THE CRYSTALLIZATION OF THE ZAGAMI SHERGOTTITE: A 1 ATM.
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Introduction. The SNC meteorites have been the subject of intense interest owing to their
likely Martian origin [1]. While numerous petrologic studies have been conducted, experimental
studies of their crystallization are sparse. Petrographic studies and partial-melting experiments
were conducted using Zagami and Shergotty [2]. The partial-melting experiments produced
pyroxenes of compositions comparable to the Mg-rich cores of natural shergottite pyroxenes
~1140°C, crystallizing ~45% pyroxene, suggesting that shergottites were cumulates. Recent
petrologic studies [3-5] of Zagami measured Mg-rich core abundances of 20±5% [3,4], far below
the inferred 45%. These studies inferred widely different crystallization histories. A two-stage
magmatic history with Mg-rich pyroxene crystallization in a deep-seated (1-2 kb) magma
chamber followed by eruption of a thick, phenocryst-bearing lava flow and cooling at ~0.1-
0.01°C/hr was favored by [3,5], while a single-stage history cooling at 5-20°C/hr and
undercooling was supported by [4]. The difference in Mg-rich pyroxene abundances,
the possibility of a complex pressure-cooling history, and the lack of dynamic crystallization
experiments to constrain the cooling history of Zagami all suggested that a new experimental
study was needed. Our equilibrium crystallization experiments are similar to [2], producing
~38% core-composition pyroxene at 1150°C. Differences in pyroxene abundances are not due to
experimental error (e.g., fO2), but reflect differences in pressure and/or composition between
the experiments and natural samples. Our dynamic crystallization experiments do not produce
Zagami-like textures at cooling rates ≥ 5°C/hr. Textures are dependent on both nuclei density
and cooling rate. Slower cooling rates (≤ 2°C/hr) and relatively few nuclei produce textures
more Zagami-like, but pyroxene zoning and mesostases texture are unlike Zagami. Zagami
probably formed during slower cooling (< 0.5°C/hr), and perhaps with a multi-stage history.

Experimental Method. We conducted 1-atm., gas-mixing experiments using a synthetic glass
of bulk Zagami composition [3] that represents the "normal Zagami" lithology studied by [2,3].
Experiments were run at QFM. Experiments proved to be sensitive to the abundance and
distribution of pre-existing nuclei and a number of thermal histories were used. Experiments
were inserted at 1000°C, heated rapidly (~1000°C/hr) to 1270°C (to allow for melting and glass
homogenization), cooled at 100°C/hr to 1150°C (pigeonite and augite crystallization), and heated
rapidly to 1230°C (the melting temperature), producing ~5% of evenly-distributed crystals.

Equilibrium Experiments. After melting at 1230°C, experiments were taken rapidly to
temperatures of 1260-1150°C (Table 1). The liquidus occurs between 1255 and 1260°C and
pigeonite is the liquidus phase. Augite first appears in the 1175°C charge. Pigeonite and augite
show a systematic increase in Fs content with decreasing temperature. Many of our experiments
crystallized very minor amounts of olivine or orthopyroxene, which nucleate more readily than
augite and pigeonite. The liquidus of [2] occurred at ~1240°C, with pigeonite as the liquidus
phase and augite appearing at ~1170°C. Our experiments closely matched the compositions of
natural Zagami Mg-rich cores (Pigeonite, Fs29.3,Wo12; Augite, Fs20,Wo32; [2]) at a temperature
of 1150°C (Table 1), producing ~18% pigeonite and ~20% augite. This temperature is slightly
above that of [2] (~1140°C) and the cores are somewhat less abundant (38 vs. 45%), but overall
the agreement is quite good. Both experiments produce more pyroxene than natural Zagami Mg-
rich cores (20±5%).

