TOO HOT, TOO COLD, OR JUST RIGHT: THE IMPORTANCE OF TARGET TEMPERATURE AND OTHER FACTORS ON IMPACT BASIN FORMATION INVESTIGATED USING iSALE HYDROCODE MODELING

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Introduction: Impact basins (Figure 1) are the largest impact structures found on planetary bodies. Given their sizes (which can be 1000s of kilometers in diameter) they can dominate planetary surfaces and greatly influence their target body's evolution. Despite their dominant surface presence, basins are the rarest crater type and, consequently, the least understood. Many experimental and numerical modeling studies have been undertaken to investigate the formation of these substantial structures and their short- and long-term effects on their target body. The majority of basin-scale impact modeling has focused on lunar basins due to their prevalence and preservation. Data gathered from lunar missions, such as the Gravity Recovery And Interior Laboratory (GRAIL) and Lunar Reconnaissance Orbiter (LRO), have provided high resolution measurements of basin attributes that can be used to constrain the numerical models.

This work summarizes a suite of modeling studies [1-7] assessing basin formation and structure. The work primarily focuses on lunar basins, but also considers impacts on to Mercury.

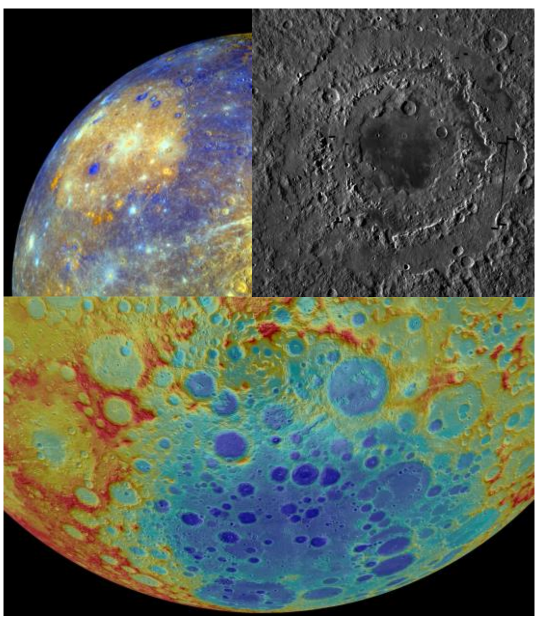

Figure 1: Clockwise from top left: Caloris, Mercury (1500 km diameter; Mercury Dual Imaging System image); Orientale, Moon (930 km diameter; Lunar Reconnaissance Orbiter Wide Angle Camera image); and South Pole-Aitken, Moon (2400 km diameter; Lunar Orbiter Laser Altimeter image). Some of the largest impact basins in the Solar System.

Methods: The iSALE shock physics code [8-10] was used to model the formation of basin-scale craters. iSALE has been used to study cratering events on a variety of scales and has been tested and validated against laboratory experiments and other modeling codes [11]. Impacts were modeled using either a half-space or spherical target (depending on the size of the basin relative to the target body's radius). Appropriate equations of state were used to represent the thermodynamic and compressible nature of the target body's crust, mantle, and core; strength and thermal properties were calculated from experimental data (e.g., [12]). Impactor diameters and velocities over a wide range, suitable for the time period of basin formation (see below), were investigated. The internal thermal state of the body was also considered. Impact basins are some of the oldest crater structures in the Solar System; the vast majority of basins are thought to have formed ~3.8-4.1 Ga (based on crater counting), during what has been termed the Late Heavy Bombardment. Planetary bodies would have had far different internal thermal structures ~4 Ga compared to today. Suitable internal temperature profiles, based on thermal evolution models (e.g., [13,14]), were, therefore, considered.

Results and discussion:

Basin formation. Figure 2 illustrates two lunar basin structures after the dynamic formation phase has ceased (~2 hours after initial impact). The impacts use the same impactor properties (size and velocity) but the targets have different thermal properties within the mantle. The initial target conditions greatly influence the final size and structure of the basins, including the basin rim (r_f: ~500 km using TP1; >600 km using TP2) and the annulus of thickened crust (r_{ca}). The excavation phase of basin formation was, however, largely unaffected by the different thermal profiles; transient crater diameters differed by <10% and the excavation depth to diameter ratio was consistently 0.12±0.01, agreeing with the vast majority of analytical, experimental, geological, and geophysical crater studies (e.g., [15,16]). Pi-scaling relationships (e.g., [17]), which allow comparison of impact events across many orders of magnitude using non-dimensionless parameters, demonstrate that impacts on to different Solar System bodies (in this case the Moon and Mercury) follow similar trends and agree with experimental impacts at far smaller scales (Figure 3).

