**HYDROCODE MODELING OF THE SIERRA MADERA IMPACT STRUCTURE.** T. J. Goldin[1], K. Wünnemann[1], H. J. Melosh[1] and G. S. Collins[1,2], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA (tgoldin@geo.arizona.edu), [2]Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK.

**Introduction:** The Sierra Madera Structure (Pecos County, Texas, USA) is the result of a Late Cretaceous or early Tertiary impact into a thick sedimentary target sequence [1]. The crater is complex, with an intensely folded and faulted central uplift. The present structure consists of central hills exposing Permian strata, a surrounding structural depression floored by Lower Cretaceous strata, and a concentric ring of outer hills topped by Lower Cretaceous strata and cut by inward-facing normal faults. The diameter of the crater, as defined by the outer limit of deformation and analogies with lunar craters and assuming the outer hills to represent the eroded rim, is 13 km [1, 2]. Impact breccias, shocked quartz, and shatter cones offer evidence for an impact origin and give shock pressure estimates. The Sierra Madera impact is of interest as it occurred in a 5.5-km thick sedimentary sequence and did not involve any crystalline basement rock, unlike most other known terrestrial craters.

**Geology:** The geology of the Sierra Madera structure has been mapped in detail based on exposures and drill cores [1, 2]. The depth of deformation beneath the crater is 1.8-2.4 km, dying out in the lowermost Permian. The Permian target rock sequence consists of predominantly dolomites and is overlain by Lower Cretaceous limestone. Impact breccia lithologies suggest that the Lower Cretaceous rocks were not completely consolidated at the time of impact, and thus might have been less resistant to shear failure (smaller yield strength) than the underlying Permian strata.

The exposed central uplift, defined as the zone of uplifted strata, is 6-8 km in diameter and the oldest exposed rocks show 1.2 km of stratigraphic uplift. The surrounding structural depression is ~1 km in width and is filled by Quaternary alluvium. The outer hills, ~0.8-km wide, expose upper Permian and Lower Cretaceous strata, the latter of which shows <30 m of stratigraphic uplift. It has been inferred in previous studies that the outer hills of Sierra Madera represent strata folded beneath the original crater rim. Scaling to the dimensions of other craters suggests ~600 m of post-impact erosion [1]. However, it is possible that previous assumptions about the outer hills' relation to the original crater morphology are incorrect and both the original crater size and subsequent erosion are greater than previous estimates.

**Shock Pressures:** Observed shock deformation features in quartz grains reveal peak pressure: (1) >20 GPa in mixed breccias near the structure's center, (2) >10 GPa in *in situ* rocks near the center, and (3) >5 GPa in rocks near the edge of the central uplift [1]. Shatter cones surrounding the central uplift support these assumptions as shatter cones are believed to result from shock pressures of 3-6 MPa [3].

**Hydrocode Modeling:** We performed hydrocode simulations of the impact event using the SALE-3MAT hydrocode [4] to reproduce the observed target deformation, crater morphology, and pressure distribution of the Sierra Madera structure. SALE-3MAT is a finite-difference 2D hydrocode based on the code by Amsden et al. [5] that incorporates some major modifications e.g. stress- and multi-material extension [6, 7]. The strength model includes pressure and temperature dependent strength, shear failure, strain softening, brittle and ductile deformation, and acoustic fluidization [7, 8]. We approximated the sedimentary target lithologies using two layers of varying strength properties: a stronger lower layer representing Permian and older carbonates overlain by a weaker upper layer representing unconsolidated Lower Cretaceous limestones. We used the Tillotson equation of state and typical rock strength parameters for limestone.

Two possible scenarios were tested: (1) a smaller final crater with a rim-to-rim diameter of 13 km and ~700 m of erosion, consistent with previous interpretations, and (2) a larger final crater with a rim-to-rim diameter of 16 km and increased (~1.2 km) erosion of Cretaceous strata. Scaling laws define the projectile parameters. The smaller crater was modeled using a projectile radius of 340 m and an impact velocity of 17.8 km/s. The upper weak layer is 1-km thick. The larger crater was modeled using a projectile radius of 500 m, an impact velocity of 17.8 km/s, and an upper weak layer thickness of 1.5 km.

**Results:** Both the smaller crater and larger crater models, taking into account erosion of all but 100-300 m of Cretaceous strata, reproduce the observed crater geology fairly well. The smaller crater model fits with previous interpretations of the original final crater [1, 2], producing a transient crater ~8 km in diameter and a final crater ~12 km in diameter. Erosion of ~700 m of Cretaceous strata reveals a crater profile similar to that which is observed, particularly in the size and amount of uplift at the center. The modeled pressure contours agree with those estimated from shocked quartz grains. The most significant problem that the smaller crater model experiences is that it predicts overturning of the upper Permian strata at the edges of the central uplift, which is inconsistent with geologic maps [1] showing no overturned stratigraphy. Additionally, the stratigraphy is depressed surrounding the central uplift and this is not conclusively seen in geologic cross sections.

