VOLUMETRIC ANALYSIS OF MICRO-CRATERS IN APOLLO 16 SAMPLES VIA X-RAY COMPUTED TOMOGRAPHY AND LASER CONFOCAL MICROSCOPY. J. B. Garvin[1], J. S. Jones[1], J. M. Sietins[2], R. Kent[1], W. H. Green[2], & T. R. Walter[2]; [1]NASA Goddard Space Flight Center (8800 Greenbelt Rd., Greenbelt, MD 20771; james.b.garvin@nasa.gov); [2]Materials and Manufacturing Science Division (MMSD), US Army Research Laboratory, Aberdeen Proving Ground, MD 21005.

Introduction: Micro-craters are well preserved and studied in Apollo samples at sub-micron scales in two-dimensions [1-5, 8-9]. Seminal efforts by Horz, Hartung, Gault, and others have outlined basic crater morphology relationships across suites of Apollo lunar samples. Theoretical and experimental work has developed a general understanding of the micro-meteorite impact process at relevant scales [3-4]. However, 3-dimensional analysis of the surface topology and interior target relationships has been slowed due to lack of suitable non-destructive evaluation (NDE) techniques at relevant scales. On the basis of recent work with x-ray computed tomography (xCT) and laser confocal microscopy (LCM) of lunar samples [7,10], it is now possible to measure sub-micron 3D relationships associated with lunar micro-craters within a variety of target types. Here we report on preliminary 3D observations of representative micro-craters on *Apollo 16* sample **64435,95** (heterogeneous impact melt breccia), as well as a search for crater features in lunar rake sample **65703,12** using xCT systems at NASA GSFC and the US Army Research Laboratory (ARL). In addition we report on sub-micron "nano-topography" of micro-craters on these samples via LCM. Volumetric (3D) data analysis and histogram-based segmentation are used to quantify newly discovered relationships.

Instruments: The GSFC NDE facility includes a custom *North Star Imaging X5000* xCT with voxel resolution as fine as ~ 2-5 μm depending on sample size, together with a *Keyence Model VK-x250* violet LCM with ~10 nm vertical precision. Via a collaboration with ARL, a *Zeiss Xradia 520 Versa* xCT system was utilized for higher volumetric resolution down to < 0.4 μm/voxel. Our focus here is on multi-scale 3D analysis of a sequence of micro-craters at < 10 μm scales using analysis methods enabled by commercial software packages such as *VG Studio*, *CTan*, *Mountains Map*, and others developed at GSFC.

Approach: xCT imaging of sample **64435,95** was conducted at both the GSFC and ARL NDE facilities at two different voxel scales: (1) ~10 μm/voxel for whole-sample context, and (2) at ~1 μm/voxel for focused analysis of specific micro-craters. In addition, LCM nano-topographic surveys of micro-craters were conducted with horizontal sampling < 100 nm.

The objective was to examine the 3D volumetric characteristics of the micro-crater topology, as well as the effect within the target rock sample due to the hypervelocity impact process. Given that sample **64435** was collected on the rim of a subdued impact crater [6] and represents a heterogeneous impact melt breccia with abundant zap pits, our hope was to document target rock deformation at new scales and link them to the surficial expression of the micro-cratering process.

Methodology: We have isolated micro-craters on the surface of the **64435,95** sample and used the GSFC xCT and LCM data to target the ARL *Zeiss Xradia* xCT measurements to the most distinctive 5 craters of interest. ***Fig. 1*** illustrates the "whole-rock" xCT scan conducted at the GSFC NDE facility in a typical false-color slice. The 4.52 g sample is heavily fractured, with some apparent emanation of near-surface fractures in response to the localized zap-pits. The largest of the zap-pits is ~ 800 μm (rim diameter).

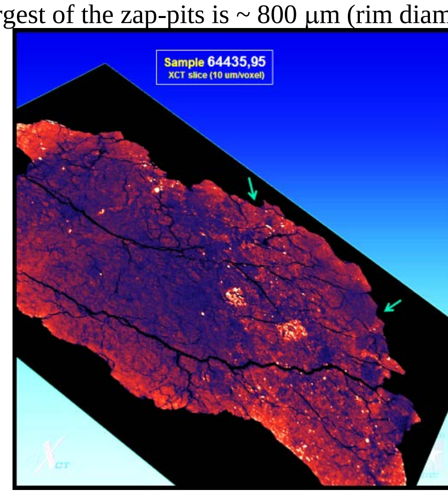

Fig. 1: *GSFC xCT slice of Sample* **64435,95** *showing interior fractures and external micro-craters (arrows). Please see text.*

Results: Analysis of the largest zap pits observable on **64435,95** in the GSFC xCT scan hinted at their impact on the larger target rock volume, but with few specifics. The LCM measurements documented the variability in central pit shape and spallation zone topography beyond the central crater up to 2-3 radii, with suggestions of continuing fractures below the surface. ***Fig. 2*** illustrates the nano-topography of a large zap pit that we targeted for micron-scale xCT using the ARL *Zeiss Xradia* system (**Fig. 3**).