Several possibilities exist to explain the differences in pyroxene abundance. Experimental error is possible. Experiments of [2] produced early Fe,Ti-oxides, which are late-
stage phases in Zagami, suggesting an unreasonably high experimental fO2. We conducted
experiments at 1150°C at fO2 of QFM+2 and QFM+3.9 (pure CO2), producing Fe,Ti-oxides
only at QFM+3.9, suggesting that the experiments of [2] were > 2 log units above QFM. While
the pyroxenes crystallized at QFM+3.9 were slightly more magnesian than at QFM, the
differences were slight. In addition, our QFM experiments did not produce early Fe,Ti-oxides,
yet yielded similar results to [2], suggesting that experimental error in \( fO_2 \) cannot explain the differences in pyroxene abundance. More likely, these experiments do not accurately reflect the early crystallization of Zagami. Several authors [2,4] have argued that Zagami is a cumulate and, thus, the bulk composition should not be used as the starting composition. Recent petrologic studies of Zagami provide direct evidence that "normal Zagami" is probably not representative of the bulk liquid. Zagami contains a "dark, mottled lithology" that comprises differences in pyroxene abundance. More likely, these experiments do not accurately reflect the Dynamic Crystallization Experiments. To constrain the cooling history of Zagami, we are conducting a set of experiments that vary both nuclei density, by varying the melting temperature (1250°C, few nuclei; 1240°C, intermediate; 1230°C, abundant nuclei), and cooling rate (10, 5, 2, 0.5°C/hr). Textures of the charges are dependent on both cooling rate and nuclei density (e.g., [7]). Similar textures have been produced at 1250°C cooling at 5°C/hr and 1240°C cooling at 10°C/hr. Our experiments do allow us to draw general conclusions. Faster cooling rates (5, 10°C/hr) do not produce textures similar to those of Zagami. Textures produced at 10°C/hr range from small (tens of \( \mu m \)), augite laths (1250°C) to radial, coarse pyroxene (1240°C) to abundant, semi-equant pyroxenes (1230°C). Large pyroxene grains (augite and pigeonite) tend to be very skeletal, unlike Zagami. The groundmass is composed of feldspathic glass ± small augites ± Fe,Ti-oxides. Experiments with abundant nuclei (1230°C) do not produce Zagami-like textures, typically producing charges with numerous small, semi-equant crystals. It appears unlikely that Zagami formed during cooling at 5-20°C/hr, as suggested by [4]. Slow-cooling of a melt with a relatively small number of nuclei appears to be favored by these experiments.

Experiments with relatively few nuclei (1240, 1250°C melting) and slow cooling (2, 0.5°C/hr) do not fully duplicate Zagami. Pyroxenes are large, non-skeletal and elongate to semi-equant, but BSE imaging shows they are extremely complex intergrowths of augite and pigeonite. While Zagami pyroxenes are complexly zoned [3-5], the experimental pyroxenes often contain Fe-rich augite and pigeonite in their cores in a complex pattern suggestive of infilling of initially skeletal grains, unlike that observed in natural Zagami. This suggests that Zagami Mg-rich pyroxenes were formed at a slower cooling rate and were less skeletal than the experimentally-produced grains. Further, we have been unable to crystallize the entire charge in Zagami-like textures. Most experiments produce feldspathic glass ± small augites ± Fe,Ti-oxides. The lack of plagioclase crystallization reflects the difficulty of nucleating this crystallographically more complex mineral and our inability to reproduce physical mechanisms present during the crystallization of Zagami (e.g., flow in the magma). In one experiment (1240°C, 2°C/hr), we have crystallized the charge completely, producing semi-equant augite-pigeonites with a groundmass of radiating plagioclase and Fe-rich augite and minor phosphates, SiO₂ and Fe,Ti-oxides. While these phases are all present in natural Zagami, the texture is typical of Nakhla, not Zagami. We suggest that groundmass textures also support slower cooling for natural Zagami. A single-stage history at slow cooling (≤ 0.5°C/hr) vs. a multi-stage history remains an open experimental question, although petrologic evidence favors the latter.


**Table 1. Equilibrium experiments with temperature (°C), phases present and pyroxene compositions.**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Temperature</th>
<th>Phase Composition</th>
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<tbody>
<tr>
<td>ZAG 053</td>
<td>1260</td>
<td>Glass</td>
</tr>
<tr>
<td>ZAG 054</td>
<td>1255</td>
<td>Glass, Pig (Fs₂₃₋₂₅, Wo₄₋₄₅)</td>
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<tr>
<td>ZAG 051</td>
<td>1240</td>
<td>Glass, Pig (Fs₂₁₋₂₃, Wo₂₀₋₂₄)</td>
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<tr>
<td>ZAG 049</td>
<td>1230</td>
<td>Glass, Pig (Fs₂₂₋₂₄, Wo₂₂₋₂₄)</td>
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<tr>
<td>ZAG 055</td>
<td>1200</td>
<td>Glass, Pig (Fs₂₃₋₂₅, Wo₁₂₋₁₄)</td>
</tr>
<tr>
<td>ZAG 056</td>
<td>1175</td>
<td>Glass, Pig (Fs₂₃₋₂₅, Wo₁₂₋₁₄, Aug (Fs₂₀₋₂₃, Wo₁₂₋₁₄))</td>
</tr>
<tr>
<td>ZAG 041</td>
<td>1150</td>
<td>Glass, Pig (Fs₂₇₋₈, Wo₁₆₋₁₈, Aug (Fs₂₀₋₂₃, Wo₁₂₋₁₄))</td>
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