Bubble nucleation in synthetic rhyolitic glasses along a thermal gradient at 1 bar

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Motivation

Bubbles drive explosive volcanic eruptions, but the mechanisms of bubble nucleation remain only partially understood.

Isolating thermal effects on nucleation provides insight that can be compared to findings from isothermal decompression experiments. Results will contribute to a model for bubble nucleation and growth in diverse magmas.

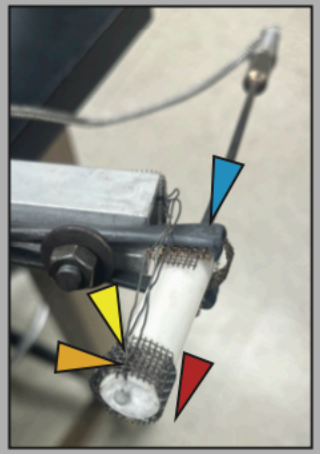
Experimental Design

We developed a protocol to trigger nucleation along a thermal gradient.

Samples are placed in a ceramic tube packed with kaolin wool. A swivel-arm is used to slowly introduce samples past an aluminum heat shield and into an open-door furnace.

The "hot end" of the sample is touched to an Inconel block in the furnace while the "cold end" remains relatively cool. Instantaneous temperature readings using K-type thermocouples along the length of the sample monitor the development of a thermal gradient within the sample.

Slow extraction from the furnace begins after the "hot end" of a sample reaches its estimated glass transition temperature (Tg), but before the "cold end" does.



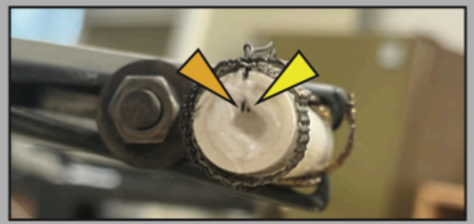


Fig. 1a: *Sample holder and thermocouples with vesiculated sample protruding from end. Colors correspond to T-t graphs, below.*

Fig. 1b: *Empty sample holder showing thermocouple placement.*

Fig. 2: *Inconel block configuration inside furnace, behind heat shield.*

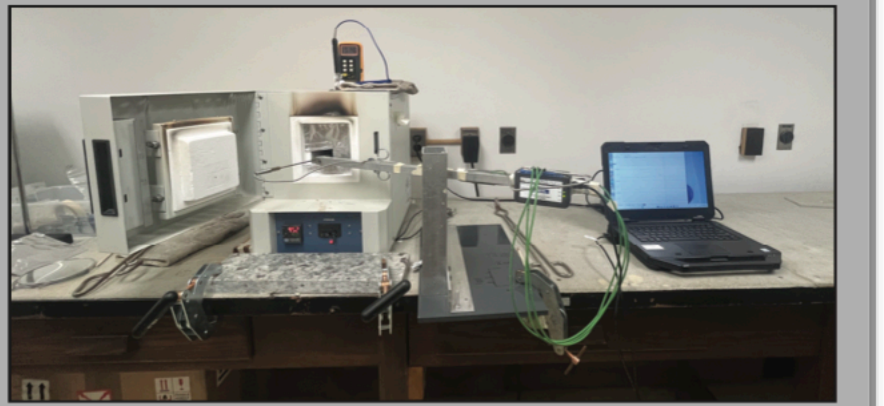


Fig. 3: *Experimental setup with furnace, heat shield, sample-swivel, thermocouples, and computer.*

Homogeneous Heating Experiments

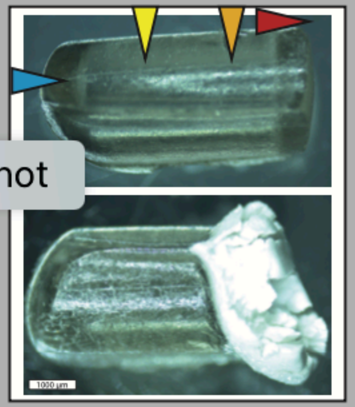


Fig. 3: *Crystal-free rhyolite with 4.9 wt% H_2O before and after heating the "hot end" above its T_g of 385˚C. Triangles represent thermocouples (Fig. 1). Prepared following Garnder et al., 2014.*

