LUNAR BASIN-FORMING PROJECTILES. P. H. Schultz[1] and D. Crawford[2], [1]Department of Geological Sciences, Brown University, Providence, RI 02912 (peter_schultz@brown.edu), [2]Sandia National Laboratories, Albuquerque, NM, USA

Introduction: Signatures of the projectile coupling zone within craters are considered lost during collapse [e.g., 1, 2]. Other studies, however, argue that these signatures can be characterized by key morphologies including the central uplift and shape in plan [3,4]. Key indicators become much more evident at basin scales because gravity-scaling relations [1,5] predict that transient craters reduce to just a few projectile diameters, especially for low-angle impacts. In fact, the ratios of the transient crater diameter to projectile diameter at basin scales are comparable to values for strength-controlled craters in laboratory experiments. For oblique impacts, the initial stages of coupling are not completely destroyed but are mapped out in different directions around basins formed by oblique impacts [3,4]. Consequently, the goal of this contribution is estimate the diameter of the impactors responsible for oblique impact basins on the Moon.

Background & Approach: As impact angle decreases, both laboratory and hydrocode experiments reveal that failed portions of the projectile (decapitation fragments) continue downrange at a reduced impact angle at the same speed as the original impactor [6]. The top of the sheared projectile travels directly downrange, whereas the two sides subtend an angle proportional to the impact angle. At low enough angles (or on curved surfaces), decapitated fragments and early-stage, high-speed ejecta decouple from the transient crater, impacting the surface downrange at low angles prior to ejecta emplacement. Such features reflect the original momentum (trajectory) of the debris and produce rimmed grooves, scours, non-radial ejecta flow patterns, and secondaries breached downrange. Such features are not radial to the final crater but trace back to the impactor at first contact. Uprange, such features set limits on the position of first contact. Combined, they establish constraints on the size and impact angle of the projectile by tracing back their directions on a great circle.

Previous efforts to estimate the impactor sizes [3] were based on available Clementine, Lunar Orbiter, Apollo, and Zond images mapped on the Apollo-based coordinate systems. Even though basin-related grooves and scours could be clearly identified, the mapped coordinate system introduced errors, especially at high latitudes and large distances (high-speed) components. Consequently, mapping was re-done with new LROC-WAC imaging and ARC-GIS based on the latest LROC-based coordinate system. Here we focus lunar basins exhibiting evidence for oblique trajectories based on asymmetries in their ejecta: Schrödinger, Moscoviense, Orientale [7,8], and Imbrium [3,9].

Results: Great circles (GS's) extrapolated back to the assumed trajectory of the Imbrium impactor reveal source regions both uprange and downrange from the center of the Imbrium basin (Fig. 1a). GS's extrapolated from uprange sets intersect the Imbrium impactor trajectory northwest of Sinus Iridum, thereby constraining the point of first contact to just southeast of this crater. Note that Rheita Vallis is attributed to Imbrium, rather than the Nectaris impact.

Other sets do not converge within the outer boundaries of Imbrium (Fig. 1b) and are interpreted as trajectories related to first contact by the Imbrium impactor. Based on these sets, the Imbrium impact angle was about 25°-35°. Histograms were generated from the intersections of these GC's with lines orthogonal to the trajectory at different distances uprange from the basin center. These histograms indicate that the diameter of the Imbrium basin was about 275km±30km. The same approach yielded impactor diameters for Schrödinger (45km), Moscoviense (100km), and Orientale (110km) basins.

Hydrocode Model: The impactor sizes for both Moscoviense and Orientale are very similar, yet they have very different morphologies. Moscoviense exhibits a well-defined, elongate innermost ring, whereas Orientale has broken, multiple inner rings. Such differences may indicate a lower speed impact. Consequently, a hydrocode model (CTH) incorporated localized shear heating for an estimated impactor diameter of 100km and impact angle of 30° at 10km/s [11]. Two different conditions were assumed. The first model used a monolithic asteroid composed of dunite and closely matched observations, including the downrange scours converging uprange (Fig. 2).

The second model used a differentiated asteroid with a 50km-diameter iron core (Fig. 3). In this case, the diameter of the final crater was not significantly changed. But the failed core resulted in an elongate (double) inner ring (similar to Moscoviense). Moreover, remnants of the core lined the inner ring.

