HOW BIG WAS THE CHESAPEAKE BAY IMPACT? INSIGHT FROM NUMERICAL MODELING.

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Introduction: Beneath the Chesapeake Bay and Delmarva Peninsula in Virginia, USA, lies a large impact structure. It was discovered as a result of an anomalous breccia layer in boreholes from the eastern seaboard of the United States [1-3]. The breccia was correlated with samples of impact-melt ejecta found across the region—the North American tektite strewn field [2, 4]—and an impact origin was confirmed by the presence of shocked minerals [5, 6]. At the time of impact (35.2 to 36.0 Ma), the locality was in a shallow marine environment: the crystalline basement was overlain by 600-1000 m of unconsolidated sediments and 200-600 m of water [7]. Aside from erosion by the tsunami and backwash generated by the impact, the crater is well preserved.

Figure 1 illustrates the main structural elements of the Chesapeake Bay impact crater (CBIC), based on the interpretation of seismic reflection data and drill cores [2, 7-10]. In schematic terms, the basement structure at the CBIC has the morphology of an inverted sombrero with a deep inner basin surrounded by a shallower brim [2, 7, 8]. The surface morphology of the crater, however, is almost entirely flat due to the presence of an unusually thick synimpact crater fill deposit, the Exmore breccia, which blankets the crater floor and laps over the outer rim.

The structural and morphologic form of the CBIC are similar to those observed at other marine craters on Earth (for example, Mjølnir, Barents Sea [11] and Lockne, Sweden [12]), but are quite unconventional when compared with similar size subaerial craters on Earth (for example, Popigai, Siberia [13]) and peak-ring craters on other planets. Furthermore, the ejecta deposit, so obvious around fresh lunar craters, is not discernible [7].

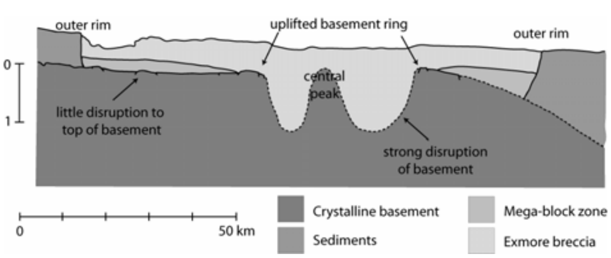

Figure 1. Schematic cross-section of Chesapeake Bay Impact Structure based on interpretation of seismic data and drill cores [2,7-10]. Dashed line indicates uncertainty in exact location of top surface of the crystalline basement.

The unusual nature of the CBIC makes it difficult to estimate the size and energy of the impacting asteroid or comet that formed it. This information is crucial for determining the environmental consequences of the impact. Previous studies [7-9] estimated a transient crater diameter of ~40 km by assuming that (1) the outer rim diameter is an analogue for the rim-to-rim diameter of extraterrestrial craters; and (2) the inner ring is a peak ring, analogous to the rugged ring of mountains, concentric and interior to the crater rim, that protrudes through the melt and breccia lens in large extraterrestrial craters. However, this procedure relies on the premise that the CBIC is morphologically equivalent to a large peak-ring crater on the moon. In this paper, we suggest that this is not the case, based on insight from numerical modeling of the Chesapeake Bay impact. We conclude that the morphology of the CBIC was strongly affected by the strength and rheology of the target rocks, and that the transient cavity formed during the development of the final crater was significantly smaller (~25 km) than previous estimates. This has important implications for the impact energy and the potential environmental consequences of the Chesapeake Bay impact event.

Modeling the Chesapeake Bay Impact: An interesting hypothesis to explain the unusual aspects of the CBIC is that, at the time of impact, the sedimentary layer was extremely weak. Poag et al. [7] suggest that the size of the outer rim of the crater may have been enhanced relative to that of the inner rim due to a considerable contrast in material properties between the crystalline basement and the weaker overlying sediments. To investigate the influence of variations in target rheology on the formation of the Chesapeake Bay impact crater we performed several hydrocode simulations of the impact. We used the SALEB hydrocode [14]—a multi-material, multi-rheology extension to the SALE hydrocode [15]. A detailed description of our strength model is presented in [16].