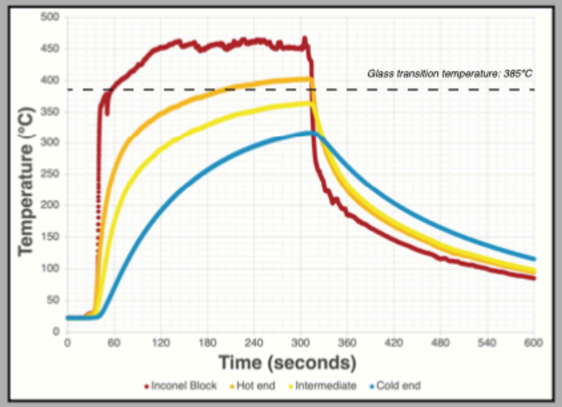


Fig. 4: *Temperature vs time graph for the homogeneous sample in Fig. 3. Colored lines represent instantaneous readings from k-type thermocopules (Fig. 1). The end of the sample touching the Inconel block was above T_g for 4.5 minutes; the "hot end" was above T_g for 2 minutes.*

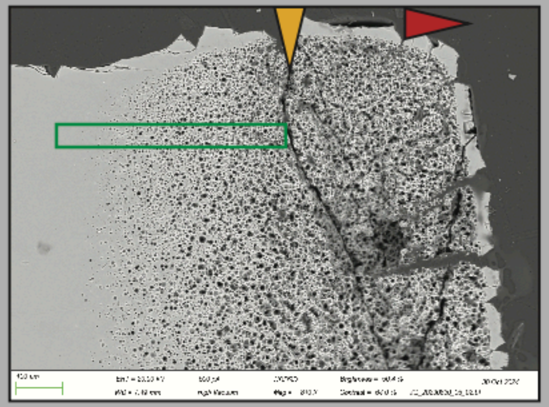
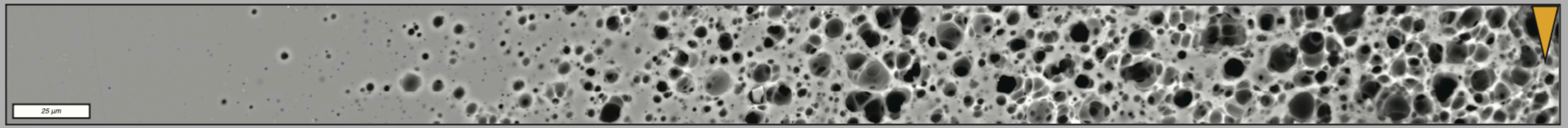


Fig. 5: *The homogeneous sample in Fig. 3 was cut, ground, and polished to expose the bubble gradient that developed along the thermal gradient. SEM-BSE imaging was conducted at Lafayette College using a Zeiss-EVO. Colored triangles represent approximate thermocouple placement.*



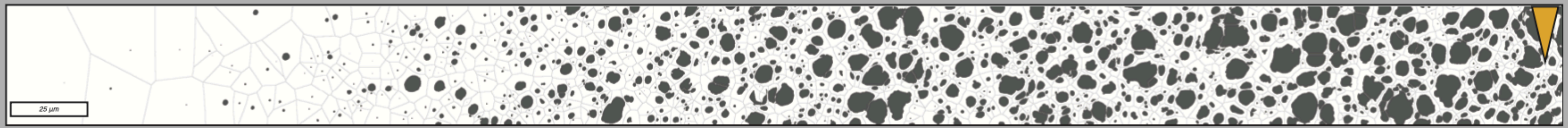


Fig. 6a (top): *A zoomed-in perspective of the green inset box shown in Fig. 5. On the right (the hot end), bubbles are large, numerous, and coalescing. On the left (the cold end), bubbles are small, sparse, and independent from one another. The orange triangle represents the approximate lateral position of the "hot end" thermocouple (on the exterior side of the sample) . Numbers below Fig. 6a represent approximate time above Tg for that position, assuming a linear thermal gradient.*

Fig. 6b (bottom): *The same bubble gradient as Fig. 6a, processed using ImageJ (threshold, binary, watershed, particle analysis, and voronoi). The dark featuers show the position, shape, and area of bubbles. Each bubble is hosted within a Voronoi cell. The boundaries for these Voronoi cells represent an equal distance between neighboring bubbles.*

