SUPERCOOL(ED) OLIVINE MORPHOLOGY IN SHERGOTTITES REVEALED USING X-RAY COMPUTED TOMOGRAPHY.

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Introduction: Shergottites comprise most of the Martian meteorites and have a mafic to ultramafic bulk composition and a diversity of igneous textures [1]. Olivine-phyric and poikilitic shergottites are sub-classes characterized by having a crystal cargo of large mafic minerals. Olivine-phyric shergottites have porphyritic textures of large olivine megacrysts set in a fine-grained groundmass of pyroxene and maskelynite [2]. The poikilitic shergottites have assemblages of olivine chadocrysts enclosed by cm-sized pyroxene oikocrysts set in a coarse-grained groundmass of olivine and maskelynite [3,4].

The large crystal cargos in these samples are some of the first minerals to crystallize from their respective parent melts and have been extensively studied to understand shergottite petrogenesis. For instance, compositions of early-formed olivine and pyroxene in equilibrium with other phases (e.g. spinels) are used to establish depths, temperatures, and redox conditions of crystallization. There is increasing agreement that olivine megacrysts and poikilitic assemblages formed at or near the crust – mantle boundary (~85 km) before entrainment, ascent, and complete crystallization at or near the surface [1,3,4,6,7,8,9]. Additionally, linear olivine megacryst crystal size distribution (CSD) patterns and observations of polyhedral morphologies [8,9,10] are commonly interpreted to reflect steady-state crystallization under equilibrium conditions. However, oscillatory phosphorus zonation patterns in olivine from many samples indicate fluctuations in growth rates [10,12].

Recent studies measuring dendritic phosphorus zonation in terrestrial olivines [13] and experimental studies measuring how undercooling (undercooling is defined as the liquidus temperature minus the temperature being considered) controls changes in olivine morphology [14] have questioned the canonical view that large olivine megacrysts grow slowly and concentrically under equilibrium conditions. Here we present X-ray CT results from olivine-phyric and poikilitic shergottites that challenge the notion that early-formed minerals grew slowly under equilibrium conditions.

Samples and Methods: Three olivine-phyric shergottites were analyzed for this study: chips (<5 g) of Larkman Nunatak (LAR) 12095(40A) and Larkman Nunatak (LAR) 12011(54A) were obtained from the Meteorite Working Group. A 2.24 g chip of Tissint was obtained from the Dupont meteorite collection at the Chicago Field Museum. One poikilitic shergottite was analyzed for this study: the main mass (35.72 g) of Roberts Massif (RBT) 04261,0. X-ray computed tomography (CT) scanning of the olivine-phyric shergottites was performed at the Astromaterials X-ray CT Lab at Johnson Space Center. RBT 04261 was scanned at the University of Texas High-Resolution X-ray CT Facility (UTCT) for the Astromaterials3D project [15]. Voxel sizes range from 8.57 µm to 19.40 µm. We used Dragonfly™ software (Object Research Systems) to visualize the data along oblique orientations, create 3D volume renderings, and measure mineral lengths.

Results: Considerable textural diversity exists among the samples and will be reported in a later publication as part of a larger CT investigation of shergottites. Here we are focusing on unique olivine morphologies that are most easily/exclusively viewed using X-ray CT.

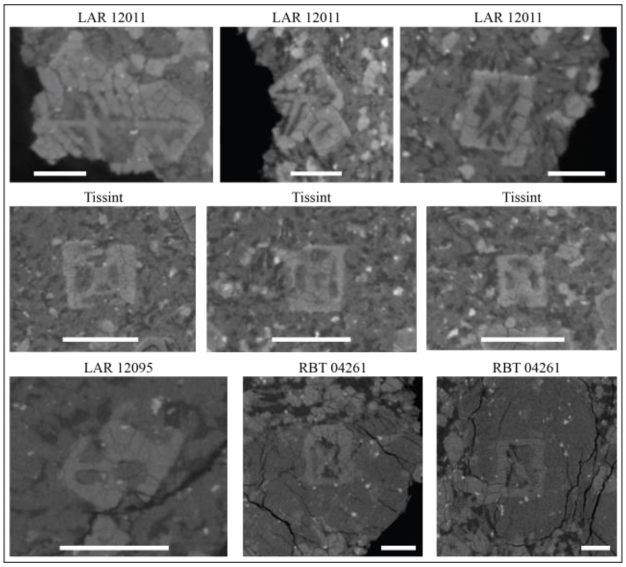

Figure 1: *CT slices obliquely-oriented to expose the central section along [010] in olivine with a hopper morphology. Scale bars are 1 mm.*

Olivine with hopper/skeletal morphologies are present in all of the analyzed samples. We found nine in LAR 12011, two in LAR 12095, four in Tissint, and nine in RBT 04261 (3 poikilitic; 6 non-poikilitic). The central section orthogonal to the crystal short axis (i.e. [010]) shows the characteristic hourglass texture found in hopper olivine [14,16] (Figure 1). This feature is characterized by a “X” of olivine dendritic limbs extending to the crystal’s vertices and trapped melt filling the surrounding area. These olivines have polyhedral exteriors with mostly flat faces and sharp edges/vertices. The hourglass texture is a planar feature around 100 µm thick and completely enclosed within the crystal (Figure 2).

