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The Utility of X-ray Computed Tomography in Astromaterials Research and Curation: a Case Study from Martian Meteorites

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Martian meteorites are the only physical materials from Mars currently available on Earth, and multiple microanalytical methods have been applied to them, providing a wealth of information on Martian geologic history—from accretionary processes to relatively recent hydrothermal activity. Despite the extensive scrutiny, there is a paucity of published work using X-ray computed tomography (CT) to investigate Martian meteorites [1,2,3,4], even though it is a non-destructive technique well suited for characterization of astromaterials [5]. Here we present a subset of results from a larger CT survey of Martian meteorites that illustrates the new kinds of information that can be gained from CT, demonstrating its utility for non-destructive examination of new and returned astromaterials, as well as enhancing the scientific return from destructive analyses.

Eight well-studied shergottites (the most abundant class of Martian meteorite, with mafic to ultramafic composition) from the four lithologic sub-classifications were used for this study: basaltic (Northwest Africa [NWA] 13134 and Zagami), gabbroic (NWA 6963), olivine-phyric (Larkman Nunatak [LAR] 12011, LAR 12095, Elephant Moraine [EETA] 79001, and Tissint), and poikilitic (Roberts Massif [RBT] 04261). X-ray CT scanning was performed at three facilities: the Astromaterials X-ray CT Lab at NASA Johnson Space Center, the University of Texas High-Resolution X-ray CT Facility (UTCT), and the Analysis and Test Lab at NASA Jet Propulsion Laboratory. The data were visualized in Dragonfly™

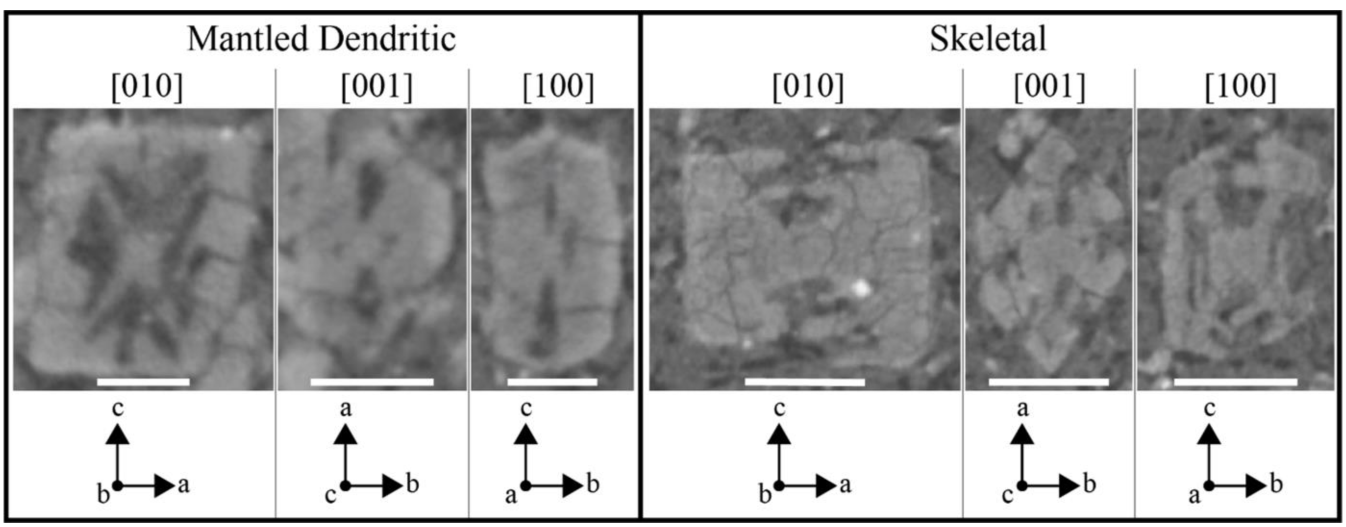

Figure 1: Examples of the two types of olivine with rapid growth morphologies from LAR 12011 (left) and Tissint (right). CT data are obliquely resliced to expose the [010], [001], and [100] planes along the central portion of the same olivine for each. In the mantled dendritic olivine, dark material is trapped melt and the lighter material is olivine. In the skeletal olivine, dark material is infiltrating groundmass and the lighter material is olivine. All scale bars are 0.5 mm.

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software (Object Research Systems) and digitally segmented using its machine learning capabilities. A variety of quantitative measurements were extracted from the segmented data using ImageJ, Blob3D [6], and Quant3D [7] software.

