HYDROCODE SIMULATION OF THE FLYNN CREEK IMPACT, TENNESSEE V. J. Bray[1], J. J. Hagerty[2], G. S. Collins[3], D. T. King, Jr.[4] and S. J. Jaret[5]. [1]The University of Arizona, Tucson, AZ, 85721. [2]Astrogeology Science Cewnter, U.S.G.S. Flagstaff, AZ, USA. [3]Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London, SW7 2AZ, United Kingdom. [4]Geosciences, 2050 Memorial Coliseum, Auburn University, Auburn, Alabama 36849 USA,[5]American Museum of Natural History, Central Park West, New York, 10024. (vjbray@lpl.arizona.edu).

Introduction: The ~200 impact craters on Earth record only a small amount of the impact history of our planet. When considering the hazard posed by impacts, a main question that arises for most impact sites is therefore: did a slow and dense projectile, or a faster, less massive impactor, form the crater? Flynn Creek (FC) crater is a ~ 3.8 km diameter, ~ 382 million year old impact structure located in north central Tennessee. Roddy [1] has suggested that the impactor that produced the crater likely struck a shallow sea before penetrating into underlying Upper Ordovician limestones. Most previous works suggest relatively low impact velocities based on the presence of shatter cones, impact melt particles, intense microtwinning of calcite, and planar fractures in quartz, but no higher-pressure shock metamorphism such as PDFs [e.g.,2-3].

Analysis of FC drill cores show no high-pressure indicators such as coesite and PDFs in quartz grains, providing an upper bound of ~ 3 GPa to the shock pressures caused by impact into sedimentary rocks [4]. [5] Also noted the presence of localized melting of finely divided silica grains within the impacted dolomite. This melting is suggestive of localized pressure spikes to ~ 5 GPa [cf. 4]. Drill core data from the crater moat also sheds light on the depth of a possible ocean resurge deposit [6]. A graded unit of ~ 35 m in thickness has been suggested by [6] to have formed as the result of marine resurge flow. This could suggest pre-impact water depths of ≥ 100 m based on analogy with other marine craters. This unit is also noted above the other crater breccia units. The different particle size distributions in these units suggest different methods of breccia formation and/or deposition [6].

Method: We have been conducting hydrocode simulation of impact into limestone, below a shallow sea of varying depth (10m-200m), to explore the possible impactor velocity-density combinations that might have formed the FC impact structure. We simulated spherical iron, dunite and ice impactors striking a layered limestone and dolomite target with various velocities (5-30kms) using the iSALE 2D shock physics code [7-9]. For our first suite of FC simulations, our aim was to determine which combination of projectile mass and velocity, scaled to create a final crater diameter of ~4km, would recreate the appropriate pressures (P) and temperatures (T) implied by the observational data. A resolution of 80 cells per projectile radius (cppr) was used to obtain accurate P and T [cf., 10], and a lagrangian tracer particle placed a 450m below

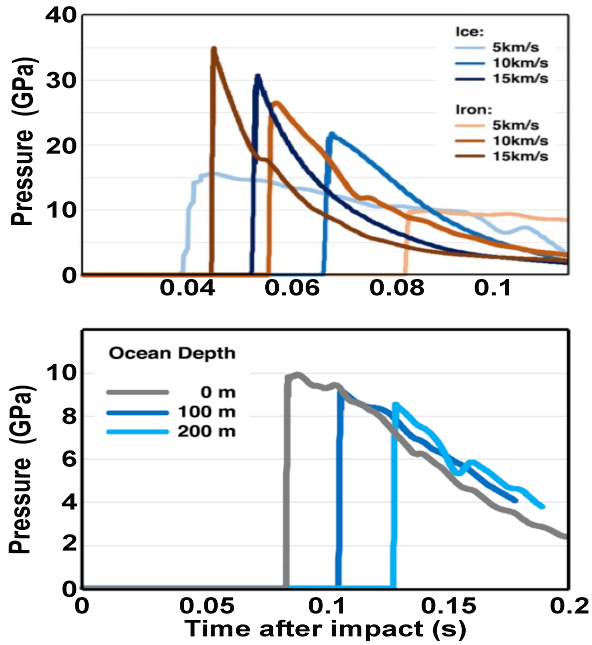

Fig. 1 (top): Graph of shock pressure experienced at a tracer particle placed at depth of 450m below pre-impact surface for a selection of impactor types and velocities. (bottom) Pressure change in the tracer particle due to introduction of water layer, for the impact of a 5km/s iron projectile.

the impact surface (the depth from which uplifted material displays shatter cones, but no indicators of higher P). The target limestone and dolomite were approximated with strength models derived from laboratory strength data [11-16], and the ANEOS for calcite [17]. Projectile properties were likewise based on established strength models and equations of state. The porous compaction and dilation model from [18-19] was used, assuming the parameters listed [20].

A second suite of simulations with a water layer above limestone were then performed to recreate final crater morphology of FC, and to fine-tune the effect of a water layer on the simulated P and T. In these models that simulated crater formation longer after the impact event, the strength model becomes more important and an additional weakening mechanism necessary. We employed the established Acoustic Fluidization Block Model parameters used for limestone of [15]. A resolution of 40cppr was employed – small enough for a faster run time, compared to the first suite of simulations, but still high enough to resolve water movements. These simulation results were compared to approximated final crater profiles of [21], and to drill core data of [5-6]. The best-fit ocean depth was chosen based on the correct crater morphology, appropriate post-impact shock P and T, centrally uplifted material from ~450m depth, and a similar depth of breccia and ocean resurge deposit.