We measured the a-, b-, and c-axis lengths of representative olivine crystals with different morphologies (i.e. hopper, elongated melt inclusion [MI],

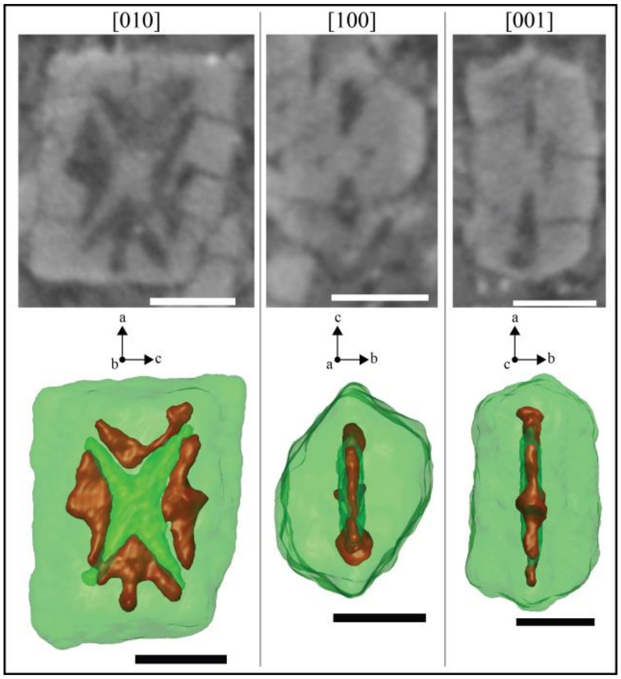

Figure 2: *(Top) Oblique CT slices oriented to expose the [010], [100], and [001] planes along the central portion of the same olivine megacryst. Dark material is trapped melt and the lighter material is olivine. (Bottom) Volume renderings corresponding to the above CT slice. Red is trapped melt and green is olivine (darker green is the central 'X-shaped' olivine). All scale bars are 0.5 mm.*

and polyhedral), as well as the CT # at the center of the crystal. To first order, lower CT # corresponds to higher Fo and lower Fa content. The hopper olivine in LAR 12011 and Tissint are some of the largest crystals and have some of the lowest CT #'s compared to polyhedral olivine within the samples. The hopper olivine in LAR 12095 are intermediate in both size and CT #'s. The poikilitic hopper olivine in RBT 04261 are larger than other poikilitic polyhedral olivine whereas the non-poikilitic hopper olivine are similarly-sized to the other non-poikilitic olivine. There is no correlation with crystal type or size and CT # in RBT 04261.

Discussion: This work is the first time olivine with hopper morphologies have been viewed in their entirety along their central sections in shergottites. Putative hopper olivine were identified in LAR 06319 [11] and Tissint [9], but only partially exposed. Hopper olivine have been shown experimentally to grow quickly under a relatively high degree of undercooling (-ΔT = ~60°C) [14,16,17]. The causes of such degrees of undercooling in natural settings are thought to be ascent/eruption, magma mixing, or vigorous convection in a magma chamber [14].

The prevalence of hopper olivine suggests that the process leading to their formation is not rare. However, as only a handful of hopper olivine are found in each sample, this process may not affect the entire olivine megacryst cargo, although some may have been lost to infilling. We believe the hopper olivine formed during the earliest stages of crystallization, as they are among the largest crystals and have the lowest fayalite content, especially in LAR 12011, Tissint, and RBT 04261.

The megacryst cargo in olivine-phyric and poikilitic shergottites is thought to have formed at ~85 km, which corresponds to depths near the crust-mantle boundary [1,3,4,6,7,8,9]. However, the high degree of undercooling required for rapid hopper growth is unexpected at these depths. We propose a model where initial pulses of melt pond in a magma chamber and lose enough heat through conductive cooling with the surrounding crust to bring about the necessary undercooling. A magma chamber with a high surface to volume ratio (i.e. thin, sill-like) is favorable and a country rock temperature at least 60 °C cooler than the olivine liquidus temperature is required for a -ΔT of 60°C. Further thermal equilibration of the magma chamber then leads to growth at conditions closer to equilibrium, mantling or enclosing the hopper olivine and crystallizing the remaining non-hopper olivine megacrysts and pyroxene oikocrysts. This crystal cargo then undergoes entrainment, ascent, and emplacement at or near the surface. The presence of non-poikilitic hopper olivine in RBT 04261 implies that not all early-formed crystals become poikilitically enclosed, or the melt undergoes another high undercooling event at or near the surface.

Conclusions: The commonality of hopper olivine in olivine-phyric and poikiltic shergottites implies that rapid cooling and crystallization in deep magma chambers are a ubiquitous process on Mars. This challenges the notion that megacryst phases exclusively grow slowly and under equilibrium conditions. This work has implications for interpretations of crystal growth rates, chemical zoning, the temperature of the Martian lower crust, magma residence times at high pressure and temperature, and deep magma chamber geometry.

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