Examination of the 3D textures and compositional variation in three olivine-phyric and one poikilitic shergottite previously established to have commenced crystallization near the Martian crust-mantle boundary [8,9,10] shows pervasive evidence of dendritic and skeletal growth in olivine megacrysts, reflecting crystallization under conditions of extreme undercooling (Figure 1). In two specimens, dendritic olivines are among the earliest formed megacrysts, indicating rapid cooling and crystal growth during initial magma pooling at the crust-mantle boundary (~85 km depth), a process that has not been documented in Earth basalts. Three specimens show skeletal and hopper olivines arising later in the crystallization sequence but before the final stages, likely during magma ascent. The ubiquity of these surprising crystal textures provides key new insights on Martian thermal structure and magma dynamics.

3D shape preferred orientations (SPO) measured in a series of terrestrial basalts with known geologic context were compared to shergottite SPOs to infer emplacement environments (i.e. lava flows, dikes, sills, cumulates). Interpretations for the emplacement of basaltic and olivine-phyric shergottites vary anywhere from sub-surface cumulates to thin extrusive flows. Similarities in SPOs between the olivine-phyric and basaltic shergottites and the terrestrial dike samples indicate that at least the basaltic and olivine-phyric samples in this investigation were likely emplaced as shallow dikes on Mars.

Three samples were specially prepared so that planes of interest identified using X-ray CT could be exposed as thick sections for subsequent *in situ* analyses. LAR 12011, LAR 12095, and EETA 79001 were each embedded in a 1-inch epoxy puck and scanned with fiducial markers so that the largest olivine crystal that did not touch the sample boundary could successfully be cut directly through its central section (Figure 2). This preparation protocol allows us to ensure that we examine the largest and thus probably earliest-nucleating complete crystal with a straightforward, easy to interpret habit, and that subsequent compositional and isotopic analyses represent true core-to-rim sampling spanning the maximum extent of the crystallization episode.

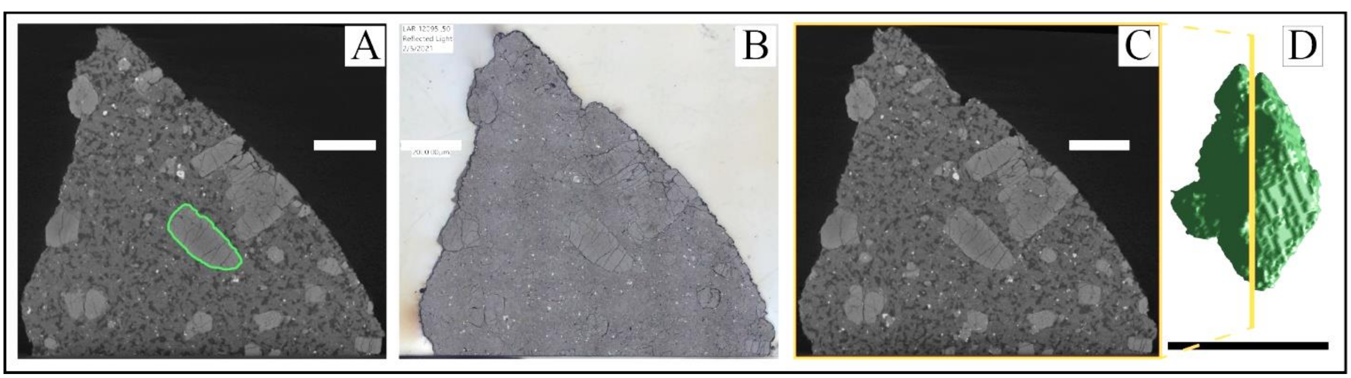

Figure 2: (A) Oblique CT slice showing central section of targeted olivine of interest (green) in LAR 12095. (B) Reflected-light image of resulting thick section. (C) Oblique CT slice (from original scan) re-oriented to best match thick section surface. (D) Volume rendering of olivine of interest with yellow line showing position of re-oriented CT slice from (C). All scale bars are 2 mm.

This work demonstrates how careful X-ray CT examination leads to fresh insights, even in well-studied material of great scientific interest, by offering a holistic, complete-specimen view that can reveal

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otherwise overlooked or unquantifiable textural information. It is also exceptionally complementary for all types of microanalytical work by allowing optimized, targeted sectioning while providing otherwise absent 3D context. CT analysis will be particularly important for optimizing the utilization of precious material brought back to Earth from asteroidal and planetary sample return missions.

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