FROM THE INSIDE OF A CENTRAL UPLIFT: THE VIEW FROM HAWKINS IMPACT CAVE. K. A. Milam[1], B. Deane[1], P. L. King[2], P. C. Lee[3], and M. Hawkins[4], [1]Dept. of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996-1410 (kmilam@utk.edu) [2] Dept. of Earth Sci., Univ. of Western Ontario, London, ON, N6A 5B7, Canada, [3]SETI Inst., NASA Ames Res. Center, Moffett Field, CA 94035-1000, [4]DeKalb Co. H.S., Smithville, TN 37166.

Introduction. Hawkins Impact Cave is the only cave in the world known to have formed inside the central uplift of a complex impact crater. Discovered in 1989 by landowner Michael Hawkins (namesake) and mapped in 2003 [1], HIC lies in the core of the central uplift of the 3.8 km diameter Flynn Creek impact structure (36˚17'N, 85˚40'W) in the Highland Rim physiographic province of north-central Tennessee, U.S [2,3]. The ~360 Ma impact occurred in flat-lying limestones, dolostones, and shale of the Lower Ordovician Knox Dolomite, Middle Ordovician Stones River Group, and Middle-Upper Ordovician Bigby-Cannon and Leipers-Catheys Formations [3]. Following impact, target rocks were uplifted ~450 m above their normal stratigraphic positions, forming a prominent ~0.75 km diameter central peak [3,4], which was buried by Devonian/Mississippian-aged marine sediment that later became the Chattanooga Shale, Fort Payne, and other formations.

Northern Flank of the Central Uplift. Most of our previous knowledge of the Flynn Creek central uplift has come from surficial mapping of limited exposures along the northern flank and qualitative examination of 8 drill cores into the central uplift [4]. Surface exposures consist of westward-dipping Knox and Stones River strata and lesser eastward-dipping rocks separated by what [3] described as a "chaotic breccia zone". They indicate that large (several tens of m's in dimension) carbonate megablocks were transported upward and from west to east along thrust faults during central uplift formation [3]. During transport, most of these northern megablocks remained coherent, showing minimal signs of internal deformation. Nearer to the so-called "chaotic breccia zone" however, blocks contain monoclinic folds that are cross-cut by microfractures (mfrs) and microfaults (mfs). Additionally, the Knox Dolomite contains the only known shock indicators, shatter cones, at the Flynn Creek structure [3, 5].

The southern two-thirds of the central uplift remains buried beneath the Chattanooga Shale and Fort Payne Formation, making study difficult. Drill cores from the center of the Flynn Creek structure resulted in a subsurface contour map [6] that revealed an generally circular, buried central uplift; however, little was known about the structural nature and petrogenesis of this and the southern third of the central uplift.

Methods. The discovery of HIC has provided an underground portal into the core and southern half of the central uplift of the Flynn Creek structure. Over several expeditions in 2005, our research team has mapped the structural complexity of this portion of the central uplift and has investigated the petrogenesis of target rocks here. Major structures inside of HIC were mapped and overlain on a 1:660 cave survey map by [1]. Additionally, we conducted several surface surveys above HIC, examining limited exposures to provide a three-dimensional view of the central uplift.

Results. Our study shows that the structural geology of the central uplift core differs from the northern part and petrofabrics and paragenetic sequences are comparable to those found at other complex craters.

Megablocks and Major Faults. HIC exposures reveal that 20 additional limestone megablocks comprise the central uplift in addition to the 9-10 mapped along the northern flank by [7]. Minimal estimated HIC megablock volumes range from 20 m^3 to 3,200 m^3 (based on mapped cross-sectional areas and passage thicknesses, with the exception of the megablock containing the cave entrance). This is in sharp contrast to megablock volumes of the northern flank, which are as large as 72,000 m^3. HIC megablocks are separated by discrete major faults that both truncate and occur normal to bedding. Rare slip indicators show that normal faulting occurred in this part of the central uplift; however, reverse faults are also likely. Fault contacts are sharp (< 1 cm), linear, and lack cataclasis, fault breccias, secondary precipitates, or void spaces. Bedding orientations to either side of some major faults indicate that substantial rotation (up to 90˚) occurred during megablock transport (Figure 1).

Microfractures and Microfaults. As near the "chaotic breccia zone" of the northern flank, HIC megablocks are internally microfractured and microfaulted (Figure 2). Both mfrs and mfs are < 0.25 mm in width, extend for several meters through strata, and occur at angles ranging from 60-85˚ to bedding. Both are distributed heterogeneously throughout HIC and elsewhere in the central uplift, with no preferred distribution about major faults. Some megablocks contain no mfrs/mfs, while others have up to 3.1/cm, densities comparable to those measured at the Middlesboro, Serpent Mound, and Wells Creek structures by the authors. Mfs show both normal and reverse displacements, with vertical offsets of typically < 0.5 mm (some <2 cm).

Cross-Cutting Relationships. All central uplift petrofabrics in HIC and at the surface display a consistent pattern of cross-cutting relationships similar to that described from impact craters of comparable size [e. g. 8-10]. Small monoclinic folds near the center of the northern flank are dissected by mfrs and mfs along fold axes. HIC samples display a first generation of mfrs that were subsequently cut by mfs. At some locales, this sequence of mfrs followed by mfs was repeated several times. Both mfrs and mfs terminate at major fault boundaries. In the northern flank, rare monomict breccias contain clasts with mfrs and mfs that were generated prior to brecciation. On the western flank of the central uplift, a superposed breccia also contains microfractured clasts. A later set of distinctly irregular fractures cross-cuts bedding, mfrs, mfs, and major faults. We did not observe any distinct shock metamorphic features, such as shatter cones, in contact with any of above features.