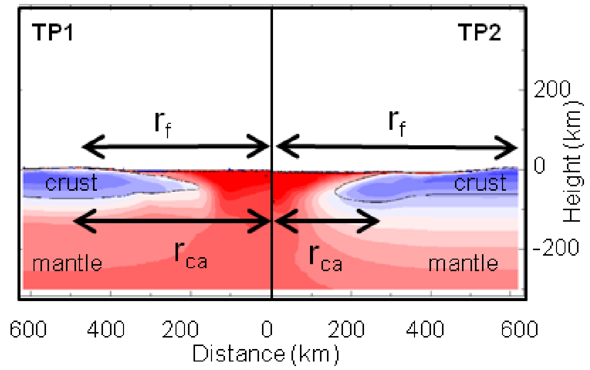

Figure 2: Final basin form for two impacts with the same energy (80 km diameter impactor, 15 km/s velocity) into targets with different thermal profiles (TP). TP1 and TP2 both have a crustal thermal gradient of 10 K/km. In the mantle, temperatures are initially at the solidus in TP1, but are sub-solidus in TP2. r_f is final basin rim radius, r_{ca} is crustal annulus radius.

Melt volume. Melt volumes for basin-scale impacts (Figure 4) are comparable to other numerical models (e.g., [18]), but produce far more melt than that predicted by some scaling laws [19] as these laws did not take into account thermal gradients. Note that these large basin-forming impacts (as shown in Figure 2) completely remove crustal material from the basin center exposing (partially) molten mantle at the surface. No impact basin, however, shows spectroscopic or gravitational evidence of surficial mantle. The volume of melt produced in these impacts (10^6-10^8 km^3), could explain the lack of mantle signatures at basin centers. Such significant volumes of melt could undergo differentiation (e.g., [20,21]), resulting in the formation of a lower-density, crustal-like layer toward the surface, masking any mantle-derived signatures.

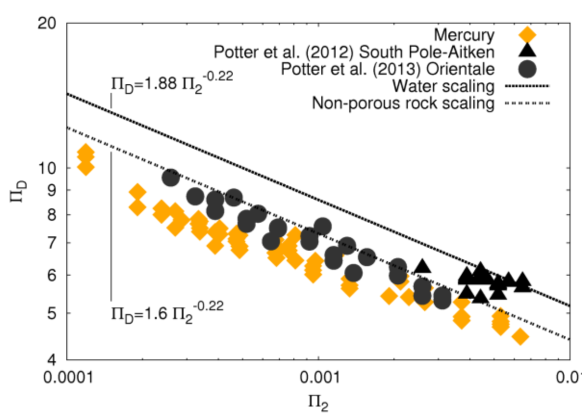

Figure 3: Π_D as a function of Π_2. Π_D is a crater size measure defined as $D_{tc}/(M_i/\rho_t)^{1/3}$. Π_2 is a gravity-scaled impact size defined as 3.22 $g\ r_i\ /u^2$. D_{tc}: transient crater diameter; M_i: impactor mass; ρ_t: target density; g: surface gravity; r_i: impactor radius; u: impact velocity. Scaling laws from [17].

Conclusions: Numerical modeling has shown many aspects of basin-scale impacts are consistent with Pi-scaling relationships, and the vast majority of analytical, experimental, geological and geophysical studies. The models demonstrate that target conditions do not greatly affect basin excavation, but have a significant effect on basin modification and final structure.

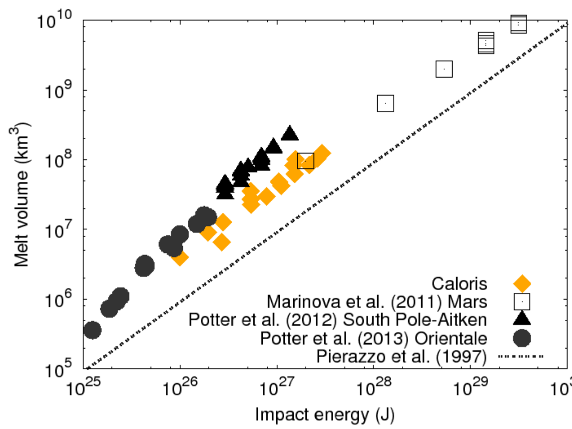

Figure 4: Melt volume as a function of impact energy for a suite of large basin-forming impacts: South Pole-Aitken and Orientale (Moon), Caloris (Mercury) and Mars.

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