Implications: Crater-scaling relations can be applied in order to estimate the size of the transient cavity (for assumed impact angles and impact speeds). For these calculations, gravity scaling is assumed for wet sand [1] yielding a transient apparent diameter of 205km for the peak-ring basin Schrödinger (v = 20km/s, θ = 30°). After a 25% correction for slumping and conversion to the apparent diameter), the final diameter (rim-to-rim) becomes 320km, which closely matches the observed rim-to-rim diameter (~330km).

Imbrium: the calculated apparent transient crater (D_A = 843km) becomes only slightly larger than the projectile diameter (2r) with $D_A/2r = 3.1$ for Imbrium (20km/s at 30°). Increasing the apparent transient diameter by 25% (for the transient rim-rim diameter), the calculated final basin diameter becomes 1054km, consistent with a transient basin extending from the northwest rim of Sinus Iridum (first contact) to just inside the Apennines. Uprange (to the northwest), the transient crater profile would have been unstable, resulting in greater rim/wall collapse (e.g., extending to Mare Frigoris). Shallower excavation downrange [4,10] would have preserved the uplifted rim, now represented by the Apennines.

Orientale: The calculated rim-rim (pre-collapse) diameter for the estimated impactor diameter is about 510km (20km/s at 30°), i.e., the Inner Rooke Mountains. If this is the case, then the Outer Rooke Mountains might correspond the collapsed rim and the Cordillera scarp, an outer slump block

Moscoviense: The hydrocode model of a differentiated asteroid forming Moscoviense reveals that the observed spinels and olivine occurring along the interior ring [12] could be relicts of the core of a differentiated asteroid, rather than uplifted mantle material.

Conclusions: Large impactor diameters derived from the convergence of first-contact secondaries are consistent with reduced cratering efficiencies at large scales. It would seem that such large projectiles should have exposed the mantle. Recent observations, however, reveal that all basin rings are composed of anorthosites uplifted from the upper crust [13, 14], consistent with the inner rings representing the extent of lateral displacement at depth [16].

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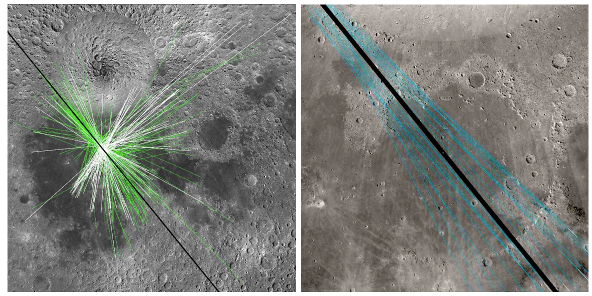

Figure 1a (left)**:** Great circles (GC's) extending along the axes of elongated/breached secondaries, grooves, and lineations associated with the Imbrium impact. White traces indicate GC's intersecting the Imbrium impactor trajectory (black line) within the basin, whereas green traces correspond to GC's converging more that 300km uprange of the basin center.

Figure 1b (right)**:** Great circles (GC's) extending from Imbrium grooves and scours that fail to cross the inferred Imbrium trajectory within the basin limit. These traces constrain the maximum diameter of the Imbrium projectile, with the assumption that the outermost limits (to either side of the trajectory) correspond to the lateral dimensions of the Imbrium impactor.

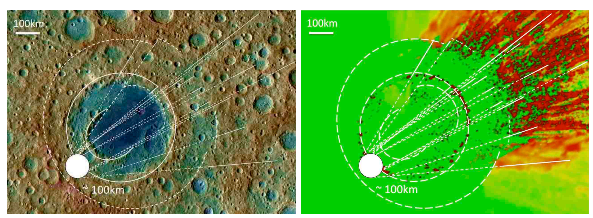

Figure 2: Hydrocode simulation of Moscoviense impact from a 100km monolithic asteroid (Fig. 2a, left) superimposed on observed patterns on the Moon (Fig. 2b, right). The red color corresponds to the projectile.

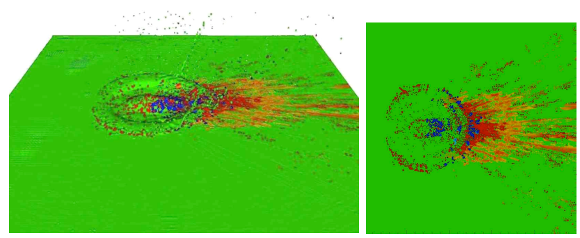

Figure 3: Hydrocode simulation of Moscoviense impact from a 100km asteroid with a 50km diameter iron core (Left: oblique view, Right: map view). Red coloration is imprinting by the asteroid mantle onto the target surface resulting in a non-radial pattern, blue coloration is imprinting by the asteroid core.

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