INVESTIGATING THE FORMATION AND STRUCTURE OF PROCELLARUM-SIZED LUNAR BASINS

Ross W. K. Potter[1,2] and James W. Head[1,2], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, 02912, USA, [2]NASA Solar System Exploration Research Virtual Institute, ross_potter@brown.edu.

Introduction: The 3200 km diameter Procellarum region is an enigmatic feature of the lunar nearside, noted for its unusually high heat flow, concentration of KREEP elements, and age (the region is thought to be one of the oldest features on the Moon). Early work [1,2] proposed that the region was the site of a giant impact event based on element concentration, thinned crust, and topographic ring-like features. Newer analyses using Gravity Recovery And Interior Laboratory (GRAIL) spacecraft gravity data [3] strongly disagree with these earlier suggestions, proposing a tectonic-magmatic origin. An impact origin, however, cannot be completely refuted; the infant Moon would have been subjected to impacts by a number of sizeable (>100 km diameter) objects [4]. It is not inconceivable, therefore, that a Procellarum-sized region could have been formed by an impact. This work, consequently, investigates the formation and structure of Procellarum-scale impact basins on the Moon using numerical modeling, and makes predictions of the types of features that could be used to recognize such a basin today.

Methods: The iSALE shock physics code [5-7] was used to model Procellarum-scale basin impacts. iSALE has been used to study other large-scale impacts within the Solar System including Caloris, Mercury [8,9], South Pole-Aitken (SPA), the Moon [10], and Hellas, Mars [11,12]. The impacts were modeled using a fully spherical target body (radius = 1750 km), with a 50 km thick crust [10,13], on top of a mantle 1350 km thick, with an iron core (radius = 350 km) at the center. A Tillotson equation of state for gabbroic anorthosite [14] and semi-analytical equations of state (ANEOS) for dunite [15] and iron [16] were used to represent the lunar crust, mantle and core, respectively. Dunite was additionally used to represent the impactor. Basins were produced using impactors ≥200 km in diameter and velocities of 10-20 km/s. Grid cell size was 10 km and comparable to other large-scale basin models [8,10]. The target thermal profile (50 K/km lithospheric temperature gradient) was taken from [10]'s best-fit scenario for the ~4.3 Ga [17] SPA basin-forming event. The profile was bounded by the solidus so that temperatures were not above the melting point at any location. Self-consistent initial gravity, pressure, strength and density fields within the Moon were computed based on this prescribed radial thermal profile. The gravity field above the surface of the Moon decayed in magnitude with radial distance squared. The gravity field over the whole mesh was fixed during the simulation; no account was taken for the change in the gravity field caused by the redistribution of mass by the impact.

Results: Figure 1 illustrates stages of a Procellarum-scale impact on the Moon. The impactor is 360 km in diameter, impacting at 15 km/s. Panels (a)-(d) show pressure and material during: (a) transient crater growth, (b) material overshoot following collapse of the crater, (c) the collapse of the overshoot and a deformed Moon, and (d) the cessation of dynamic activity; (e) and (f) illustrate the distribution of temperature and strain, respectively, following the cessation of dynamic activity five hours after the initial impact. Basin formation follows that predicted for others, such as SPA. The Procellarum-sized impacts do, however, involve the creation of a substantially large material overshoot following transient crater collapse (Fig. 1b). This is likely a consequence of the two-dimensional nature of the code (the overshoot occurs at the axis of symmetry where mass must be conserved) and is, therefore, an overestimate. The collapse of such an overshoot results in mantle material being pushed into the lunar core (Fig. 1c). Over time, however, this material returns to the mantle (Fig. 1d). Such significant overshoot and its subsequent collapse is, therefore, unlikely to have a large influence on final basin structure.

Discussion: The models demonstrate that these scale of impacts completely excavate crustal material (assuming 50 km thickness) for hundreds of kilometers around the impact site, creating a large surficial expanse of mantle material. The mantle material is heated to temperatures above the solidus to depths of hundreds of kilometers, creating a large volume of melt (>10^7 km^3), agreeing with scaling predictions [18]. Such a melt volume is likely to undergo differentiation [19,20]. The antipodal hemisphere is also affected by the impact; temperatures are slightly elevated in excess of the solidus, while strains are comparable to those experienced on the impact side. Such high strains and pressure variations during the impact could create pathways for magma to later ascend. The SPA basin-forming impact has been linked in such a way to a major lunar magmatic event 4.3 Ga [21,22]. If correct, Procellarum-sized events could have aided very early lunar magmatic events. The models also suggest that the Moon would be highly deformed by this scale of impact. Though beyond the scope of this work, such impacts might also reorient the Moon (e.g., [23]). It is clear that the consequences of such mega-scale impacts are global in extent and would have likely affected the formation and structure of younger basins, including SPA.

Comparing to Procellarum's observed features, the generally broad-scale low topography could be a consequence of melt sheet differentiation. The thinner crust beneath Procellarum, relative to the rest of the lunar nearside, could also be a consequence of differentiation and may represent the thickness of an original melt sheet. The concentration of high heat producing elements (KREEP) beneath Procellarum may be the result of excavation and uplift of originally deep sub-crustal layers (KREEP is thought to have been present at the base of the crust), similar to that observed at SPA [24]. From GRAIL data, the Procellarum region lacks the bulls-eye pattern associated with confirmed basins and has a gravity low at the edge of the region compared to highs at confirmed basins [3]. The gravity signatures over the modeled basins should be compared to that for Procellarum.