Formation of the Flynn Creek Central Uplift. Initial data, mostly from the northern flank area, suggested that formation of the Flynn Creek central uplift occurred by uplift of large megablocks, from west to east, along thrust faults [3]. Exploration of HIC reveals a structural change in the style of uplift nearer to the center of the central peak. Here, smaller megablocks of material have been transported along normal (and likely thrust) faults, generating no apparent cataclasis or fault breccias, and, intriguingly, leaving behind no void spaces between blocks. Thus far, we have not identified secondary precipitates that might indicate the presence of fluids which might reduce frictional resistance during megablock transport. If fluids or gases were present, they did not leave evidence on the hand sample scale; therefore, they were not likely trapped between megablocks for a significant length of time. Thus, at present, the agent responsible for reduction of the frictional coefficient between blocks during transport remains an enigma.

The petrofabrics in the Flynn Creek central uplift reveal a detailed petrogenesis. Following deposition, lithification, and diagenesis, rocks experienced compression, forming monoclinic folds. This was succeeded by an initial generation of microfractures. Microfault movement soon followed and likely occurred contemporaneously with subsequent generations of mfrs and mfs. While such features are cannot be unambiguously interpreted as impact deformation, no such fabrics have been found in the Stones River Group outside of the Flynn Creek impact structure. They have been noted at the center of other impact craters [8-10]. Therefore, we interpret folds, mfrs, and mfs here to represent deformation that occurred during the contact/compression and ejection/excavation stages of impact. Shock wave passage and reverberations resulted in compression and decompression, fracturing, and moving target rocks (i.e. mfrs and mfs). Microfracturing and microfaulting, in turn, were followed by rise of the central uplift. This is expressed by major fault movement along megablock boundaries, which truncate all of the above features. This sequence is similar to that in other impact craters of comparable size [9-10]. Although each of the features cannot be described as exclusively exogenic, when considered collectively and sequentially, may be indicative of central uplift formation in complex craters (< 20 km).

References. [1] Oeser et al. (2003) *TN Cave Survey*, Hawkins Impact Cave Map. [2] Milam K. A. et al. (2005) *68th METSOC*, Abstract #5221. [3] Roddy D. J. (1968) *Shock Met. of Nat. Materials,* Mono Books, pp. 291-322. [4] Roddy D. J. (1979) *Proc. Lunar Planet Sci.10th*, pp. 2519-2534. [5] *Impacts in the Field* (2004), *1*, 5. [6] Roddy D. J. (1966) *PhD Thesis*, Caltech, 232 p. [7] Wilson C. W. Jr. and Roddy D. J. (1990) Geol. & Min. Res. Gainesboro Quad., TN, 1:24000 map, *TN Div. Geol.* [8] Milam K. A. et al (2004) *LPS XXXV*, Abstract #2073. [9] Wilson C. W. Jr. and Stearns R. G. (1968) *TN Div. of Geol.,* Bull. 68. [10] Dressler B.O. and Sharpton V. L. (1997) *Tectonophysics*, *275*, 285-311.

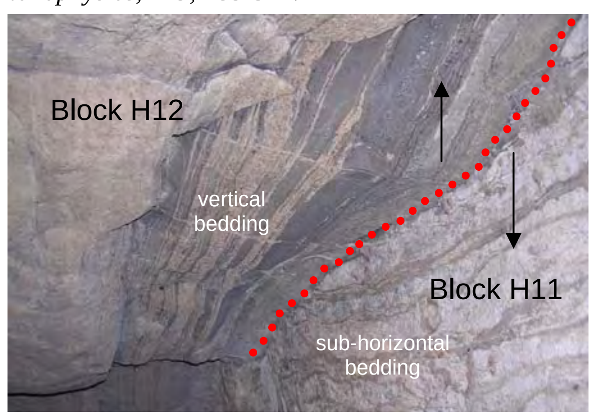

Figure 1. Major normal fault (red line) between two major megablocks exposed in HIC whose bedding orientations differ by ~ 90˚. Black arrows denote relative movements along fault.

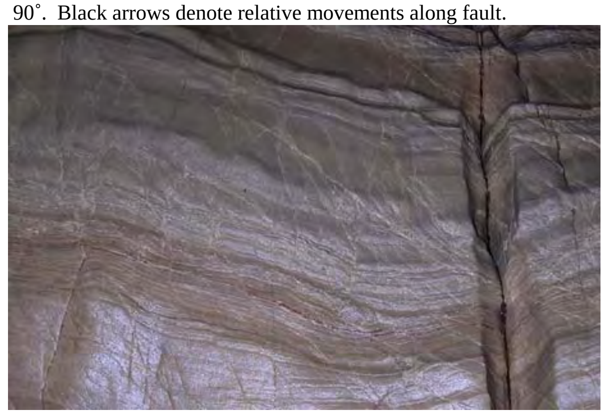

Figure 2. Microfractured and microfaulted Stones River Group strata in an eastern passage of HIC. The view is ~0.5 m across.