COMPARING LABORATORY AND HYDROCODE EXPERIMENTS FOR OBLIQUE IMPACTS INTO SPHERICAL TARGETS.

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Introduction: In spherical targets, intersecting shocks and rarefactions off the free surface result in multiple failure planes deep inside the opposite side (antipodal). With increasing specific energy (well below catastrophic disruption), antipodal convergence can result in spallation off the opposite side of the sphere (see Figure 1). While PMMA is not a natural material, it does allow watching the consequences in three dimensions. Here we test the observations from the laboratory experiments by comparisons with preliminary CTH hydrocode results using a layered Moon with self-gravity.

Background: The South-Pole-Aitken (SPA) Basin represents one of the extreme examples of a major collision.The diameter of SPA (~2000-2500km) actually exceeds the radius of the Moon [1,2]. At such extremes, the size of the impactor approaches 500-800 km, particularly for an oblique trajectory. The first contact induces the initial strong shock. In an oblique impact, the impactor continues to penetrate and achieves maximum coupling downrange (and deeper), but still resides within the transient crater. For SPA, the offset between first contact and transient crater center should exceed 500-800 km. This means that any asymmetry due to the initial coupling may be expressed on the surface.

In 1976, it was proposed that the convergence of shock waves at the antipode of a spherical body could induce significant surface and subsurface disruption [3]. Possible surface expressions on the Moon (opposite to Imbrium and Orientale) and Mercury (opposite to Caloris) included disrupted (hilly and lineated) terrains. Subsequent efforts [4] tested this suggestion with an early hydrocode and concluded that the initial estimates were too conservative. Since then, various studies have continued to examine the consequences of convergent antipodal shock and seismic waves for the Moon [5, 6] and icy bodies [6], among other objects. While the relative role of convergent ejecta versus shock/seismic waves will continue to be debated, one test for the possible antipodal effects is to assess the consequences at the largest scales, i.e., the SPA Basin

Comparisons: Oblique impacts into spherical targets result in a series multiple sets of convergence corresponding to the asymmetry in the initial shock. Internal failure appears to be antipodal to the first point of contact, rather than the final crater (Fig. 1). In addition, there is a “haze” in the PMMA offset from the antipode (expressed as micro-cracks). High-speed imaging indicates that these are the first pattern of failure to emerge.

A preliminary 3D hydrocode computation used an improved version of CTH, including self-gravity and a molten core. For the model, an undifferentiated dunite body 800 km in diameter collided with the Moon at 10 km/s at an angle of 30° (from the impact tangent plane at first contact). The calculation used a simple MGRUN equations-of-state with a core radius of 350 km. In this case, the impact kinetic energy (KE) represents about 0.3% of the total gravitational potential energy of the Moon. Due to the oblique impact, however, some of this initial KE is decoupled as the impactor decapitates and continues downrange [7]. A second calculation used a faster (20 km/s) and smaller impactor (500 km) and yielded very similar results.

As shown in Figure 2, both the hydrocode and the laboratory experiments exhibit the same basic phenomena: the focus of tensile stresses is near the antipode to the point of first contact but with most extensive damage is offset toward the incoming trajectory. This should be expected because of the 3D geometry and the shock asymmetry. The hydrocode further demonstrates, however, that the duration of extension at the antipode evolves over more than 15 minutes and approaches the core, in spite of inclusion of self-gravity. Future one-to-one comparison between hydrocode and experiments will provide a better understanding the actual damage done, its possible depth, stresses on the surface, and combinations of scales and speeds. This approach is distinct from some other efforts [8], who focused on just the basin. Both the code and high-speed imaging of the experiment reveal that different styles of failure evolve and overlap.

Implications: In 1980, Whitaker [9] proposed an ancient Procellarum impact basin helps to account for the nearside maria and a pattern radial and concetric system of ridges and graben. While this hypothesis could help to account for the localization of the high-Th and KREEP [10, 11], preserved geophysical evidence for such a large impact, however, is lacking [12-14]. The basic observations made by Whitaker are not in question. Rather, it is suggested that the pattern of concentric and radial ridges and graben should be called the “Procellarum System.” While subtle, this is an important distinction. The term “basin” on the Moon implicitly connotes an impact structure. With such a distinction, there could be several working hypotheses to explain Whitaker's System. One hypothesis is that it is indeed an ancient impact that has been completely overprinted. Another is that it represents a long-lasting expression of the SPA Basin on the opposite side of the Moon [15]. The problem is that the center of the Procellarum System (PS) is not antipodal to the SPA. A simple way to account for the offset between the SPA antipode and PS is if SPA was formed by an oblique trajectory, thereby accounting for the offset of the maximum antipodal effects from the SPA center as illustrated above.

