THE METEOR CRATER SAMPLE COLLECTION: CONTRIBUTIONS TO IMPACT CRATERING STUDIES. T. A. Gaither, and J. J. Hagerty, U.S. Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001 (tgaither@usgs.gov)

Introduction: In consultation with the USGS Core Research Center and the USGS Geologic Materials Repository, we have completed curation of the rotary drilling samples that were collected during the early 1970s by Dr. David J. Roddy under the auspices of the USGS. This collection represents an invaluable source of material that provides geologic context for impact generated lithologies and spans the entire extent of the ejecta blanket. The collection is now available to the planetary science community to investigate outstanding science questions regarding the formation of Meteor Crater. In an effort to facilitate scientific utilization of, and the broadest possible access to, this invaluable collection, we have created a publicly available website with a searchable database, which allows end users to obtain lithologic and textural information on samples and submit sample requests:

http://astrogeology.usgs.gov/research/Meteor-Crater-Sample-Collection

In addition to the curation aspect of this project, our overarching research objective was to characterize the lateral and vertical distribution patterns and compositional variability of impact generated materials, such as ballistically dispersed impact melts and metallic spherules, within the ejecta. The importance of knowing the geologic context or location of geologic samples was demonstrated by early studies of the Canyon Diablo meteorites [1 and references therein]: specimens found on or near the crater rim are highly shocked, with a progressive decrease in the extent of shock metamorphic effects with increasing distance from the crater [1]. Therefore, we have documented the gross stratigraphy and internal structure of the ejecta blanket as represented by the samples, and performed electron microprobe analysis (EMPA) and scanning electron microscopy (SEM) to obtain compositional and textural information about impact generated lithologies found within the drill cuttings. Herein, we present initial results of our investigation of samples from the USGS Meteor Crater sample collection.

Methods: During the sample curation process, stratigraphic unit designations were assigned to individual samples following the methods of Roddy et al. [2]; units were designated based on the overall color and apparent lithology of clasts and smaller particles within each sample, with a minimal amount of handling to avoid sample contamination and to preserve the maximum volume of material for future users. To assess the distribution patterns of Meteor Crater impact melts, we estimated modal percent impact melt versus target rock matrix within samples along four primary transects identified by Roddy et al. [2]. Magnetic impact melts and meteoritic fragments were removed with a hand magnet, and non-magnetic melt objects were removed using a binocular microscope and picking tweezers. Representative fragments were mounted in 1-inch epoxy rounds and were characterized with the SEM at the Department of Geology at Northern Arizona University. We used backscattered electron (BSE) imaging and Energy Dispersive Spectroscopy (EDS) to evaluate and document the various types of impact melt fragments. Impact melt glasses and metallic inclusions were also analyzed by EMPA for major and minor element concentrations (Al, Ti, Na, Mn, P, Si, Mg, Fe, K, Co, Ca, Ni, and Zn). Analyses were conducted on the JEOL JXA 8200 electron microprobe at UNM's Department of Earth and Planetary Sciences, using 15 kV, 20 nA, and a 1 μm spot size.

Results: The lithic clasts within many drill cutting samples have thick coatings of adhering fine material that obscure the true lithology of ejected clasts. Removal of the adhering fine material from a subset of samples revealed that many samples are composed of clasts from multiple lithologies, in contrast to single-lithology samples expected based on the overturned flap model of ejecta emplacement [2,3]. Using unit thickness estimates acquired during the curation process, we were able to use RockWorks software to generate preliminary stratigraphic cross sections of the Meteor Crater ejecta blanket. The model-generated cross sections have shown several stratigraphic anomalies (e.g., abrupt changes in stratigraphic thickness and depth over short distances). These anomalies suggest unexpected complexities in the subsurface stratigraphy that require additional scrutiny and may imply that traditional models of ejecta emplacement may need to be modified.

During the curation process we also identified abundant shock-melted Coconino Sandstone (i.e., lechatelierite) mixed with fragmented, less shocked lithologies, as well as inclusions of lechatelierite within ballistically dispersed, vesicular impact melt particles.

Preliminary assessment of the lateral and vertical distribution patterns of meteoritic materials within the ejecta blanket reveals that, in the NE, SW, and SE transects, impact melts are concentrated within a zone ~270-300 m from the crater rim, at depths of 2-4 m. We find that impact melts are rare nearer to the rim and further out than ~300 m. Only trace amounts (<2%) of impact melts are present at depths of 0-2 m and deeper than ~4 m, although intact melt clasts are found as deep as 10.5 m. Interestingly, samples from drill holes in the NW transect contain only trace amounts of meteoritic material.

