Making the Man in the Moon: Origin of the Imbrium Basin. Peter H. Schultz, Dept. of Geological Sciences, Brown University, Providence, RI.

The lunar nearside is dominated by the effects of the Imbrium impact from its initial stages of formation to subsequent mare flooding (1, 2). It is also enigmatic due to asymmetry in the distribution of certain ejecta facies (3, 4), massif rings, wrinkle ridge pattern, and concentric pattern of crustal failure. Baldwin (5) and Wilhelms (4) previously suggested that Imbrium may have formed by an oblique strike from the northwest. New insights about the oblique impact process (6, 7, 8) allow re-examining such a proposal. We conclude that a 30° impact from the northwest would not only account for the asymmetry in the topographic expression and ejecta facies but also for the offset in the geophysical expression. Moreover, the proposed Procellarum basin (9) would be an expected consequence of the trajectory.

Imbrium Asymmetry: Imbrium exhibits subtle but significant asymmetry in its topographic, geophysical, and morphologic expressions even though the over-all pattern is generally symmetric (3). As discussed below, these two observations are not mutually exclusive but reflect a time- and space-dependent transfer of energy during an oblique impact. Different choices for the center of symmetry (e.g., see 3 and 4) may reflect the existence of an evolving source for energy transfer. The topographic asymmetry is best illustrated by the high-relief Apennine/Carpathian/Caucasus mountain ring to the south and the nearly non-existent relief to the north (see 10). Instead, the concentric pattern to the north is principally expressed by the much lower relief of the highlands beyond Mare Frigoris or Alpes Montes. In detail, the arcuate pattern of both Mare Frigoris and wrinkle ridges to the northwest centers in Mare Imbrium southeast of the oblong interior ring of wrinkle ridges. The well-defined relief of the southern mountain ring also exhibits a subarcuate plan but with a center of curvature offset to the northwest in Mare Imbrium. As a result, Imbrium sculpture in this region is not perpendicular to the Caucasus front. Previous geophysical studies indicated that the Imbrium mascon was significantly offset to the northwest portion of Mare Imbrium (11). This placement of the mascon is now reconfirmed in Clementine data (10), which further reveals a slightly elongate shape oriented NW/SE closely approximating the interior ring. Even though the Imbrium basin is one of the largest impact structures, its gravity anomaly curiously is not.

The morphologic expression for Imbrium exhibits patterns of both symmetry and asymmetry. Relict massifs within Mare Imbrium generally follow the oblong pattern of wrinkle ridges oriented NW/SE and offset to the northwest nearly coincident with the Bouguer anomaly (10). Arcuate wrinkle ridges at greater distances, however, center more on the general geometric center of Mare Imbrium. Mapping of grooves from Imbrium ("sculpture") also reveals two offset centers of convergence originally recognized by Hartmann (12). While one component of the sculpture converges on a center in northwest Imbrium nearly coincident with the gravity high, secondary craters and lineations of the Fra Mauro are more radial to the massif rim, i.e. focusing closer to the geometric center of Imbrium.

Consequences of an Oblique Impact: At the scale of Imbrium, the penetration phase of crater formation comprises a significant fraction of crater growth (13). Because the impactor fails and ricochets downrange before significant penetration, it creates a pattern of hypervelocity debris over an azimuth that depends on impact angle. Laboratory experiments further reveal that the resulting pattern converges on a "source" that evolves with time: initially uprange but eventually centered on the geometric center (7). Typically three trajectories are observed: on-trajectory fragments from the top portion of the impactor and two components to either side of the trajectory from middle portion. This penetration phase can be identified in smaller basins such as Crisium (6, 8), Antoniadi (14), Orientale (7), or Bach on Mercury (7) as well as numerous craters/basins on Venus (7). At basin scales, however, surface curvature extends the downrange horizon and the resulting effects of hypervelocity ricochet craters ("siblings"). For example, a 300 km diameter impactor striking at only 25° from the horizontal would create siblings extending more than 1000 km from the point of first contact, which would be beyond the basin rim but over-ridden by later arriving secondaries.

The transfer of kinetic energy and momentum from impactor to target results in the greatest depth uprange (15). Equally important, shock damage (prior to excavation) is asymmetric with reduced shock effects directly uprange and maximum shock damage offset downrange. Transfer of KE by the upper portion of the impactor, however, results in reduced damage at depth downrange and shallow excavation. Consequently the overall limits of surface failure for low-angle impacts (20°-35°) form an oblong shape perpendicular to the trajectory and offset downrange from the maximum depth. At greater distances, the target damage (including contributions from the hypervelocity ricochet) collectively resembles a point source centered downrange (14).

Formation of Imbrium: The elongate mascon offset to the northwest is proposed to correspond to the region of greatest displacement and excavation produced during the initial stages of penetration. Because structural uplift and shock damage is reduced uprange, topographic expression is poorly developed. Rebound and collapse centered on this region nevertheless creates deep listric faults affecting the distribution of Mare Frigoris. Pre-excavation scouring and elongate sibling craters due to hypervelocity ricochet of the impactor created an early-stage component of the Imbrium sculpture that has a "source" region in the northwest portion of Mare Imbrium close to the gravity high. Based on the azimuthal distribution of uprange-centered sculpture, the angle of impact was probably not much lower than 25°. Such an impact angle nevertheless would create melt/vapor products engulfing the nearside *prior to* secondary cratering and emplacement of continuous ejecta deposits perhaps contributing to the nearside compositional anomaly (1, 3). Ballistic ejecta from the excavation stage overprinted the earlier sculpture and any melt/vapor with a time-averaged "source" region closer to the geometric center, downrange from the maximum depth of excavation.

The 3-D response to the oblique trajectory results in subarcuate limits of failure with the greatest diameter perpendicular to the NW/SE trajectory. This pattern is not only observed in laboratory experiments but can be documented in numerous lunar craters exhibiting asymmetric ejecta, including Tycho, Antoniadi, Tsiolkovsky, and Orientale (7, 14). The subarcuate plan of the Apennine/Carpathian massif/scarp is proposed to have a similar origin but complicated somewhat during the modification stage. While collapse of the offset transient cavity to the northwest largely removed the low-relief uprange rim during modification, shallower excavation downrange by the shearing and failing portions of the impactor precluded a similar response. Instead, isostatic readjustment raised the Apennine front relatively intact into one of the highest mountain ranges on the Moon.

At greater distances from the point of first contact, crustal failure reflects the combined energy transferred during both penetration and ricochet. Failure created in the upper crust, therefore, would center slightly downrange from the Imbrium basin center, thereby accounting for the enigmatic pattern corresponding to "Procellarum Basin." In this revised picture, both the eccentric ring boundaries (1) and the concentric circular patterns at greater distances (3, 16) can be reconciled by a single but time-dependent transfer of energy during an oblique impact from the northwest.

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