CENTRAL UPLIFT FORMATION AT THE MIDDLESBORO IMPACT STRUCTURE, KENTUCKY, USA.
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Introduction: Processes responsible for central uplift formation in complex impact craters have been the focus of much scientific study [1] and are still being resolved. Present models call for hydrodynamic rock movement following crater collapse resulting in a central uplift or peak. Near instantaneous changes in target rheology that produce fluidized movement are thought to result from extreme pressure variations and/or thermal softening during shock wave passage (referred to as acoustic fluidization) [1]. Geologic observations of the central uplifts in some smaller complex craters, however, suggest that fluidization may not be the only process responsible for central formation. Central peaks in some complex craters show preservation of original bedding and evidence of post-compressional stage faulting/fracturing, suggestive of a brittle component to central peak formation.

Uplifted exposures in the center of the Middlesboro impact structure in southeastern KY, have allowed us to examine processes involved in central uplift formation. The uplift preserves a paragenesis that includes the impact event, shock metamorphic effects, and appears to record central uplift formation.

Geologic Setting. The Middlesboro structure (36˚ 37' N, 83˚ 44' W) is a ~5.5 km diameter, post-Alleghenian, complex impact crater located in Middlesboro, KY in the Southern Appalachians. Middlesboro is superimposed upon the Pine Mountain Thrust Sheet, the westernmost extent of major Alleghenian deformation in eastern Kentucky. The impact affected rocks of the Lower Pennsylvanian Lee and Breathitt Formations and Upper Mississippian strata of the Pennington Formation and Newman Limestone.

Initial investigations of the structure proposed that the Middlesboro Basin resulted from stresses experienced during regional tectonism [2-4]. However, USGS mapping of this area [5,6] in the 1960s led [7] to propose Middlesboro as an eroded impact crater, or astrobleme. Their equivocal evidence included: a circular basin, severely deformed strata, "shattered" quartz grains, and a core of uplifted strata (Pennsylvanian-aged conglomeratic sandstone from the Lee Fm.) near the center of the structure. The central uplift was found to contain shatter cones and 'shatter-cone like striations' in Breathitt siltstones [8] and shocked quartz [9,10] confirming and impact origin for Middlesboro.

The Central Uplift: The Middlesboro central uplift is expressed as a topographic high (~325 m^2 area) in the center of the structure (~ 2.75 km from the modified rim) with exposures of uplifted Lee Fm. Very well-sorted, well-cemented quartzose sandstones with quartz pebbles were collected from central uplift exposures for petrographic and geochemical analyses.

Shock metamorphism. Central uplift sandstones show evidence of shock metamorphism, such as shatter cones (Fig. 1). As with previous studies [9,10], we have detected planar deformation features (PDFs) with crystallographic orientations indicative of impact in 9.5-22% of all quartz grains [11], in addition to planar fractures (PFs). PDFs were discovered in silica overgrowth cements as well. Shocked quartz is found only in the Lee Fm. exposed here and not outside of the structure. X-ray diffraction (XRD) analyses have, to date, failed to detect coesite or stishovite.

Figure 1. Shatter cones in sandstone from the central uplift of the Middlesboro impact structure. Sample is ~ 2.5 x 7.5 cm.

Sandstones are extensively faulted and fractured, with minor (< 1 cm) displacements along fault planes oriented 60-84˚ to bedding. Faults contain thin (16μm-1mm) veinlets (Fig. 2) of micro-breccias, or cataclasis, comprised entirely of fine-grained sand to clay-size quartz derived from the sandstone. Shocked quartz fragments have been observed in veinlets. Very fine-grained material occurs in some veinlets, giving a glassy appearance. XRD analyses, however, show no evidence of melt. Veinlets cross-cut quartz grains, quartz pebbles, silica cement, PFs, and PDFs.

Stratigraphic Uplift. Although [8] originally estimated that the center of Middlesboro had been uplifted ~244 m above its normal position, morphometric models of complex terrestrial craters and analysis of post-[8] drilling logs better constrain the amount of uplift. [12] showed that the amount of stratigraphic uplift for a crater's center, h_{SU}, is approximately $h_{SU} = 0.06D^{1.1}$ in terrestrial craters (D = final crater diameter (km)).

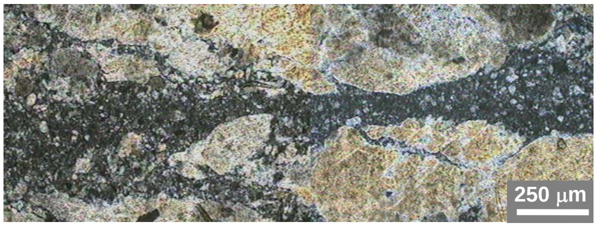

Figure 2. Photomicrograph (x-polars) of veinlet in Lee sandstone showing ground-up, fine-grained quartz cataclasis.

