S_{equiv} is the surface area of a sphere of equivalent volume and S is the measured surface area, such that a spherical vesicle has a form factor of 1. We use the same definition of form factor in 2D, with surface areas replaced by perimeters. We measure only the largest bubbles to avoid uncertainties related to image resolution (Liu et al., 2015). 3D diktytaxitic textures analyzed in Figure S5 are from voids not connected to the main vug network and have sizes that are similar to the groundmass vesicles. Both diktytaxitic vugs and groundmass vesicles have low form factors, indicating a large degree of deformation. In 3D, the larger groundmass vesicles have higher form factors than diktytaxitic vugs of equivalent volume, indicating less tortuous bubbles in the groundmass than in the diktytaxitic zones. The fully connected network of vugs has a form factor of ~ 0.02 , significantly less than all bubbles analyzed in Figure S7. In 2D, groundmass vesicles have lower form factors than the diktytaxitic vugs; this is most likely due to wall roughness that was not captured in the XCT images.

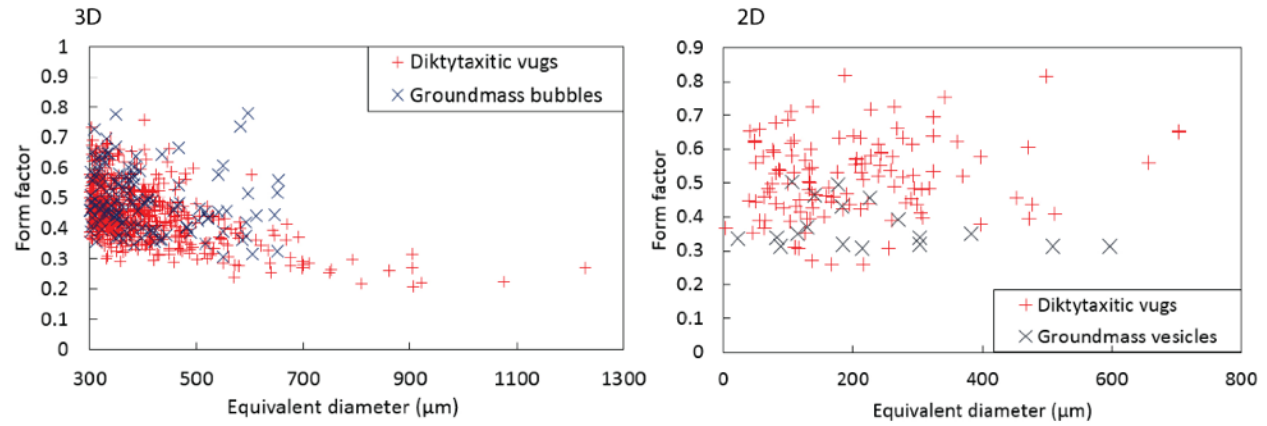


Figure S7. Comparison of pore shapes in diktytaxitic vugs and groundmass vesicles in the large enclave. Measurements made in 3D from XMT scans extend to larger sizes but at lower resolution than measurements made in 2D from BSE images. Resolution is important for form factor, which uses surface area/perimeter.