Impact melts analyzed in this study are typically 1-3 mm in diameter (though many are 1 cm or larger), round, oblong, or teardrop shaped and are often coated with white/tan carbonate and quartz rinds. The fragments have black or brown exteriors, highly vesicular interiors of red-orange glass, and contain mineral and lithic inclusions. The majority of impact melts discussed here are generally similar to those described by [4, 5], with some important differences (see discussion below).

Discussion: The observations of lechatelierite mixed with minimally-shocked ejected materials and the presence of lechatelierite within mafic impact glasses are at odds with the ejecta formation models of Hörz et al. [4], Mittlefehldt et al. [5], and Artemieva and Pierazzo [6], which suggest that the Coconino experienced shock melting, but did not participate in the mixing of the melted upper units (i.e., Moenkopi and Kaibab) and was not ejected from the transient crater.

Examination of the impact melt distribution indicates that the zone of greatest impact melt abundance (2-4 m deep) is dominated by Kaibab ejecta, with variable contributions from the Coconino and Moenkopi Formations. We suggest that this zone of high impact melt concentration is an original feature of the ejecta blanket, while the melt fragments in the upper 2 m were subjected to alluvial and/or colluvial processes. We plan to more rigorously quantify and describe the distribution of impact melt fragments and metallic spherules as part of a lithostratigraphic analysis of the drill hole samples. We also plan to document the relative proportions of target lithologies and impact-generated materials within the ejecta samples.

Previous studies of impact melts from Meteor Crater [4, 5] have reported a large range of compositions, including chemically fractionated projectile-derived Fe-Ni metal alloys and sulfides, and variable olivine, pyroxene, and melt compositions. Impact melt fragments studied here are compositionally heterogeneous and have a groundmass consistent with a mafic glass. Compositional variation between and within melt clasts is similar to that described by Hörz et al. [4]. For instance, the mafic groundmass has two variations: a homogenous Fe-rich glass from which pyroxene needles grew, and a Mg- and Ca-rich glass from which dendritic pyroxene crystals grew. The majority of the melt fragments contain angular, fractured quartz grains, which frequently display apparent disequilibrium textures (i.e., partially resorbed grain boundaries) as well as metallic spherules.

Additionally, we observed carbonate lithic inclusions in several melt fragments, in contrast to the near-absence of carbonate inclusions noted in other studies [i.e., 4, 5]. Furthermore, we identify inclusions of lechatelierite within impact melts, which provide clues to the sequence of formation for these materials.

Conclusions: The drill cuttings from the Meteor Crater ejecta blanket are providing new data that confirm the results of previous studies while also providing exciting new information. Our preliminary results have allowed us to make the following conclusions:

- The compositions and textures observed within the impact melts indicate that melting and mixing processes were more complex than previously thought.
- Lechatelierite is common, if not pervasive, within deeper portions of the ejecta blanket. Quantification of the volume of lechatelierite within the drill hole samples may lead to an upward revision of the volume of Coconino Sandstone-derived impact melt ejected from the transient crater.
- Inclusions of lechatelierite within impact melt clasts indicate that shock-melted Coconino Sandstone may have had a greater role in mixing processes that occurred during melt formation than suggested previously by [4].
- Inclusions of dolomite and calcite within several melt clasts suggest that the carbonate-rich Kaibab target rock was not completely volatilized after melting, supporting the interpretations of [7].
- Although Shoemaker and Kieffer [3] characterized the internal structure of the ejecta blanket as consisting of mainly blocky, fragmented beds that are continuous but lie in an inverted stratigraphic order, it is now clear that this idealized model of the continuous ejecta blanket is complicated by local complexities within the debris that were only briefly acknowledged by Roddy et al. [2].

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References: [1] Buchwald V.F. (1975), *Handbook of Iron Meteorites, pp. 1418*; [2] Roddy D.J., et al. (1975) *Proceedings of the Sixth Lunar Science Conference*, 3, 2621; [3] Shoemaker and Kieffer (1974), *Guidebook to the geology of Meteor Crater, pp. 66*; [4] Hörz et al. (2002) *Meteor. Planet. Sci.*, 37, 501-531; [5] Mittlefehldt et al. (2005), *GSA Special Paper*, 384, 367-390; [6] Artemieva and Pierazzo (2011) *Meteor. Planet. Sci.*, 46, 805-829; [7] Osinski et al. (2008), *GSA Special Paper*, 437, 1-18.