IMPACTOR SURVIVORS AS ADDITIONAL SOURCES FOR THE LATE HEAVY BOMBARDMENT. P. H. Schultz[1] and D. A. Crawford[2], [1]Department of Geological Sciences Brown University, Box 1846, Providence, RI 02912; [2]Sandia National Laboratories, MS 0836, P. O. Box 5800, Albuquerque, NM 87185 (dacrawf@sandia.gov)

Introduction: Before the last major basin-forming events on the Moon and elsewhere, the cratering rate was orders-of-magnitude higher. During this period, crater statistics also document a size distribution of craters different from the last 3.8 Ga, with an excess of craters 1 to 20 km in diameter (for the lunar highlands). Several hypotheses have been proposed to interpret the source of the objects responsible for both the enhanced flux (e.g., [1,2,3]). Significantly, this distribution is recorded on the Orientale ejecta facies. Because Orientale was the last major basin produced on the Moon capable of producing sufficiently large secondaries, returning ballistic ejecta could not be the cause. Here we propose that significant masses of large basin-forming objects survive collisions at modest impact angles (< 40º from the surface tangent) and contribute to the period of heavy bombardment. This suggestion, however, still begs the question as to the origin of the large basin-forming objects.

Background: On flat surfaces, oblique collisions (< 15º) result in large portions of the original impactor (50% of the mass) surviving and re-impacting downrange. This process is well documented in laboratory experiments where the loss of kinetic energy and momentum corresponds to a decrease in the crater size [4], shock coupling [5], and enhanced frictional shear heating [6]. The process has been called "decapitation" and the surviving impactor fragments termed "siblings" [4].

Hypervelocity impact experiments reveal that the energy initially coupled to the projectile results in reduced peak pressures. As the shock reflects off the rear of the projectile, it fails by spallation and shear. The resulting size distribution of surviving siblings departs from expectations for catastrophic failure [4]. Typically, there are 5 to 10 large pieces of nearly equal mass (totaling 50% of the initial projectile mass), in addition to a power-law distribution for smaller fragments similar to results for catastrophic disruption.

Experiments were designed to isolate the siblings before re-impacting the target downrange (Fig. 1). The point of impact was uprange from the edge of the target. The crater formed nominally and the isolated siblings impacted a witness plate downrange, close to the original trajectory. Because the siblings did not re-impact the target, they were larger (the largest approaching 30 to 50% of the initial projectile mass).

A curved surface also prevents the siblings from re-impacting the target and becomes more important as the projectile radius (r) exceeds 10% of that of the target (R). Moreover, the diameter and depth of the resulting crater decreases since a significant fraction of the initial energy/momentum has been decoupled [7]. The impact angle measured by the angle from the tangent plane at first contact progressively resembles a much lower angle collision. For example, the surviving siblings from a 45º impact (the most likely) for a projectile 4R effectively resembles a <15º impact on a planar target. Highly oblique impact craters on the Moon and Mars exhibit remarkably similar patterns, including cases where local slopes (crater walls) acted to isolate the effects of downrange siblings [7]. Consequently, decapitation is a fundamental process, not restricted to laboratory-scale experiments.

The Moon, Mercury, Mars, and Vesta all retain evidence of a collision that approached 0.001% to 0.3% of their gravitational potential energy. Simple geometry reveals that decapitation of basin-forming asteroids yields downrange siblings that cannot re-impact the surface immediately following the event. For shear-controlled failure, a simple geometric relation [7] predicts that one half of the impactor will be decoupled when the impact angle (θ) approaches $\cos(\theta) = R/(r+R)$. As a result, a single mega-impactor (> 700 km) could yield multiple large siblings that will be (by definition) in a planet-crossing orbit initially. In addition to the 5 to 10 largest masses, many more much smaller objects add to the background cratering record. A mega-basin, therefore, may appear much older (based on crater statistics) due to the overprinting by sibling debris arriving over the next 10^2 to 10^8 years.