Heterogeneous Heating Experiments

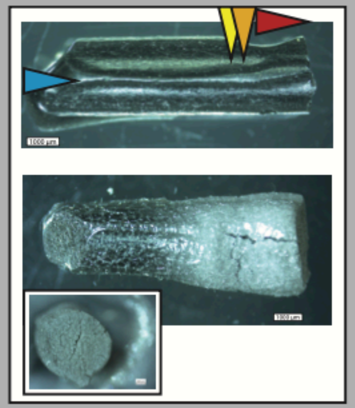


Fig. 8: *Rhyolite with abundant magnetite needles and an estimated 1.5 wt% H_2O, before and after heating. Triangles represent approximate thermocouple placement (Fig. 1).*

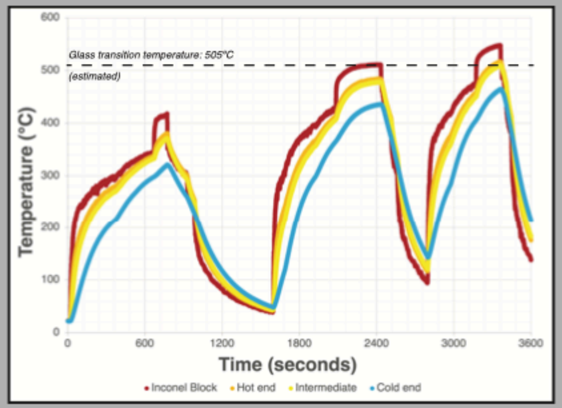


Fig. 9: *Temperature vs time graph for the heterogeneous sample in Fig. 8. The H_2O content was not known at the time of the experiment, so the T_g was determined empirically through a series of gradual heating and cooling steps. We estimate T_g to be 505˚C and H_2O to be 1.5 wt%.*

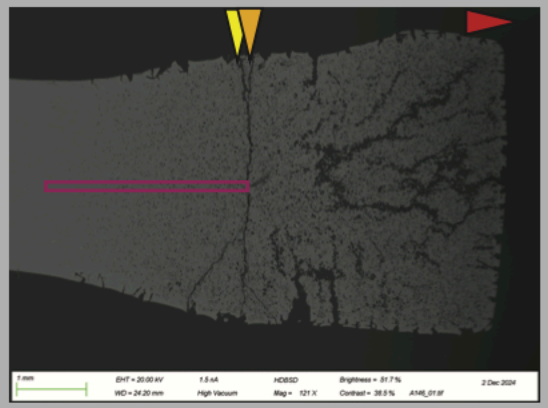


Fig. 10: *SEM-BSE Image of the bubble gradient that formed in the heterogeneous sample in Fig. 8. Cracks typically form at the intersection of samples and thermocouples, clarifying temperature-position relationships after the fact.* ***Fig. 11:*** *The inset box shows the position for the long gradient, below.*

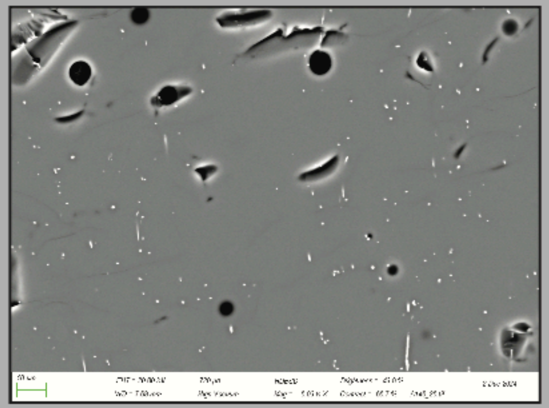


Fig. 12: *SEM-BSE image showing the cold end of the gradient featured in Figs. 10 and 11. Bubbles (and grind/polish irregularities) are small and sparse. Magnetite cubes and needles are distributed throughout the glass; some are attached to bubbles, others are not.*

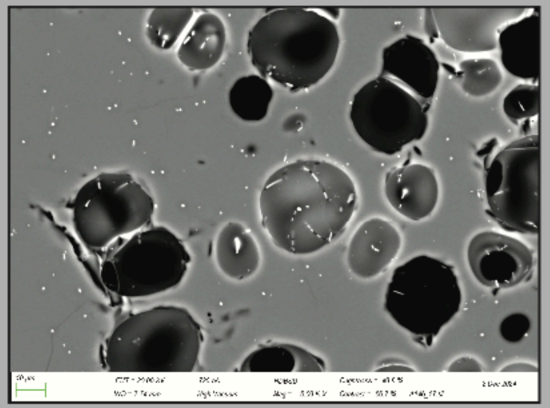


Fig. 13 *SEM-BSE at an intermediate position along the gradient (see purple star,Fig. 11). Bubbles are larger and are starting to coalesce. Magnetite cubes distributed inthe glass. Magnetite needles are oriented and linked to one another in "trains" or "necklaces", and are associated with larger bubbles.*