The larger crater model produces a transient crater ~10 km in diameter and a final crater ~16 km in diameter. Erosion of ~1.2 km of Cretaceous strata also reveals a structure similar to Sierra Madera, with respect to the geometry of the central uplift and also that of the surrounding region. Although an overturned flap is expected, it is small and would be mostly removed by erosion. Some stratigraphic depression surrounding the central uplift is expected, but it is less pronounced than that of the smaller crater model. The diameter of the post-erosion “rim” is ~12 km, which is consistent with the low outer hills at Sierra Madera. However, this more energetic impact event creates potential problems. The pressure contours indicate that rocks exposed in the central uplift experienced pressures exceeding 40 GPa, which is higher than previously estimated maximum shock pressures. Additionally, the extent of damage is much greater for a larger impact and no evidence for impact related deformation has been described beyond the outer hills or deeper than a few kilometers.

Neither model can be ruled out at this stage. It is possible that the overturning of upper Permian strata in the smaller crater models may exist at Sierra Madera, but was not detected previously from the single drill core in this region of the crater. It is also possible that the high maximum pressures in the larger crater model are due to rocks, which have experienced a higher degree of shock, being weaker and preferentially eroded. The extent of damage and strain at Sierra Madera may be greater than previously thought as estimates are based on the extent of folding and faulting of the stratigraphy as seen in drill cores [1]. Gravity mapping may help in this debate as a larger crater should be associated with a larger gravity anomaly than a smaller crater due to a greater volume of material with reduced density. An unusually low impact velocity may also eliminate problems with the larger crater model.

Both these models reproduce the observed Sierra Madera structure, which has not previously been modeled. Although the size of the original final crater diameter remains uncertain, we suggest that the diameter of the original crater may have been several kilometers bigger than previously reported. If so, we predict a larger gravity anomaly, higher maximum peak pressures, and little overturned strata, which can be tested by further field and geophysical studies. This has implications for the pressure and temperature profiles of the target stratigraphy, as well as related properties.

**References:** [1] Wilshire H. G. et al. (1972) *USGS Prof. Paper 590-H*. [2] Howard K. A. et al. (1972) *GSA Bull.*, *83*, 2795-2808. [3] Baratoux D. and Melosh H. J. (2003) *EPSL*, *216*, 43-54. [4] Wünnemann K. et al. (2005) *GSA Spec. Paper #384*, 67-83. [5] Amsden A. et al. (1980) *Los Alamos National Laboratory Report LA-8095*, Los Alamos, 101 pp. [6] Ivanov B. et al. (1997) *Int. J. Impact Engin.*, *17*, 375-386. [7] Collins G. S. et al. (2004) *Meteoritics Planet. Sci.*, *39*, 217-231. [8] Wünnemann K. and Ivanov B. (2003) *Planet. Space Sci.*, *51*, 831-845.

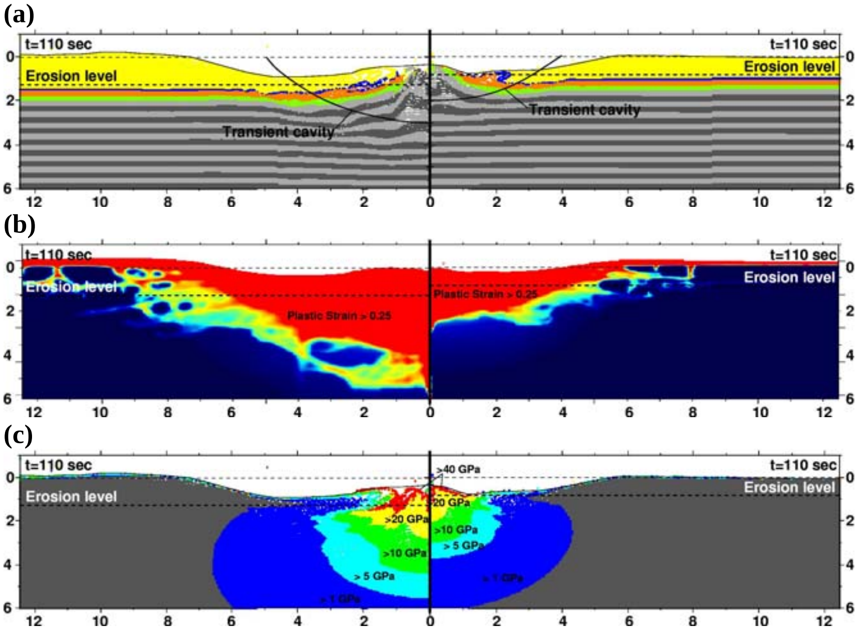

**Figure 1.** *Final crater cross-sections for the larger crater (left) and smaller crater (right) models. The hypothesized erosion level is indicated and all axes are in km. (a) Geologic structure of the final crater showing the displacement of the Word Formation (green), Gilliam Limestone (orange), Tessey Limestone (blue), and Cretaceous strata (yellow). (b) Plastic strain contours (warmer colors indicate greater plastic strain). (c) Maximum pressure contours.*