NEW CONTRAINTS ON IMPACT PROCESSES AT METEOR CRATER: EJECTA EMPLACEMENT AND FORMATION OF IMPACT MELTS AND METALLIC SPHERULES.

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Introduction: Barringer Meteorite crater (hereafter referred to as Meteor Crater) is a 180 m deep, 1.2 km diameter, bowl-shaped depression located in north-central Arizona [1] (**Figure 1**). This impact crater is thought to have formed ~50,000 years ago [2,3] by the impact of the ~100,000 ton iron-nickel Canyon Diablo meteorite, roughly 30 m in diameter, which struck at a speed that has been estimated to be anywhere between 12 and 20 km/sec [4-7]. The crater and surrounding rim have since experienced limited erosion, providing one of the best preserved, young impact craters on Earth [8-10]. Recent sample analyses and numerical models [e.g., 12-19], indicate that the formation of Meteor Crater was much more complex than previously thought. Current models are insufficient for explaining certain aspects of the impact melting process, target rock-projectile mixing, siderophile element fractionation trends, and ejecta blanket formation processes, and require further investigation to understand newly identified complexities.

These issues can be addressed through the use the USGS Meteor Crater Sample Collection. The samples in this collection consist of over 2,500 m of drill cuttings from 161 well-documented drill holes into the ejecta blanket of Meteor Crater. Our proposed work will utilize these drill cuttings to study the composition and spatial distribution of impact-generated materials associated with the ejecta blanket, in an effort to better understand the complexity of cratering processes and products. We will integrate observations of impact melt geochemistry, metallic inclusion and spherule compositions, shocked mineral and lithic inclusions, and a detailed stratigraphic and sedimentological analysis of the ejecta deposits. The resulting comprehensive data set will make it possible to construct new models for: 1) target rock and projectile melting, 2) mixing of target and projectile melts and other variably shocked materials, 3) melt flow and ejection from the transient crater, and 4) siderophile element fractionation. All sample mounts and thin sections produced during the proposed research will be incorporated into the sample collection and will be available to interested researchers.

Lithostratigraphic analysis. The morphology of Meteor Crater and its ejecta blanket, as well as the composition and distribution of impactite lithologies, resulted from the complex interplay of processes that occurred during impact. The continuity of the inverted strata within the ejecta blanket led Roddy et. al [8] to use the term "overturned flap" to emphasize the well-ordered inversion. It is now clear that this idealized model of the continuous ejecta blanket is complicated by local complexities within the debris [11]. Our recent results [16-19] indicate the ejecta formation process involved a greater degree of mixing between lithologic units than predicted by the "overturned flap" model.

We will formulate a detailed, field-based model for crater excavation and ejecta emplacement processes through a detailed lithostratigraphic analysis of the internal structure of the ejecta blanket. The extent of lithologic mixing within the ejecta blanket will be quantified by identifying ejecta facies that represent contrasting mixtures of target rock lithologies, impact melts, metallic spherules, and Canyon Diablo fragments. Using these data and RockWorks software, we will construct detailed stratigraphic and lithologic columns that emphasize not only overturned flap morphology, but mixed-lithology facies and the relative abundances of each component. Using these detailed stratigraphic and lithlogic columns, RockWorks will be used to interpolate surfaces, creating a subsurface model from which we can generate fence diagrams, cross sections, and isopach maps. These derived products will provide a representation of the complete ejecta blanket, including possible internal structures and lateral and vertical variations in lithologic composition.

Analysis of impact melts and their inclusions. Impact melt types at Meteor Crater include: 1) ballistically dispersed melt bombs (~cm-sized) composed of mixtures of melted target rock and melted projectile; 2) shocked and frothy Coconino (lechatelierite) found in the crater floor beneath alluvium and in the ejecta blanket; and 3) ballistically dispersed metallic spherules. While these particles have been studied for decades [12, 13], several unresolved issues remain, specifically correlations between: 1) amount of projectile component and melt source depth, 2) fractionation trends of the projectile component and melt source depth, 3) source depths of ejected melts and total melt zone depth, and 4) the relative importance of target rock melting, decomposition, and devolatilization, and the role of volatiles. To investigate the relationships between melt source depth, projectile content, and fractionation between projectile and target rock melts, we will use optical petrography, scanning electron microscope (SEM) characterization, and electron microprobe analysis to measure compositions and chemical gradients in samples of impact glasses (with appropriate three dimensional representation within the ejecta).

