SEM CHARACTERIZATION OF IMPACT EJECTA DEPOSITS FROM METEOR CRATER, ARIZONA.

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Introduction: During the early 1970s, the USGS led a program of rotary drilling on the rim and flanks of Meteor Crater [1]. During this program, 161 drill holes were completed, and over 2,500 m of drill cuttings were collected [1]. Drill depths ranged from a few meters to 50 m, and drill cuttings were sampled every 0.3 m. Approximately 72% of these holes were drilled in the over-turned ejecta flap, with the remaining 28% drilled beyond the flap [1,2]. The drill cuttings are now being curated by the U.S. Geological Survey's Astrogeology Science Center in Flagstaff, AZ and are available for request. 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.

Curation: To facilitate scientific access to and analysis of the Meteor Crater drill cutting inventory, we have engaged in a dedicated program of cataloging and curation. We have transferred individual samples from their original storage bags to a climate controlled environment. As of August 2011, ~80% of the sample collection has been fully curated. Our curation efforts include documenting the condition of the sample prior to transfer, designating geologic units to individual samples, documenting the presence of metallic spherules and impact melts, and identifying the approximate contact between ejecta deposits and target rock.

We are also in the process of addressing specific questions regarding the composition and distribution of Meteor Crater ejecta. To this end we are documenting the distribution and compositions of impact melts, metallic spherules, and meteoritic fragments as a function of location within the ejecta blanket. Previous, detailed studies [3, 4, and 5] reported impact melts with a large range of compositions, chemically fractionated projectile-derived Fe-Ni metal alloys and sulfides, and variable olivine and pyroxene compositions. We are combining this existing data with new data derived from the ejecta blanket in an effort to map the spatial distributions of meteoritic components impact melts.

Methods: To assess the physical distribution patterns of Meteor Crater impact melts, we estimate modal percent impact melt versus target rock matrix within drill hole samples along four primary transects identified by Roddy et al. [1]. The presence of specific melt types and their variation with depth were also noted. 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 analyzed with the scanning electron microscope (SEM) at the Department of Geology of 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.

Results: Prior to our SEM analyses we identified five possible types of impact melts from the Meteor Crater drill cuttings, which are described below.

- Type 1: Black or brown, minimally to moderately vesicular, irregularly shaped, and <1 mm to 2 mm in diameter. Similar to those described by [3].
- Type 2: Typically black or brown exteriors with highly vesicular interiors of red-orange glass. Round, oblong, or teardrop shaped and often coated with white/tan carbonate/quartz sand. May contain metallic spherules, some of which are magnetic. Typically 1-3 mm in diameter but many are 1 cm or larger. Similar to those described [3].
- Type 3: 1-10 mm round or oblong clasts consisting of quartz grains embedded in a black, glassy, non-vesicular matrix, and clast surfaces are typically rough and oxidized.
- Type 4: Possible carbonate lapilli consisting of accreted carbonate particles with stalactite-like features and possible metallic particles.
- Type 5: White or tan, frothy, highly vesicular clasts with quartz grains embedded in the matrix, and 1 mm to 1 cm in diameter.

BSE imaging and EDS analyses suggest that melt Types 3 and 4 were not likely produced as a result of the impact. Type 3 clasts contain large, rounded, intact quartz grains surrounded by a pure FeO cement, and do not contain obvious evidence of impact derived materials. Type 4 clasts consist mostly of dolomitic groundmass with an abundance of accessory phases (e.g., barite, rutile, ilmenite, and apatite), but no evidence of impact derived materials. We interpret these materials to have a simple sedimentary origin.

Types 1 and 2 (Figs. 1 and 2) have compositions distinct from one another; therefore ruling out the possibility that Type 1 fragments were derived from the larger Type 2 melts. Type 1 melts contain an Al-rich (i.e., 8 – 15 wt.% Al_2O_3) groundmass relative to Type 2 melts, possible maskelynite grains, abundant examples of flow banding, and meteoritic fragments of variable composition (high and low Ni). Type 2 fragments are compositionally heterogeneous, contain an abundance of Ni-rich metallic spherules, and have a groundmass consistent with a mafic glass (i.e., Si, Mg, Fe, Ca) similar to that described by Hörz et al. [3]. The mafic groundmass has two variations: a homogenous Fe-rich glass from which pyroxene needles grew (center of fragment in Fig. 2), and a granular Mg and Ca-rich glass (edges of fragment in Fig. 2). Type 2 fragments contain angular, fractured quartz grains, which frequently display apparent disequilibrium textures (partially resorbed grain boundaries). Type 2 fragments also contain carbonate fragments, which have not been identified by other studies [i.e., 3 and 5].