If we assume D = 5.5 km for Middlesboro (based on the distance between the average outer boundaries between deformed/non-deformed strata) then the estimated h_{SU} for the central uplift is 391 m, 147 m greater than the displacement estimated by [9].

Oil & gas well logs from recent drilling in and outside of Middlesboro have allowed us to produce a cross-section showing the crater's subsurface and the true nature of the central uplift. Immediately adjacent to the impact structure, the mean elevation of the base of the Lee Fm. is ~ -183 m, while it is locally depressed (-518 m) within the crater surrounding the central uplift. If we assume that the highest elevation (360 m) of exposed conglomeratic sandstones in the central peak represents the base of the Lee, then the maximum amount of stratigraphic uplift is 543 m. The upper contact of the Lee outside the structure lies at a mean elevation of 228 m. Assuming the central uplift exposes the upper contact, strata would have been uplifted a minimum of 132 m. While the lithologic similarity among sandstone members of the Lee prevent us from determining precisely which member the central uplift exposes, subsurface stratigraphy allows us to constrain the amount of uplift of strata at Middlesboro to 132-543 m above normal stratigraphic positions.

Discussion: Petrographic and geochemical studies of the central uplift provide some insight into the impact event at Middlesboro. Cross-cutting relationships between PFs, PDFs, and micro-breccia veinlets, show a paragenesis consistent with presently-accepted impact sequences. Central uplift sandstones show the following sequence: (1) deposition of quartz grains, (2) silica cementation, (3) production of PFs and PDFs, (4) micro-brecciation event, and (5) subsequent fracturing. The simultaneous occurrence of PDFs (with π{1012} and r/z {1011} orientations) and shatter cones in the central uplift suggest peak shock pressures 20-30 GPa. Breccia veinlets cross-cutting PFs and PDFs suggest that the microbrecciation event occurred following the initial shock wave passage.

Two plausible processes may be responsible for generating micro-breccias: decompression following initial shock wave passage or strain experienced during central uplift formation. Decompression would have resulted in fracturing and little or no movement along fracture planes. However, faulting along veinlets, in addition to the communition of coarser-grained quartz into fine-grained cataclasis, suggest significant movement occurred. Subsurface stratigraphy shows that the 62-78˚ slope between uplifted Lee and that adjacent to the central uplift correspond with fault plane orientations (60-84˚) in our samples. Because of these observations, we propose that, following the initial shock event, brittle deformation of target rocks occurred, resulting in micro-brecciated veinlets produced as the Lee Fm. was being uplifted. Preservation of original bedding structures and pre-impact (PDF-containing) cements along with the lack of whole-scale brecciation further suggests that major deformation was confined to the veinlet network.

While our model may account for the paragenesis of central uplift target rocks and brittle deformation features, minor offsets along fault planes are not solely responsible for central uplift formation at Middlesboro. Estimates of the accumulated displacement along veinlets (< 53 m) do not account for the total amount of stratigraphic uplift in the Lee Fm. (132-543 m). Faults with larger vertical displacements surrounding the central uplift (at depth and not exposed) may account for this discrepancy, but require further investigation.

Summary: The central uplift at Middlesboro provides a means of studying shock metamorphic events in sedimentary targets and provides insight into central uplift formation in complex craters. Results indicate that, following the shock wave passage, the center of the structure 'rebounded' in a brittle fashion. So, although fluidization may quantitatively explain the behavior of target rock material in some impacts, rise of the central uplift in some impact structures may occur by minor displacements along faults in target rock.

References: [1] for a historical review see Melosh, H. J. (1989) Oxford Univ. Pr., 245 p. [2] Ashley, G.H. (1904) *Science*, *19*, 856. [3] Ashley, G.H. and Glenn, L.C. (1906) *USGS Prof. Paper*, *49*. [4] Rich, J.L. (1933) *GSA Bull.*, *44*, 1219-1236. [5] Englund K.J. (1964) *USGS Geol. Sur. GQ Map-301*. [6] Englund K. J. et al. (1964) *USGS Geol. Sur. GQ Map-300*. [7] Englund, K.J. and J.B. Roen (1962) *USGS Prof. Paper 405-E*, E20-E22. [8] Dietz, R.S. (1966) *Meteoritics*, *3*, 27-29. [9] Bunch, T.E. (1968) In *Shock Met. Nat. Materials*, Mono Book, 413-432. [10] Carter, N.L. (1968) In *Shock Met. Nat. Materials*, Mono Book, 453-474. [12] Milam, K.A. and Kuehn, K. (2002) *Abs. NC-SE GSA Ann. Meeting*. [12] Grieve et al. (1981) *Proc. Lunar Plan. Sci. Conf.*, 12A, 37-57.