Diktytaxitic textures

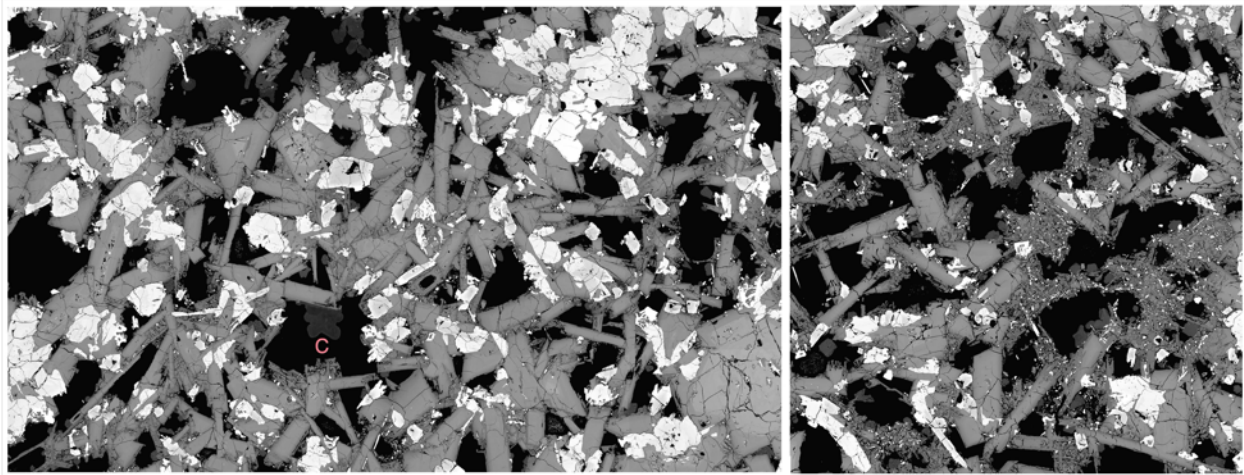


Figure S8. Examples of diktytaxitic textures in the core of the large enclave showing well developed crystal network with angular vugs and cristobalite (C; left) and clumps of microcrystalline groundmass within diktytaxitic framework.

Spatial resolution of 3D images can be unreliable for analyses of the connected porosity, since all objects (pores or films separating pores) smaller than the voxel size (here $14.4\mu\text{m}$ per voxel) is not detected. Such films could be resolved in the SEM images, however, and no glass films were observed in thin section in the diktytaxitic areas: the angular vesicles are separated exclusively by crystal walls and crystal-glass aggregates. Nevertheless, we ran a sensitivity analysis for the connected network of vugs in the diktytaxitic textures by eroding the network by 1, then 2 voxels with a rolling ball method. This significantly reduced the volume of thresholded material (blue in Figure S9). A reduction of 2 voxels produced a significantly under-thresholded image (Figure S9.C): the blue areas are surrounded by a thick layer of dark pixels (pore-space) and several vesicles are omitted. This last scenario is therefore unlikely. The full diktytaxitic network of vugs had a volume of 675 mm^3 in this scan; erosion by 1 voxel produced smaller networks of bubbles (up to 44.4 mm^3); erosion by 2 voxels produced many smaller bubbles (up to 2.7 mm^3).

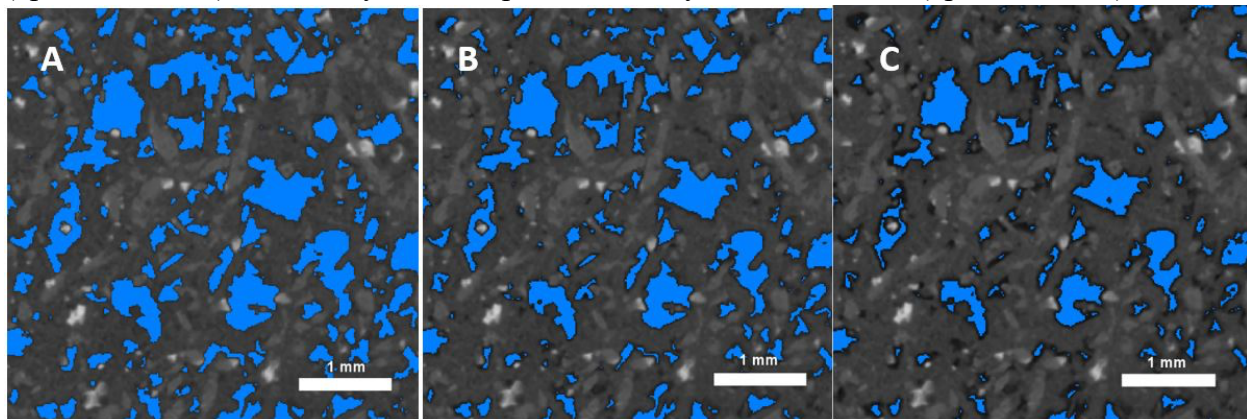


Figure S9. Illustrations of the zones included in the main network of diktytaxitic vugs for (A) the original threshold, (B) erosion by 1 voxel, and (C) erosion by 2 voxels. Areas in blue are the thresholded pores.