Type 5 clasts were presumed to be lechatelierite, and this was confirmed with EDS analysis that showed almost pure SiO_2 compositions and with BSE images that showed highly porous textures. During the curation process we have observed the pervasive occurrence of lechatelierite within the drill cuttings regardless of location within the ejecta blanket. In several instances, we have also identified fragments of lechatelierite within Type 2 melts, providing clues to the sequence of formation for these materials.

As part of our investigation, we also characterized several types of apparent meteorite fragments. Within the Type 1 and 2 melt fragments, we found that meteoritic fragments are found in every example of melt and are often located near vesicle edges. These spherules ranged in composition from the expected Canyon Diablo composition (e.g., 92 wt.% Fe, 8 wt.% Ni [5]) to a more Ni-rich composition (70-80% Ni). BSE and EDS data also revealed that numerous meteorite fragments contained small patches of Fe-Ni-S bearing phases in addition to the troilite, schreibersite, and cohenite typically found in IAB iron meteorites [5].

We have also identified a unique suite of metallic fragments, assumed to be meteoritic in origin based on their highly magnetic character and deeply oxidized exteriors. However, SEM analyses showed that these fragments have unique textures and compositions (Fig. 5) relative to the other melt types. In contrast to Types 1 and 2, these non-vesicular fragments have a Fe-rich, compositionally banded groundmass, with varying proportions of Fe, Ni, and Si. These fragments also contain angular, shattered quartz grains as well as Ca- and Mg- rich lithic inclusions.

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

- Two new types of impact melts have been identified, indicating that impact melt compositions, and thus impact mixing processes, were more complex than previously indicated.
- Lechatelierite is much more pervasive than previously thought, indicating that the impact event must have indeed accessed and melted the SiO_2-rich Coconino Sandstone.
- Inclusions of calcite and dolomite have been found in many impact melts suggesting that the carbonate-rich Kaibab target rock was not completely volatilized, as was suggested by prior studies [e.g., 3, 5].
- Meteoritic fragments, of highly variable composition, are omnipresent in all three types of impact melts suggesting that the impactor was highly fragmented at the earliest stages of crater formation, perhaps even prior to impacting the target rock [e.g., 6].

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References: [1] Roddy D.J., et al. (1975) *Proceedings of the Sixth Lunar Science Conference*, 3, 2621; [2] Hughes J.P., et al. (2006) *9th Mars Crater Cons. Meeting*, abstract #0906; [3] Hörz et al. (2002) *Meteor. Planet. Sci.*, 37, 501-531; [4] See et al. (2002) NASA/TM-2002-210787, 23; [5] Mittlefehldt et al. (2005), *GSA Special Paper*, 384, 367-390; [6] Artemieva and Pierazzo (2011), *Meteor. Planet. Sci.*, 46, 805-829.

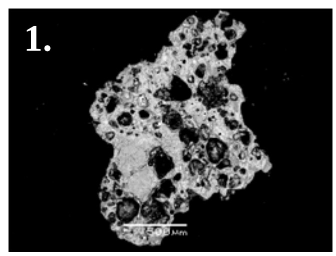

Figure 1. BSE image of a Type 1 impact melt fragment.

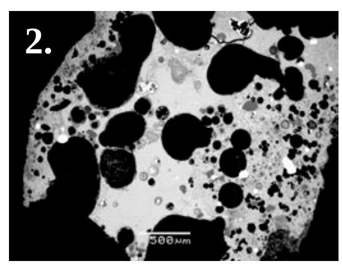

Figure 2. BSE image of a Type 2 impact melt fragment.

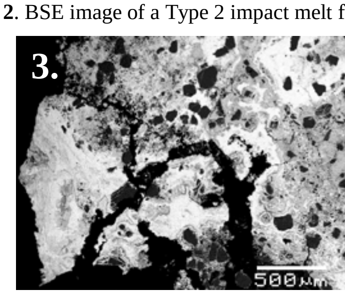

Figure 3. BSE image of a previously unidentified clast type.