Computations: In order to test this hypothesis, we used the three-dimensional CTH hydrocode to assess the consequences of undifferentiated dunite bodies of 140-700 km in diameter colliding with the Moon at 20 km/s and angles of 30°, 45°, 60° and 90° (from the impact tangent plane at first contact). This approach kept the energy couple to the Moon approximately the same. The calculations used ANEOS equations-of-state [8] for the dunite, the lunar mantle and the 350 km radius molten iron core with a temperature profile at the time of impact based on theoretical models [9]. The calculations have not fully incorporated fragmentation or shear to the resolution necessary to address the physical state of the siblings (to be addressed in the future). Nevertheless, the results demonstrate the significant decoupling and continued trajectory of the survivors of the collision. The code used an Adaptive

Mesh Refinement (AMR) approach where the resolution of the finest computational zoning was 40 km (cubical zones). The total computational domain was 20,000 km in each direction. The finest resolution (40 km) was reserved for any material with a density greater than 0.1 g/cc, thereby allowing vapor to flow into low-resolution mesh. Consequently, regions of interest (the solid Moon and impactor) could be resolved while not wasting computational resources on the vapor.

Numerical resolution was adequate to capture shock compression, release and tensile fracture (spall) in the bulk of the Moon. For the largest energy events, the impact kinetic energy (KE) represents a significant fraction (up to about 30%) of the total gravitational potential (binding) energy of the Moon. For oblique impacts (30°), however, much of the initial KE (>50%) decouples from the process as the impactor decapitates and continues downrange (Figs. 2 and 3). The subsequent trajectory and speed is modified only slightly (<10° and 10%, respectively).

Implications and Conclusions: At least half of the population of large basins on the inner planets was oblique (<45°). Lower angle collisions (<30°) ensured that a significant portion of the impacting body survived and contributed to subsequent bombardment, whether on the original target planet or on other planets. The Crisium Basin on the Moon illustrates an extremely low-angle impact where the massif-ring was only slightly larger (factors of 3) than the impactor. Downrange siblings from an oblique basin-forming impact would have contributed 20% to 80% of the original impactor. The size distribution of the siblings would not have followed a single power-law distribution because multiple processes control the process (e.g., shear, spallation). Larger masses (or weakly bound masses) would have contributed to subsequent bombardment (later basins), whereas smaller masses would have bombarded the planets or were ejected from the inner solar system. In this scenario, one mega-basin could create its own heavy bombardment. The last oblique basin-forming collision yielded smaller debris with a short dynamical lifetime.

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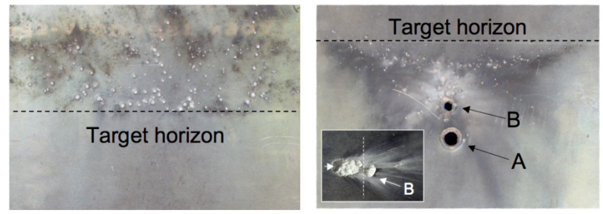

Figure 1. Witness plates positioned vertically downrange for 15° impacts into water (left) and aluminum (right). The source of the downrange pit was isolated by aiming at the edge of the target (line, inset). The decapitated impactor isolated from re-impacting downrange (B), only slightly deflected from the original trajectory (A).

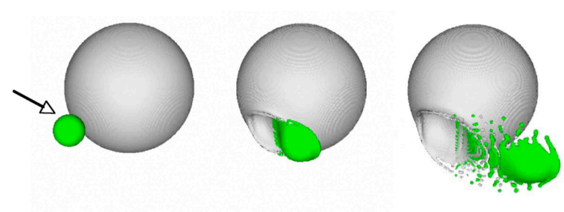

Figure 2: Survival of large impactor (800 km diameter) colliding with the Moon at 10 km/s at an angle of 30° to the surface tangent. Times represent 0, 150 and 300s after impact.

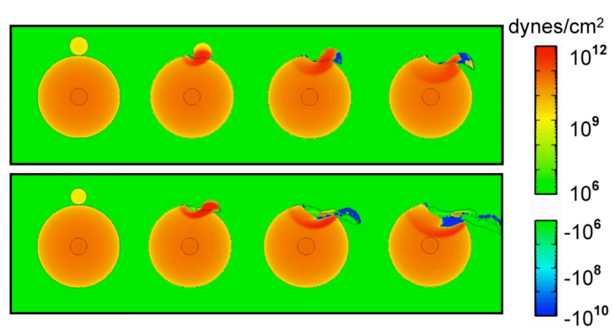

Figure 3: Trajectory and pressure conditions inside the Moon and impacting body impacting at 30° to the surface tangent. Top panel shows an 800 km diameter body at 10 km/s; the bottom panel shows a 700 km diameter body at 20 km/s, both coupling the same energy to the surface. Times represent 0, 50, 150, and 200 s after impact.