EFFECT OF ASTEROID DECAPITATION ON CRATERS AND BASINS. P. H. Schultz[1], A.M. Stickle[1], and D. A. Crawford[2], [1]Brown University Geological Sciences, 324 Brook St., Box 1846, Providence, RI 02912. (peter_schultz@brown.edu), [2]Sandia National Laboratories, P.O. Box 5800, MS 0836, Albuquerque, NM 87185.

Introduction: Multi-ring impact basins do not always form simple, concentric circles. Instead, some basins have an offset central ring, incomplete massif ring, and extension to one side. We propose that some of these asymmetries reflect the effect of an oblique impact and result from the failed projectile impacting downrange. This process not only affects crater excavation but support of elevated basin rim during the collapse phase.

Case studies: Several relatively fresh, large impact basins provide important clues about expressions of the impact trajectory.

Imbrium: The Apennine Mountains stand in high relief southeast of the basin center, unlike the Atlas Mountains or the highlands north of Mare Frigoris. Moreover, the Apennines forms an oblong arc to the northeast and southwest (departing from a perfect circle, see Fig. 1). There are different interpretations for the location of basin rings [e.g., 1-3]. If the Atlas Mountains represent the uprange equivalent of the Apennines, then the inner ring is significantly offset to the northwest from the basin center. Moreover, the inter-ring shelf (the Archimedes Platform) extends much farther to the southeast. Alternatively, the highlands bordering Mare Frigoris represent all that is left of an uprange rim. In either case, the expression of the basin rim downrange to the southeast (Apennines) is in striking contrast with its expression to the northwest uprange.

Crisium: The Crisium basin is one of the most obvious oblique impact basins [2-5]. In this case the inner massif ring forms a distinct EW oblong shape. Remnants of ejecta scours and an eastern basin extension indicate a W to E trajectory. The gravity high is offset toward the west, leaving a broad shelf similar to the Archimedes platform. Previous studies proposed that the oblong massifs represent the inner ring surrounded by a much larger faint, outer scarp slightly elongate perpendicular to the trajectory [4]. Just as for Imbrium, however, the highest massifs occur downrange to the east with the lowest, uprange.

Moscoviense: *Selene* and *LOLA* topography provide new insights into the structure of this basin, which was formed by an oblique impact from the southwest as indicated by grooves converging uprange. Its distinct double inner ring creates a tomahawk-like shape [6] with the highest relief of the inner ring downrange. As in Imbrium and Crisium, the gravity high is offset uprange (SW).

Implications: These three oblique-impact basins reveal consistent patterns: central gravity anomaly offset uprange; interior extension (shelf) downrange; outer ring elongate perpendicular to the trajectory; lowest massifs uprange; and highest massifs downrange. We propose that these five observations can be explained as expressions of the failed projectile.

Effect of Impactor decapitation: During a highly oblique impact (<15°), the projectile will fail (decapitate) and impact downrange [8]. This process is well documented in laboratory experiments but not well captured in hydrocode constitutive and fracture and failure models [9]. The underlying process of failure is not just catastrophic fragmentation. Shear failure is necessary in order to account for both the size distribution and downrange trajectory of surviving fragments when the failed projectile is decoupled from re-impacting downrange by experimental design (e.g., [6,8]. First contact creates the maximum coupling and the greatest depth. Projectile failure, however, induces shallower excavation downrange.

Laboratory experiments reveal that significant fractions of the projectile can survive impact and produce distinctive "ears" downrange corresponding to re-impacts by the "decapitated" projectile fragments [8]. These fragments re-impact the target at half the initial impact angle and significantly affect the amount of melting and vaporization [10, 11]. Mapping the trajectories of failed projectiles can be used to characterize the evolving flow field, including the size and impact location of the basin forming projectile [6]. Experiments also have been designed to prevent these fragments from re-impacting downrange and track their trajectories, speeds, and sizes [6]. Other experiments have explored their effect on target damage [9]. Low-angle impacts (<15) into solid targets expose the initial coupling process. Impacts into aluminum targets also produce a downrange "shelf" where the impactor failure extends coupling farther downrange.

The effect of these surviving fragments on the cratering process is not easily modeled. Instead, the effect of an oblique impact depicts damage offset downrange from the point of first contact. Without including the effects of shear failure in the projectile, the extended zone of damage downrange is not captured even for hydrocode models at laboratory scales [9], unless artificially introducing failure planes within the projectile. Both experiments and hydrocode models document the reduction in coupling with the target, especially for large-body impacts [12].