Our modeling approach was to perform numerous simulations of the Chesapeake Bay impact, varying certain model parameters, and assess which model produced the best fit to the observational constraints. We approximated the target lithology at the impact site by a granite half-space beneath either (1) a single weak layer 1-1.5 km in thickness, which represented both the water column and the unconsolidated, water-saturated sediments; or (2) individual layers of water (500-m thick) and sediment (1-km thick). The free parameters in our simulations were the impactor diameter and the strength model parameters for the sedimentary unit; all other model parameters were held constant. In all simulations the impact velocity was 17 km/s and the impactor density was 2700 kg/m^3. All simulations were of vertical impacts, enforced by the axisymmetric nature of the model. The effective strength of the basement rock was controlled primarily by acoustic fluidization [17, 18, 19].

Results: Our simulation results produced the best fit with observational constraints when the sedimentary unit was modeled with the equation of state of wet tuff (density = 2000 kg/m^3) and when the strength model was such that the sedimentary layer was relatively strong in the intact state but very weak when damaged. The success of this unusual strength model suggests that parts of the sedimentary unit were essentially fluidized during the cratering process.

An example of the final modeled crater is shown in Figure 2. In this image the solid "tracer" lines connect the final positions of tracer particles that marked the center of each computational cell at the beginning of the simulation and followed the particle paths of the material in that cell. Where the separation between tracer particles that were originally horizontally adjacent to each other exceeds twice the original separation, no line is drawn connecting these points. Consequently, this figure illustrates the impact-induced disruption within the target—regions that are relatively undisturbed are marked by continuous tracer lines; regions that are heavily disturbed are almost devoid of tracer lines.

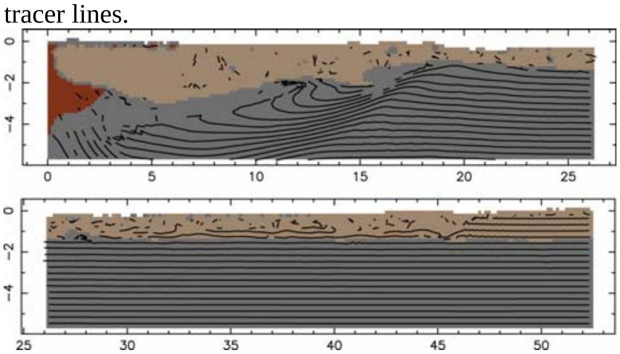

***Figure 2**. Detail of final modeled crater structure. Colors indicate material type). Solid "tracer lines" connect final location of tracer particles used to track material flow during the simulations. (a) inner basin and inner ring; (b) outer basin and outer rim.*

Figure 2 allows us to distinguish several aspects of the final modeled crater structure that are analogous to those observed in the seismic data. The inner basin of the final simulated crater (Fig. 2a) is filled with heavily deformed and disrupted, predominantly-sedimentary material. At Chesapeake Bay the corresponding rock unit, in both location and bulk composition, is the Exmore breccia [7]. Beneath this, the upper part of the crystalline basement is strongly disrupted and incoherent. This is consistent with the interface between the Exmore breccia and the basement below being difficult to discern in seismic profiles across the CBIC [7]. At the center of our modeled crater, the basement is uplifted. Outside of this there is a semi-coherent slump unit underlying more disrupted basement material. Both of these features have been identified in reflection seismic profiles across the CBIC [9]. In our model, the inner ring is marked by a distinct increase in the coherence of the basement material, and represents the remnant of the uplifted transient crater rim. The maximum height of the basement uplift is ~200 m above the pre-impact basement level, in good agreement with the interpretations of Poag et al. [9].

The outer basin of the final modeled crater (Fig. 2b) is also consistent with observation [8]. The crystalline basement underneath the outer basin is almost undisturbed. Above this, the sedimentary material in our model can be divided into two units: a completely disrupted unit, which drapes over the entire outer basin, analogous to the Exmore breccia layer, and a moderately deformed unit below, which might be analogous to the zone of decimeter- to kilometer-scale displaced blocks that lies between the basement and the Exmore breccia just inside the outer rim of the CBIC [8]. The outer rim of our modeled crater does not appear as a topographic feature, but is nevertheless discernible as a distinct change in coherence at a radius of ~47 km.

Conclusions: The excellent qualitative agreement between our model results and observational constraints from the seismic data across the CBIC strongly supports the hypothesis that the Chesapeake Bay impact was greatly affected by rheologic variation within the target. Our estimate of the size of the transient crater that collapsed to form the CBIC is significantly smaller than previous estimates. We also conclude that the inner ring was not formed in the same manner as the peak ring at larger terrestrial craters such as Chicxulub, Gulf of Mexico. The impactor size for our preferred model of the CBIC is 3.2 km, which implies an impact energy of ~1.75×10^6 MegaTons.

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