The lunar interior antipodal to SPA may have developed deep pathways for deep-seated magma. At this point, there are no claims for melting induced by the convergent shocks; nor is it proposed that the magma immediately erupted over the surface following the impact. Rather it is suggested that the early internal plumbing on the nearside may have been created by SPA. Conversely, the absence of pathways on the lunar farside is due to the absence of deep-seated failure, not to mention the absence of any farside effects from a comparable-size Procellarum impact on the nearside. Subsequent excavation of nearside intrusions by the Imbrium impact to the north of the SPA offset antipode could then help explain the localization of high Th and KREEP across the nearside.

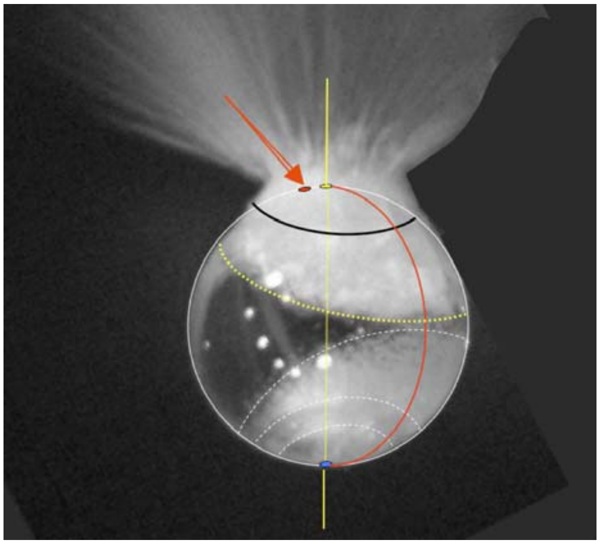

Figure 1: Oblique impact into acrylic sphere at 45º (0.64cm Pyrex sphere, right) at ~ 5.4km/s. Oblique trajectory (red) resulted in higher peak pressures downrange with antipodal failure opposite to the point of first contact, offset from the center of excavation.

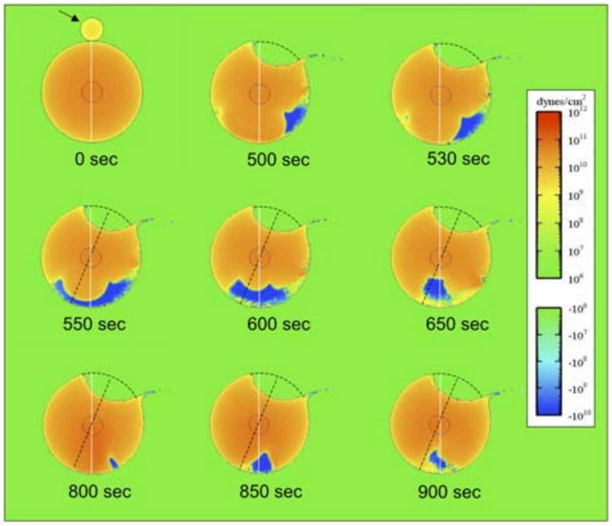

Figure 2: Results of CTH hydrocode simulation of an 800km diameter dunite body colliding with the Moon at an angle of 30°. Hydrocode reveals a pattern of offset antipodal failure that is similar to the experimental results.

References: [1] Stuart-Alexander, Stuart-Alexander, D. E., (1978) *U.S. Geol. Survey Misc. Geol. Inv. Map I-1047*; [2] Wilhelms D. E. (1984) *Geologic History of the Moon*, US Geological Survey Professional Paper 1348; [3] Schultz P.H. and Gault D.E. (1975), *The Moon*, *12*, pp. 159-177; [4] Hughes H.G., et al. (1977), *Phys. Earth Planet. Inter*. *15*, 251–263; [5] Bruesch L. S. and Asphaug E. (2004) *Icarus 168*, 457-466; [6] Hood L. L., Artemieva N. A. 2006. LPSC-37, abstr.#2137; [7] Schultz P.H. and Gault D.E. (1990), *Geol. Soc. of Amer. Sp. Paper 247*, 239-261; [8] Collins G. S. and Melosh H. J. (2004), *Lunar Planet. Sci. 35*, abstr. # 1375; [9] Whitaker, E. A. (1981), In *Multi-ring basins: Formation and evolution; Proceedings of the Lunar and Planetary Science Conference*, Houston, TX, November 10-12, 1980. New York and Oxford, Pergamon Press, 1981, p. 105-111; [10] Haskin L. A. (1998), *J. Geophys. Res.* 103, 1679–1689; [11] Korotev, R.L. (2000), *Jour. Geophys. Res. 105*, E5, 4317-4345; [12] Zuber et al. (1995), *Science 266* 1839-1843; [13] Neumann G. et al., J.Geophys.Res.101,16,841-16,843; [14] Wieczorek M. A. and Zuber M.T. (2004), *J. Geophys. Res., 109*, E01009; [15] Garrick-Bethel, I. and Zuber, M. T. (2005), *Lunar Planet. Sci. 36*, abstr. # 2372.