MICROSTRUCTURAL EVOLUTION OF THE CIVET CAT NORITE (72255). T. M. Erickson[1,2] and K. Prissel[1,2], R. Christoffersen[1], J. J. Barnes J[3], W. P. Buckley[1,2], C. Crow[4], S. Eckley[1,2], T. M. Hahn[5], L. P. Keller[2], J. Kent[1,2,6], P. Kinny[7], J. Setera[1,8], Simon J.[2], and Valencia S.[9,10], [1]Jacobs-JETS II, [2]ARES Division, NASA JSC, 2101 NASA Parkway, Houston, TX 77058 (Timmons.m.erickson@nasa.gov), [3]Lunar and Planetary Laboratory, University of Arizona, [4]University of Colorado, Boulder, [5]CAMECA Instruments Inc., [6]GeoControl Systems, [7]School of Earth and Planetary Science, Curtin University, [8]CASSMAR, University of Texas at El Paso, [9]NASA Goddard, [10]University of Maryland College Park

Introduction: The 'Civet Cat Norite' is a ~ 2.5 cm clast within the Apollo impact melt breccia sample 72255 collected during Apollo 17 EVA 2 at Boulder 1. The norite is primarily composed of plagioclase and orthopyroxene with fine-scale exsolution lamellae of augite. The plagioclase and orthopyroxene (OPX) coexist with minor quartz and augitic clinopyroxene (CPX), and accessory apatite, baddeleyite, chromite, ilmenite, loveringite, merrillite, rutile and zircon [1, this study]. The major minerals range from 1 to 4 mm in size and show a cataclastic texture indicated by banding of the light and dark phases [1]. The chemical composition of the orthopyroxene, augitic exsolution lamellae, and exsolved oxides suggest the norite crystallized in the lower crust of the Moon (10 – 70 km depth) and was subsequently excavated by impact(s) [2]. Shock pressure estimates for the norite range from 15 – 35 GPa based on maskeleynite formation within the plagioclase, kink banding in pyroxenes, and granular recrystallization in the accessory phosphates [3].

Previous Rb-Sr and $^{40}Ar/^{39}Ar$ analyses recalculated with modern decay constants yield relatively young ages of 4.16 ± 0.05 Ga and 3.99 ± 0.03 Ga, respectively [4,5]. However, recent U-Pb analyses of some zircon grains from within the Civet Cat yield an age of 4.45 ± 0.03 Ga [6,7]. While this is the oldest age for any rock recovered from the Moon, the full age spread of zircon from the Civet Cat range from ca. 4.46 to 4.02 Ga [6], indicating variable Pb-loss and complicating interpretation of the primary age. Recent atom probe analyses indicate minimal Pb mobilization within the oldest zircon grain from Civet Cat [7], supporting the interpretation that these ancient zircon ages reflect the age of the norite, rather than an apparent antiquity caused by reverse discordance [6].

To investigate the potential antiquity and deep crustal origin of the Civet Cat norite, we have undertaken high resolution microstructural analyses of the major, minor, and accessory minerals to characterize the primary igneous textures and secondary overprinting by impact and metamorphism. The employed analytical techniques include scanning electron microscope-based electron backscatter diffraction (EBSD) analyses, electron probe microanalyzer (EPMA) chemical analyses, and transmission electron microscopy (TEM) of pyroxene, plagioclase, quartz, zircon, and phosphates.

Results: Consistent with previous studies [1,3] plagioclase displays extensive amorphization and development of maskeleynite. However, EBSD mapping reveals lamellae of strained plagioclase between recrystallized granular domains (Fig. 1). This microstructure appears to have formed through an anisotropic response to shock, wherein twin planes were moderately strained and the host domain was subject to full amorphization, subsequent recrystallization, and thermal annealing.

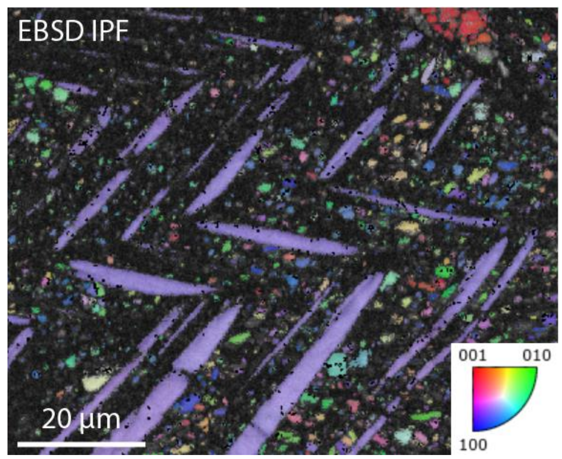

Figure 1. EBSD Inverse pole figure map of shocked plagioclase displaying strained lamellae (purple) and recrystallized granules within amorphous maskeleynite domains.

Orthopyroxene grains ($En_{72}Fs_{25}Wo_3$) show submicron exsolution lamellae of augite that are truncated by oxide phases. EBSD diffraction indexing identify the oxides as chromite and loveringite (Figure 2). Host orthopyroxenes show moderate levels of plastic strain including kinking of the exsolution lamellae. Small intergrown grains of augite ($En_{46}Fs_{11}Wo_{44}$) are found together with the OPX and exhibit mechanical twinning and grain boundary recrystallization substructures. At the boundaries between pyroxenes are recrystallized polygonal grains that exhibit a slight rehomogenization of the OPX-CPX host ($En_{69}Fs_{25}Wo_6$). However, chromite and loveringite in these domains appear to have been coarsened and not reincorporated into the pyroxene crystal chemistry.