These models demonstrate that Procellarum-sized impacts on to the Moon would have had dramatic global consequences. We are exploring further effects within the impacted- and antipodal-hemispheres.

Acknowledgments: We thank iSALE developers Gareth Collins, Boris Ivanov, Jay Melosh, Kai Wünnemann and Dirk Elbeshausen.

References: [1] Cadogan, P. H. (1974) *Nature*, 250, 315-316. [2] Whitaker, E. A. (1981) *Proc. Lunar Planet. Sci.*, 12A, 105-111. [3] Andrews-Hanna, J. C. et al. (2014) *Nature*, 514, 68-71. [4] Marchi, S. et al. (2014) *Nature*, 511, 578-582. [5] Amsden, A. A. et al. (1980) Los Alamos National Laboratory Report LA-8095. [6] Collins, G. S. et al. (2004) *MAPS*, 39, 217-231. [7] Wünnemann, K. et al. (2006) *Icarus*, 180, 514-527. [8] Potter, R. W. K. and Head, J. W. (2015) *LPSC XLVI*, #1993. [9] Potter, R. W. K. and Head, J. W. (2016) *LPSC XLVII*, #1117. [10] Potter, R. W. K. et al. (2012) *Icarus*, 220, 730-741. [11] Bierhaus, M. et al. (2011) *LPSC XLII*, #2128. [12] Bierhaus, M. et al. (2013) *LPSC XLIV*, #2420. [13] Wieczorek, M. A. et al. (2013) *Science*, 339, 671-675. [14] O'Keefe, J. D. and Ahrens, T. J. (1982) *GSA Spec. Pap.*, 190, 103-120. [15] Benz, W. et al. (1989) *Icarus*, 81, 113-131. [16] Thompson, S. L. and Lauson, H. S. (1972) Sandia National Laboratory Report SC-RR-71 0714. [17] Morbidelli, A. et al. (2012) *EPSL*, 355-356, 144-151. [18] Abramov, O. et al. (2013) *Icarus*, 218, 906-916. [19] Vaughan, W. M. et al (2013) *Icarus*, 223, 744-765. [20] Hurwitz, D. M. and Kring, D. A. (2014) *JGR*, 119, 1110-1133. [21] Kring, D. A. et al. (2015) *Early Sol. Sys. Imp. Bombardment III*, #3009. [22] McGovern, P. J. et al. (2015) *Early Sol. Sys. Imp. Bombardment III*, #3027. [23] Ong, L. and Melosh, H. J. (2010) *LPSC XLI*, #1363. [24] Jolliff, B. L. et al. (2000) *JGR*, 105, 4197-4216.

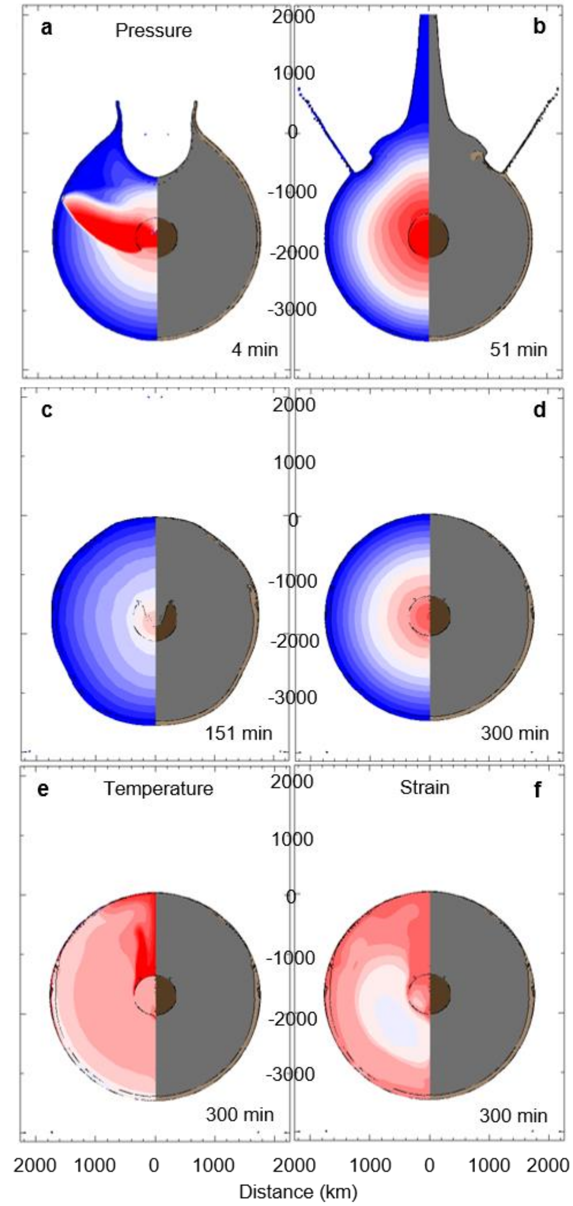

Figure 1: Time steps for a 360 km diameter impactor hitting the Moon at 15 km/s. (a)-(d) show pressure (blues are low; reds are high) and material (beige: crust; gray: mantle; brown: core) illustrating: (a) the opening of the transient crater, (b) the overshoot of material following transient crater collapse, (c) deformation of the Moon's shape following collapse of the overshoot, and (d) the state following the cessation of dynamic activity. (e) Temperature (dark reds are high) and (f) strain (reds are high) are also shown at the cessation of dynamic activity.