PETROGRAPHIC OBSERVATIONS OF CENTRAL UPLIFT FORMATION IN COMPLEX CRATERS.

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Introduction. Central uplifts in complex impact craters are thought to form during the modification stage of impact by uplift of target strata in the crater floor through a process known as acoustic fluidization [1]. Deformation during the contact/compression stage of impact results in target rock weakening [2], creating potential pathways for subsequent movement of large-blocks of material from depth in craters ~ 3-5 km in diameter [3] on Earth. Target rock from central uplifts shows signs of fracturing, faulting, shock deformation, and even localized melting (pseudotachylites), most of which appear to be related to impact. While central uplifts have been the subject of some study, only limited investigations have begun to uncover the complex petrogenesis that their rocks reveal [4-6]. This information can be useful for modeling target properties such as block size and rock response during central uplift formation in complex craters.

This study has examined the central uplifts from six complex terrestrial impact craters in North America: Flynn Creek, TN (36°17'N 85°40'W; 3.8 km diameter), Kentland, IN (40°45'N 87°4'W), Middlesboro, KY (36°37'N 83°44'W; 6 km), Serpent Mound, OH (39°2'N 83°24'W; 8 km), Sierra Madera, TX (30°36'N 102°55'W) and Wells Creek, TN (36°23'N 87°40'W; 12 km). Shock deformation features and features common to complex craters have been identified and interpreted as being related to crater and central uplift formation. These petrofabrics occur in a predictable petrogenetic sequence that reflect general models for crater formation and provide insight into the behavior of target rocks during and following impact.

Microfractures/Microfaults. All uplifts studiedshow field relationships indicating that large (cm to several hundred meter-sized) blocks of material are uplifted above their normal stratigraphic positions as the result of impact. Many blocks show minimal or no signs of strain, however, many are internally fractured or faulted. Such deformation is occasionally visible in the field or in hand specimen, but most microfractures/microfaults (< 1 mm thickness) are only discernable by microscope. Microfractures and microfaults cut across bedding and other sedimentary features and often occur in primarily parallel and sympathetic sets. It is possible that some microfractures could precede the impact event, but most are distinguished from subsequent (weathering-related) fractures by their lack of extension, termination at block boundaries, and lack of dissolution/precipitation petrofabrics. All microfaults terminate at block boundaries and are responsible for minor offsets (typically < mm's) of target rock strata in major blocks.

Microbreccias. Microfaults often contain silt and clay-sized cataclasis that we term microbreccia (also termed breccia dikes or clastic dikes by others). Petrographic and geochemical analyses (XRD,XRF) indicate that microbreccias are locally-derived. Those from the Middlesboro central uplift even contain shocked quartz fragments [7].

Major faults. Major faults have been observed and mapped in the central uplifts of all craters studied [8-11]. They bound the major blocks and show signifcantly more offset (hundreds of m's) of target strata than do microfaults. Centimeter- to meter-thick faults are typically oriented sub-perpendicular to bedding planes, although fault orientations at other impacts have been shown to be highly variable [12]. These faults are most likely responsible for the amount of stratigraphic uplift (SU) of floor material ($SU=0.086D^{1.03}$) at major impacts [13]. Major faults at Flynn Creek, Kentland, and Middlesboro are sharp and do bear a striking resemblance to microfaults. Some also occur oriented similar to microfaults, suggesting that some microfault surface can become major faults, resulting in larger displacement of target rock strata during central uplift rise and collapse.

Fault Breccias. Major faults at the Middlesboro and Wells Creek impacts contain significant amounts of brecciated material. We use the term fault breccia when referring to breccias generated along major central uplift faults to distinguish these from breccias formed from ejecta. These are similar to those generated by other terrestrial (non-impact) processes and elsewhere along crater floors [4]. Fault breccias are either monomict (Middlesboro, Wells Creek) or polymict (Wells Creek). At Wells Creek, fault breccias contain a wide size range (pebble- to silt-sized) of angular grains. At both locations, many breccias grade from coarse-grained centers to fine-grained outer margins, with some outer margins displaying flow textures. Petrographic, XRD, and XRF analyses of monomict Middlesboro breccias support a local derivation from wall rock material. Similar analyses of Wells Creek polymict fault breccias (referred to as heterogeneous breccias by [11]), indicate host rock mixed with other target lithologies. This is consistent with observed larger displacements along major fault boundaries.

Mechanism of Formation? All of the above features are not unique to impact sites, but can form by other geologic processes. However, at complex craters, these features are particularly concentrated in crater-floors and along central uplifts, while showing a close association with other unambiguous shock features (shocked mineral phases, high pressure phases, melting, and shatter cones). Shatter cones have been found in the central uplifts of all impacts studied here, while shocked quartz has only been detected at Middlesboro [7,14,15] and at Serpent Mound [16].

Cross-Cutting Relationships. While not all of the central uplifts studied have preserved a complete list of the above features, all present features show similar cross-cutting relationships. Sedimentary features (such as bedding, cementation, fossils, and, in the case of Flynn Creek, trace fossils) have been cross-cut and/or offset by microfractures, microfaults, and faults. We interpret the similar appearance and orientations of microfractures and microfaults to suggest that these features were generated contemporaneously and, prior to movement, were essentially the same feature. However, microfaults experienced later movement (when in contact, microfaults offset microfractures). Subsequent (weathering-related) fractures cut across all of these features. Shatter cones cut across sedimentary and diagenetic features at all of the studied craters. Occasionally shatter cones are found in direct contact with microfaults/faults. At Wells Creek some have been cut by faults and fault breccias [11] attesting to displacement of target strata after shatter cone formation. Shatter cone surfaces at Wells Creek have been offset by microfault planes, suggesting that microfault movement occurred following shatter cone formation. Planar fractures (PFs) and planar deformation features (PDFs) in quartz grains from Middlesboro have been cross-cut by faults and microfaults, suggesting that they too preceded fault movement [7].

Petrogenesis. Relationships between sedimentary, diagenetic, deformation, and shock metamorphic fabrics reveals an overall petrogenetic sequence for crater floor target rocks that rise to form central uplifts. This sequence is consistent with the general model of impact crater formation: contact/compression, excavation/ejection, and modification [1] and these observations are consistent with other models proposed for larger impact structures [17,18]. Steps 1-2 are processes involved in pre-impact formation of target rock. Step 3 results from passage of the compressional front of a shock wave, while step 4 represents subsequent decompression, both occurring during the contact/compression stage. Steps 5 and 6 are interpreted to represent rise of the central uplift. Step 5 likely occurs early during the modification stage, immediately followed by major fault movement (step 6). While the sum of offsets from minor faults cannot account for the total stratigraphic uplift in central peaks, major faults are likely responsible and represent the final stages of central uplift formation. Microfaults allow for minor displacements in strained target blocks. Following uplift, weathering processes serve to further modify central uplift morphology.

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Table 1. Petrogenetic sequence for central uplifts

(1) deposition of target rock
(2) lithification/diagenesis
some microfractures generated (?)
(3) production of shatter cones/shocked minerals
(4) microfracture generation
(5) microfault movement/microbreccia generation
(6) fault movement/fault breccia generation
(7) fracturing from exposure/weathering