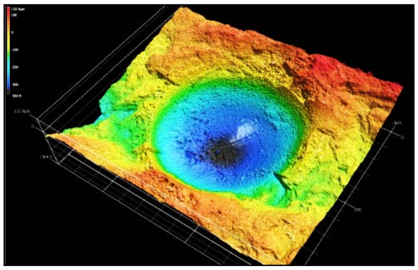

Fig. 2: *LCM micro-relief image of a ~ 800 μm diameter micro-crater on* **64435,95** *with ~ 370 μm of total relief.*

By investigating the target volume beneath the largest 5 zap pits in the sample, we have been able to evaluate the extent to which the relatively fresh-appearing micro-craters produced internal displacements, melting, and fracturing within their target volumes, and the relation to diameter (KE of the impact). For the largest of the zap-pits, a zone of impact deformation could be identified in the 1-2 μm/voxel xCT scan, with a radial extent up to 50% of the radius of the crater cavity (**Fig. 3**). Beyond this, an outer zone of likely impact related damage forms a fracture network radiating roughly 5-6 radii from the center.

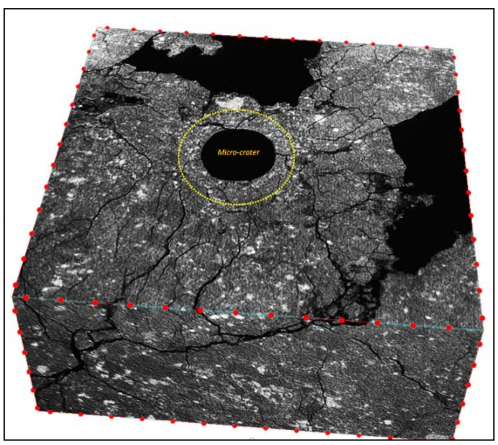

Fig. 3: *~1 μm/voxel xCT "volume" of a large micro-crater on* **64435,95** *showing a zone of deformation around the cavity. This Zeiss Xradia view is a cut across the interior of the sample; "black" areas are voids in this case.*

Figure 3 shows a 3D xCT "volume" rendering with strong evidence of the effect of the impact on the fracturing pattern within the target rock. Preliminary analysis of the other zap-pits suggests a broadly similar pattern of sub-crater floor deformation, but additional 3D analysis is required to quantify the extent (in volume % or normalized to cavity volume).

Discussion: These preliminary observations and the ongoing analyses point to target response to the micro-cratering process beyond a simple "skin deep" excavation, with consequence to the mechanical properties of a zone beneath the defining cavity of potentially altered material phases.

In order to evaluate the uniqueness of these multi-scale measurements, we next explored two Apollo 16 rake samples (**65703,12**) where potential zap pits had been documented [6]. Our aim was to characterize the interiors of these particles at sub-micron scales using the ARL *Xradia* xCT in search of internal deformation associated with micro-cratering. Initial LCM and SEM surveys cast doubt on the origin of the bright surficial features classified as zap pits. xCT scans at 0.6 to 2.7 μm/voxel revealed an internal network of voids as well as a distribution of x-ray absorbers (possible metal oxide precipitates). The distribution of voids was mapped using surfacing, segmentation and classification techniques optimized by ARL (**Fig. 4**) and indicates ~ 1.26 to 2.2 volume %. These values are far smaller than estimates for vesicles in typical lunar basalts (> 15 vol. %). We believe these new estimates are pathfinders for what volumetric analysis of voids in lunar samples across a range of compositions could reveal by means of xCT analysis.

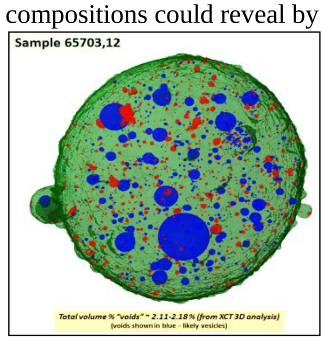

Fig. 4: *Spheroidal rake sample particle from* **65703,12** *segmented into voids (blue), x-ray absorbers (red), and matrix (green). Particle diameter is ~ 1 mm.*

SUMMARY: We have commenced an initial set of multi-scale observations of the interiors of lunar samples using xCT methods that have revealed "volumetric" patterns previously difficult to quantify [1-5] due to the limitations of 2D analysis methods. Our first-order characterization of zones of deformation within micro-crater target rock volumes suggests that even in a strength-scaling regime there are measureable target responses to the cratering process beyond surficial expressions (pits, spalls).

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References: [1] Horz F., *et al.* (1975) *Planet. Space Sci. 23(1),* 151-172. [2] Horz F., *et al.* (1971*) J. Geophys. Res. 76*, 5770-5798.[3] Fechtig H., *et al.* (1973) *Cosmochem. Moon Planets*, 585-604. [4] Schneider E., *et al*. (1973) *Proc. 4th Lunar Sci. Conf.*, 3277-3290. [5] Morrisson D., *et al.* (1973) *Proc. 4th Lunar Sci Conf.*, 3235. [6] Ulrich G. *et al.* (1981) *USGS Prof. Paper 1048*. [7] Galmed A. *et al.* (2017) *Spectrochemica Acta Part B 19*, 75-82. [8] Noble S. K. *et al*. (2016) *47th LPSC*, #1465. [9] Christoffersen R. *et al.* (2017) *48th LPSC*, Abstract # 2578. [10] Ketcham R. (2005) *Geosphere 1*, p. 32-41 (see also: *Comp. Geosci. 27*, p. 381-400).