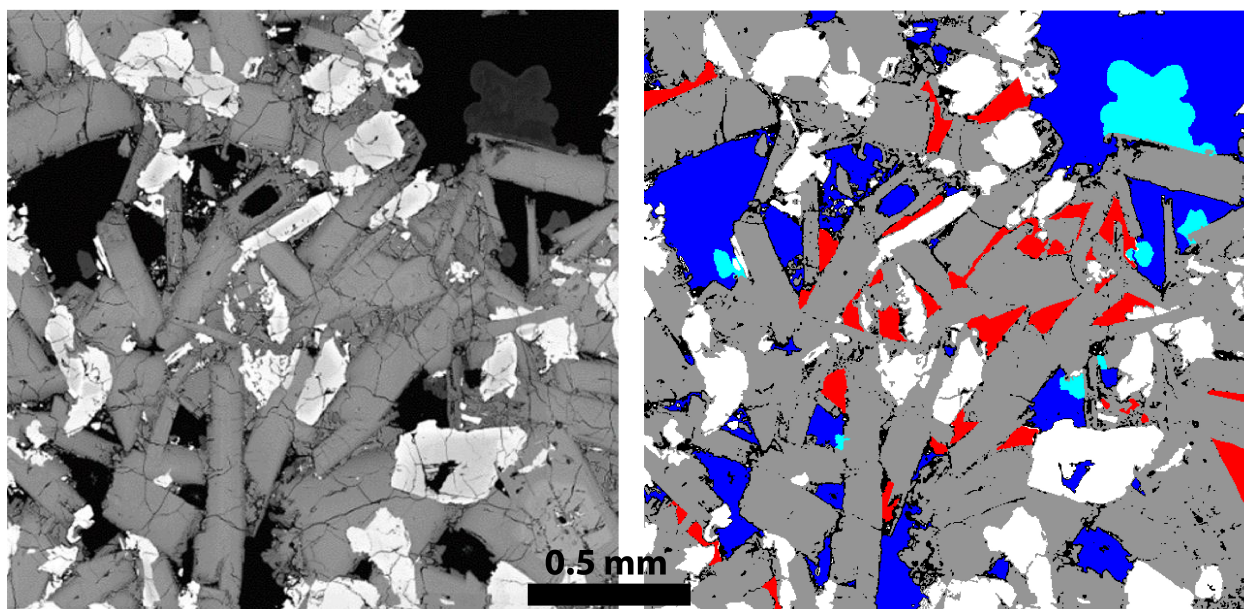


Figure S10. Melt in the diktytaxitic core of the large enclave either occurred in segregation patches or in “zonations” within the crystal framework. Here, a zone of melt in the crystal framework between diktytaxitic textures, in a BSE SEM photomicrograph (left). The different phases were isolated into a false colour image (right), with red = glass, grey = plagioclase, white = oxides, light blue = cristobalite, and dark blue = void space.

Supplementary videos

The videos provided in supplement show the following features:

- ***84C1155_Core-to-Rind_Transition_XY***: a view through the 25 mm diameter cylinder taken from the large enclave (84C1155). This sample shows the transition between the core and the rind of the large enclave. The 3D render shown in Figure 10 of the manuscript was made in this sample
- ***84C1155_Core-to-Rind_transition_YZ***: a flipped view of the same sample (as above), where the core-to-rind transition is visible in each image.
- ***84C1155_5mm8_Rind***: A close-up of the glass-rich rind of the large enclave (84C1155). This is a 3D scan taken of the 5mm-diameter cylinder from the large enclave (8th scan in a series of 9 scans through this cylinder).
- ***84C1155_5mm3_Core***: A close-up of the diktytaxitic core of the large enclave. This is a 3D scan taken of the 5mm-diameter cylinder from the large enclave (3rd scan in a series of 9 scans through this cylinder).
- ***84C1155_5mm3_pyroxenes***: A 3D render of the pyroxenes in the same sample shown in “84C1155_5mm3_Core”. The colors represent connected crystals. The crystals in red represent a large network of touching crystals.
- ***84C1162_Small-enclave***: a view of the 3D scan of small enclave 84C1162. This scan shows the glass-filled “fracture” in 3D through the sample.
- ***84C1163_Small-enclave***: a view through the 3D scan of small enclave 84C1163. Since the sample was very small, the coring process to extract a cylinder was difficult, and led to part of the sample having more of an oval shape.

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