Results: Pressure at 450m pre-impact depth is shown in Figure 1A. All simulations create pressures in excess of 5GPa. The closest result to the observational data is that of a 5km/s iron projectile, which produces a shock peak pressure of 10GPa, without an ocean (down to 8.5GPa with a 200m deep ocean – Figure 1B). This simulation also results in material from ~450m being uplifted to surface as part of the central peak. The broad morphology of FC crater is successfully recreated by simulations (Figure 2). An observed breccia moat depth of ~100m at the base of the crater walls, and 30-50m surrounding the central peak [cf., 21] is best recreated using an iron projectile, impacting a 50*m deep ocean at 5km/s. Impact into water depths >50*m produced multiple stages of crater wall collapse, creating a stratified breccia deposit.

Discussion: The record of sporadic melt and the absence of high pressure polymorphs imply shock pressure maximum bounds that are in conflict. The possibilities for explaining this mix of high and low pressure observational results are: a) PDFs, coesite and stishovite were missed during inspection of limited drill core thin sections, by multiple works, or b) shockwave focusing at material and grain boundaries led to spatially increased shock pressures, leading to localized melting. This presents a difficult dataset for simulation validation. Due to the relative scarcity of the melt and the fact the multiple analysis [2-4] have not noted PDFs, etc., we will proceed with the low shock pressures implied by absence of high-pressure shock polymorphs. All peak shock pressures experienced at the 450m deep lagrangian tracer particle exceed the 5GPa limit imposed by observational data. The closest result to the observations is that of a 5km/s iron projectile into 50 m of ocean, which produces a shock peak pressure of ~ 9 GPa.

When considering the depth of ocean resurge deposit within the crater, only the 50 m ocean simulated the correct amount of rim destruction and resurge of breccia into the crater as well as the correct crater morphology (Fig.2) [when compared to 24]. Water layer simulations also illustrated that a deep enough water layer not only erodes rim height during resurge of water into the crater cavity, but will prevent stable deposition of the over-turned rim flap, allowing it to destabilize and collapse back into the crater.

REFS: [1] Roddy 1977, in Impact and Explosion Cratering 277-308. [2] Evenick et al., 2004, LPSC abs. [3] Roddy 1966, Am. Min. 51:pp270. [4] Kowitz et al., 2013. EPSL 384:17-26. [5] Adrian et al., 2018 MAPS. [6] De Marchi et al., 2018, LPSC 49 abst. [7] Amsden, A. et al. (1980) LANL Report, LA-8095. [8] Collins, G. S. et al. (2004) MAPS, 38, 217-231. [9] Wünnemann, K. et al. (2006) Icarus, 180, 514-527. [10] Wunnemann et al., 2008. EPSL 269(3):530-539. [11] Kohli and Zoback 2013. JGR Solid Earth 118(9):5109-5125. [12] Chang et al., 2006. J. Pet. Sci & Eng 51:223-237. [13] Williams & McNamara, 1992. J. Eng. Geol.& Hydro. 25(2):131-135. [14] Perras & Diederichs 2014. Geotech. & Geo. Eng. 32(2):525-546. [15] Goldin et al., 2006. MAPS 41(12). [16] Collins et al., 2008. MAPS 43(12):1955-1977. [17] Pierazzo et al., 1998. JGR Planets 103(E12):28607-28625. [18] Wünnemann et al. 2006. Icarus 180(2):514-527. [19] Bradley 1986, USGS and USEPA Report 85-4304. [20] Bray et al., (2019/in prep). [21] Roddy 1979a and b, LPSC 10.

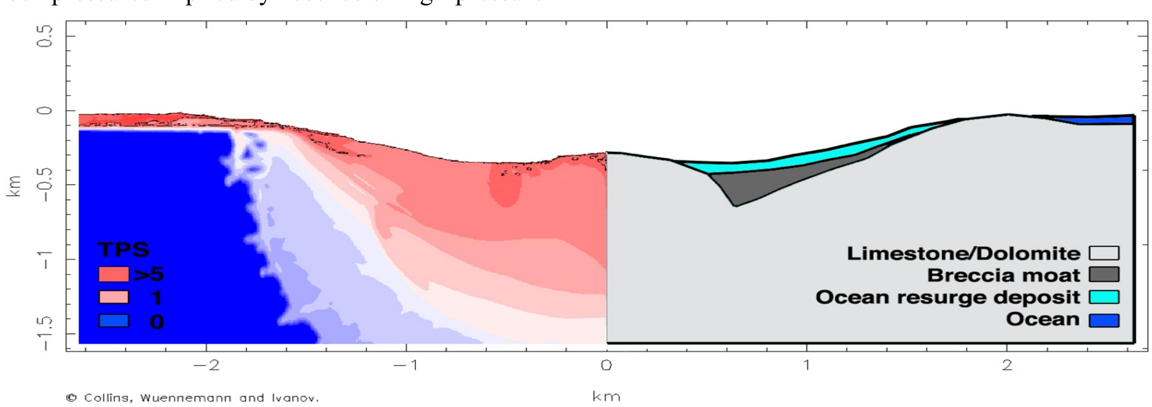

Fig. 2: simulation result. LHS: Total Plastic Strain. Red: highly displaced/brecciated area. RHS: Approximate locations of bedrock (intact, fractured & brecciated), the breccia moat, and ocean resurge deposit. Locations were measured from simulation profiles after peak formation had finished (t=23s), rim collapse had completed (50s), and after ocean resurge respectively (100s).