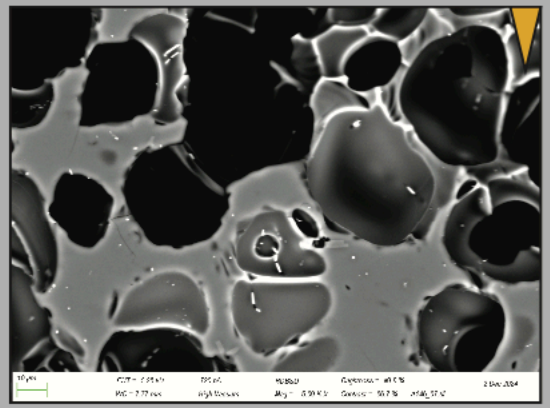
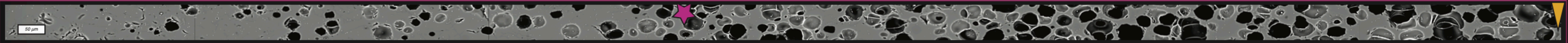
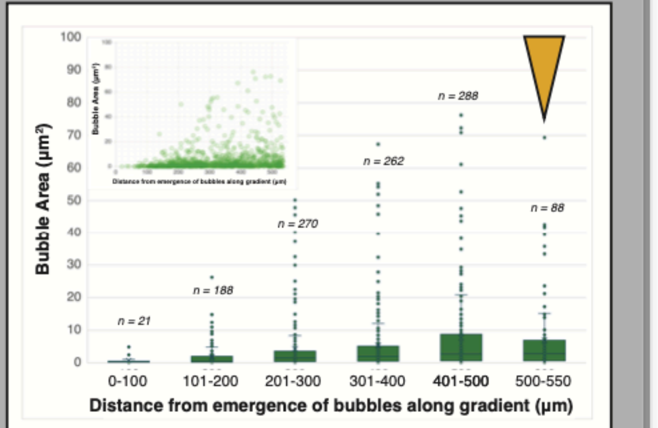


Fig. 14 *SEM-BSE image closer still to the hot end of the gradient featured in Figs. 10 and 11. Bubbles are larger and coalescence is more common. Magnetite cubes distributed throughout the glass. Magnetite needles are again linked to one another and associated with large bubble walls.*





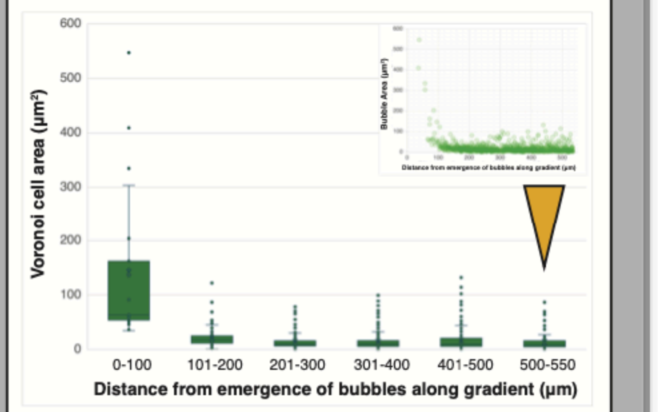


Fig. 7a (top): *Bubble size distribution; and* ***Fig. 7b*** *(bottom) Voronoi cell size distribution. X-axes are oriented from cold (left) to hot (right). Axis values indicate distance from the first observed bubbles at the cold end of the gradient (Fig. 5-6).*

Significance and Next Steps

The unique contribution of these experiments is linked to the development of gradients--in temperature, in bubble nucleation sites, in bubble number densities, in bubble size densities. It is powerful to extract diverse temporal, thermal, and spatial information about bubble nucleation and growth from single samples. We are catching bubble nucleation "in the act" and documenting subsequent growth.

Bubbles and bubble nucleation sites in Voronoi networks will refine understanding of water mobility in diverse magmas under variable environmental conditions preceding eruptions. Bubble nucleation density, coupled with knowledge of time spent above T_g, will be used to better-model nucleation conditions and nucleation rates in magmas across a range of water contents and crystal populations.

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Upcoming Workshop

Bubble Nucleation in Magmatic Systems

May 28-30, 2025

Lehigh University, Bethlehem, PA USA

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