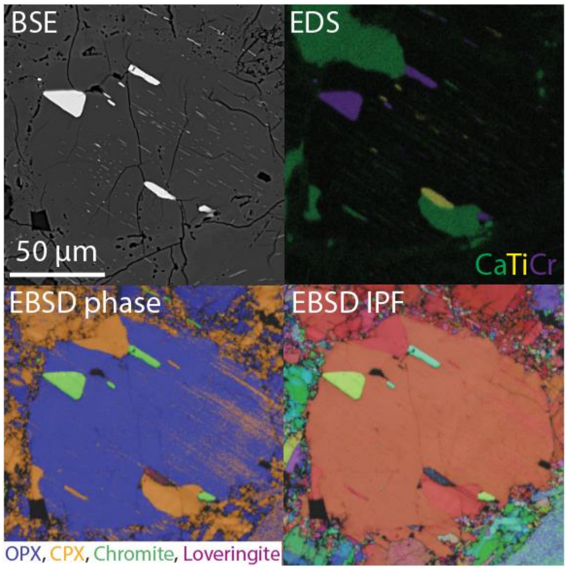

Figure 2. Maps of pyroxene grains exhibiting augite lamellae, chromite and loveringite textures, fine augite grains, and polygonal recrystallized domains. BSE: Backscatter electron. EDS: energy dispersive spectrometry with Ca-green, Ti-yellow, Cr-purple. EBSD phase: opx-blue, cpx-orange, chromite-green, loveringite-pink. EBSD IPF: inverse polyfigure.

Zircon grains range from ~ 10 – 75 µm in size and exhibit an array of textures including {112} mechanical shock twins, plastic strain, and grain boundary rotation substructures (Fig. 3). While the majority of zircon grains gave strong EBSD diffraction patterns, a subset appeared amorphous, likely due to metamictization of the crystal lattice. Baddeleyite substructures include cores with complex twin intergrowths consistent with transformation twins via a solid state transformation, as well as strain-free neoblasts (Figure 4). The baddeleyite orientation variants are consistent with a cubic parent phase, which can form from high-temperature or high-pressure conditions. Cubic zircon phase heritage within other Mg suite samples (e.g. 76535) has been previously inferred to reflect crystallization from a superheated impact melt [8]. However, based on the shock microstructures in adjacent phases identified here, we favor shock pressure-induced transformation to cubic zirconia and subsequent reversion to baddeleyite upon pressure release. Thermal annealing of the high-strain host baddeleyite has led to grain growth of the strain-free neoblasts. Apatite grains exhibit plastic strain and neoblastic recrystallization, similar to the results of [3], whereas merrillite grains are composed entirely of strain-free neoblasts with grain-boundary triple junctions.

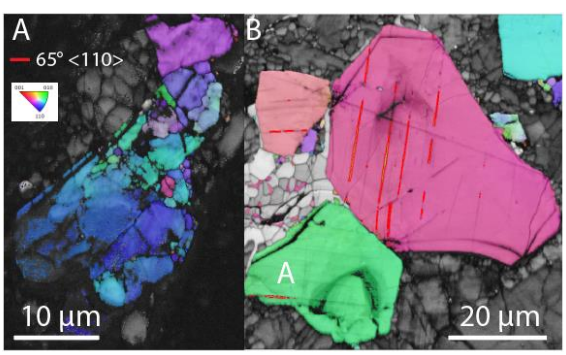

Figure 3. EBSD inverse pole figure (IPF) maps of shocked zircon exhibiting plastic strain and subgrains (A), and mechanical twins (B). The {112} twin boundaries are highlighted in red.

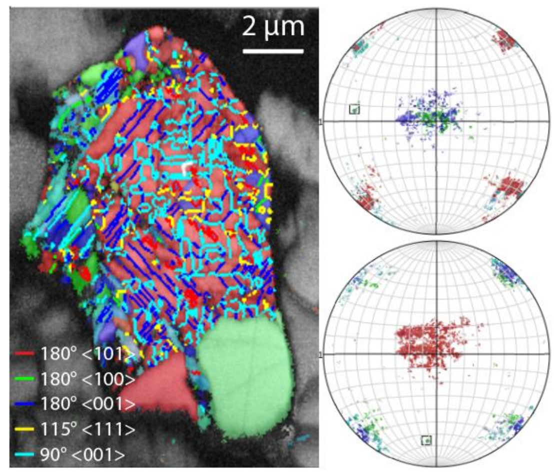

Figure 4. Shock-transformed baddeleyite with misorientation substructures indicating reversion from high-P cubic zirconia and thermal annealing.

Conclusions: The Civet Cat norite exhibits an array of shock microstructures that place constraints on the shock conditions and thermal history of the clast. Based on the plastically deformed pyroxene, diaplectic plagioclase, {112} zircon twins, and evidence for cubic zirconia phase heritage within the baddeleyite, shock pressures ranged from 25 – 35 GPa. The fine-scale exsolution of augite together with loveringite and chromite indicate extended heating in a deep-seated environment. Dynamic recrystallization and grain boundary bulge occurred after cataclasis, potentially when the norite was entrained within the aphanitic host matrix of 72255. These microstructural results, together with high resolution major element, trace element, and isotopic data, will provide further insights into the evolution of the Civet Cat norite.

References: [1] Ryder et al. (1975) The Moon 14, 491-504. [2] Takeda et al. (1982) JGR Solid Earth 87, A124. [3] Cernok et al. (2019) Meteoritics and Planetary Science 54, 1262-1282. [4] Compston et al. (1975) The Moon 14, 445-462. [5] Leich et al.(1975) The Moon 14, 407-444. [6] Zhang et al. (2021) EPSL 302, 175-193. [7] Greer et al. (2023) Geochm. Pers. Letts. 27, 49-53. [8] White et al. (2020) Nature Astronomy 4, 974-978.