Our analytical plan includes documentation of how Fe, Fe/Ni, and other siderophile element ratios and concentrations change with distance from: 1) metallic inclusions, 2) carbonate glass spherules, 3) olivine/pyroxene crystals, 4) vesicles, and 5) in shallow vs. deep-seated melts. We will characterize the compositions and variability of metallic inclusions to understand the phase relations and siderophile element fractionation between silicate melt, carbonate melt, and metallic inclusions, as well as the relationship of the metallic inclusions to the metallic spherules. Further, we will use optical and scanning electron microscopy to quantify and describe the types of lithic and mineral inclusions (unmelted clasts of carbonates, quartz, and zircon) and their shock levels, to document evidence for the interaction of lightly and highly shocked material during the cratering process. We will use the SEM to document chemical and textural evidence for carbonate melts, such as CaO-MgO-CO_2-rich glass compositions, silicate-carbonate liquid immiscibility textures, calcite quench textures, carbonate glass spherules, and euhedral calcite crystals within glass.

Additionally, using the lithostratigraphic data, we will compare and contrast the compositions and textural features of impact melts: 1) from the distal, basal layers of the continuous ejecta blanket vs. the proximal, surficial layers; 2) from single-lithology ejecta facies vs. mixed-lithology facies; and 3) impact melts containing variable amounts and types of inclusions (i.e., carbonate glass spherules, lechatelierite, metallic inclusions, lithics, Coconino-derived shocked quartz, and olivine and pyroxene crystals).

Analysis of metallic spherules. At Meteor Crater, metallic spherules were deposited around the crater as isolated, opaque melt droplets that formed either as a direct impact melt product or as a molten condensate from an impact-generated vapor cloud [11]. Despite decades of research, the formation mechanism(s), compositional range, and relationship between the spherules and metallic inclusions have not been definitively established [13]. True bulk analysis of spherules, including their oxide coatings, is required to establish their true compositions; validation (or invalidation) of their siderophile element fractionation trends is essential to furthering our understanding of projectile melting and/or vaporization that occurred during the Meteor Crater impact. We will carefully select and analyze a suite of metallic spherules via petrographic and microbeam methods in order to establish the compositional variability of the spherule population. Establishing the true compositions of the spherules and confirmation of their siderophile element fractionation trends is essential to furthering our understanding of the projectile and target rock melting and mixing processes that occurred during the Meteor Crater impact.

References: [1] Shoemaker E.M., and Kieffer S.W. (1974) *Guidebook to the geology of Meteor Crater*, Arizona, Publ. 17, 66 pp; [2] Nishiizumi K., et al. (1991) *Geochim. Cosmochim. Acta*, *55*, 2699; [3] Phillips F.M., et al. (1991) *Geochim. Cosmochim. Acta*, *55*, 2695; [4] Shoemaker E.M. (1960) Impact mechanics at Meteor Crater Arizona: unpublished Princeton PhD Thesis, 55 pp; [5] Melosh H.J. (1980) *Ann. Rev. Earth Planet. Sci*, *8*, 65; [6] Melosh H.J. and Collins G.S. (2005) *Nature*, *434*, 156;
[7] Artemieva N. and Pierazzo E. (2009) *Meteor. Planet. Sci., 44*, 25; [8] Roddy D.J., et al. (1975) *Proceedings of the Sixth Lunar Science Conference*, *3*, 2621; [9] Grant J.A., and Schultz P.H. (1993) *J. Geophys. Res*., *98*, 15,033; [10] Ramsey M.S. (2002) *J. Geophys. Res., 107(E8),* 5059;
[11] Kring D.A. (2007) *Lunar and Planetary Institute LPI Contribution No.* 1355; [12] Hörz et al. (2002) *Meteor. Planet. Sci., 37*, 501; [13] Mittlefehldt et al. (2005), *GSA Special Paper*, *384*, 367; [14] Osinski et al. (2008) *Meteor. Planet. Sci., 43,* 1939; [15] Artemieva N. and Pierazzo E. (2011) *Meteor. Planet. Sci., 46*, 805; [16] Gaither et al., (2012) *LPSC 43*, abstract #1601; [17] Hagerty et al. (2012) *75^{th} Annual Meeting of the Meteoritical Society*, abstract #5296; [18] Hagerty et al., (2010) *LPSC 41*, abstract #2213; [19] Hagerty et al., (2011) PCC 2, abstract #1109.

Figure 1. Meteor Crater (1.2 km in diameter and 180 m deep) and its ejecta blanket, labeled with drill hole numbers from the USGS drilling program.