Implications for basin scales: The early stages of coupling from laboratory and computational experiments provide important clues asymmetries within large impact basins.

***Loss of uprange massif rim*:** The along-trajectory transient cavity for an oblique basin-forming impact is initially asymmetric uprange with a steeply dipping wall, reduced structural uplift, and reduced ejecta emplacement. During uplift, the uprange rim/wall collapses, thereby removing expression of the uprange massifs (e.g., the Cordilleras of Orientale and the Atlas Mountains of Imbrium. The enhanced collapse uprange circularizes the basin shape-in plan without a clear expression of a rim, e.g., the mare-highland contact of Mare Frigoris uprange from Imbrium. In addition, the extensional uprange mega-slump represents deep faults most likely to tap magma later (e.g., Mare Frigoris for Imbrium and Lacus Veris and Autumni for Orientale).

***Enhanced downrange massif rim*:** Downrange, shallow excavation supports the structurally uplifted rim (and emplaced ejecta) on a less-damaged lithosphere due to shallower excavation (e.g., the Apennines of Imbrium). Nevertheless, downrange scouring by the failed projectile fragments creates "sculpturing" that disrupts the rim even before excavation and uplift [6], e.g., the downrange discontinuous massifs downrange of the Crisium basin.

Transverse outer ring: Modestly oblique impacts (15°-30°) produce widening of the cross-trajectory transient cavity. This widening is less appreciated but represents a fundamental process recognized as oblong crater shape transverse to the trajectory [13], the ejecta curtain for particulate targets [14], and damage pattern in solid targets [15]. The transverse widening results from migration of flow field: reduced damage and flow uprange and subsequent maximum coupling downrange [6]. The outer ring centers on the averaged zone of coupling, between first contact by the projectile and its decapitated fragments downrange. At low impact angles, this process is more easily recognized as the butterfly ejecta pattern. Transverse widening is recognized in Orientale and Imbrium. Smaller scale examples include Antoniadi (Fig. 2), Petavius-B and Buys-Ballot but may be masked by enhanced uprange wall failure [16].

***Oblong inner ring*:** The elliptical shape of the inner massif ring along the trajectory preserves direct evidence for initial coupling by oblique impacts, e.g., Crisium and Imbrium). The direction of impact can be determined from the convergence of non-radial secondary groove, the NW-SE oblong central ring, and the uprange offset of the central mascon [5]. In some cases, however, projectile decapitation results in downrange disruption (e.g., Orientale) or even the appearance of a double impact (e.g., Moscoviense), likely due to lower speed collisions or denser projectiles (resulting in a larger coupling zone relative to the excavation diameter). Smaller scale examples include Antoniadi (Fig. 2), Schrodinger, and examples on Venus [16]. In the case of Antoniadi (and other examples), the basin floor retains structural elements or scouring extending downrange. Because this region expresses maximum coupling, subsequent uplift of the Moho occurs within the portion of the basin and accounts for the offset mascon in Imbrium, Crisium, Orientale, and Moscoviense. The oblong shape of the inner massif ring can be interpreted as uplift of the deformed lower crust [16]. If this interpretation is correct, then oblique impact basins preserve expressions of the initial stages of the impact process due to the lower shock pressures and damage at depth.

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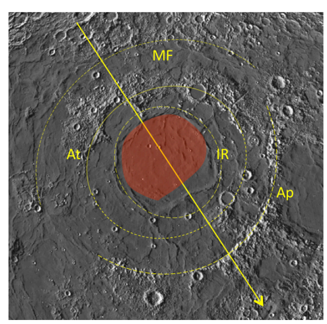

Figure 1: The Imbrium Basin showing: inner ring offset uprange and oblong along the trajectory (IR); oblong shape transverse to the trajectory; and contrast between preserved massif rim uprange (Mare Frigoris, MF) and the Atlas (At) Mountains and the Apennines (Ap) downrange. (Projection M. Collins).

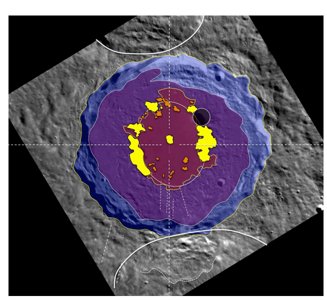

Figure 2: Antoniadi basin showing oblong inner ring (yellow) along the trajectory (from the top) and widening transverse to the traje-tory. Grooves on the crater floor parallel the trajectory.