SECONDARY CRATERING ON MARS: 3-D SIMULATIONS AND HIGH-RESOLUTION MORPHOMETRY

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We present 3-D simulations of low-velocity impacts to examine the dependence of crater shape on impact velocity in the range 0.5-1.5 km/s. Results are compared to the morphometry of recent secondary impact craters associated with the best-preserved primary complex craters on Mars [1,2,3]. The goals of this work are to (1) examine the transition from subsonic (displacement-dominated) to hypervelocity (shock-dominated) cratering, and (2) to illuminate the nature of secondary crater populations, which form a significant fraction of small craters on many planetary surfaces, with implications for surface age dating as well as understanding processes that modify surfaces over time [4, 5,6].

Model description. The impact hydrocode iSALE-3D was used to model impacts with velocities of 0.5, 1.0 and 1.5 km/s [7]. The impact angle was 45°; only a half space was simulated. The projectile was resolved by 8 cells, with a cell size of 1.25 meters (10 m radius). We used a basalt-like material model, with parameters appropriate for young lava plains in which the majority of the secondaries in our study were found [3]. Surface and projectile materials are characterized using a model of yield strength as a function of pressure, temperature, and damage [8], and a damage model, describing scalar damage as a function of plastic strain [9]. The target is nonporous. Thermodynamic response is described by an ANEOS-derived equation of state table for basalt [10]. A larger set of 2-D axisymmetric simulations have been carried out to examine the dependence of diameter-normalized crater depth and rim height (d/D and h/D, respectively) for the same material parameters and a larger range of impact velocities (0.25 to 2 km/s).

Morphometry. Nearly 2,800 secondary impact craters from four well-preserved martian primary craters (Corinto, Gratteri, Tomini, and Zunil) [3] were characterized morphometrically using HiRISE stereo DTMs (1 m/pixel) [11]. These craters range from 25 m to 400 m in diameter and 30 km to 1500 km in down-range distance (L). Impact velocity was estimated from L using a numerical ballistics model incorporating planetary curvature and atmospheric drag for current atmospheric surface pressure, and a range of launch angles (20°-60°), drag coefficients, projectile densities and sizes. The morphometric parameters characterize the orientation of cavity and planform asymmetries (e.g., Fig 1A & 1B), as well as d/D and h/D.

Results. A marked asymmetry in cavity shape is clearly expressed in the model craters (Fig. 2), consistent with previous observations of low-velocity impacts in nuclear explosion secondaries [12], low-velocity missile impacts [13], and the morphometry of secondary crater populations measured on Mars [2,3]. In particular, the uprange cavity slope is significantly steeper and the lowest cavity elevation is displaced in the uprange direction. In our measurements of martian secondaries, craters that formed with v_i < 1.0 km/s usually exhibit this asymmetry; there is a slight tendency for some populations to exhibit this bias up to 1.5 km/s, consistent with model results.

We also find some marked differences between the observations and model craters. First, there is no planimetric elongation in the models until the excavation stage of crater growth has stopped. Slight elongation then occurs in the cross-range direction, and diminishes from a bit over 10% (at 0.5 and 1 km/s) to 3% (at 1.5 km/s); more runs are required to confirm this result. The ratio of long-axis to short-axis length (a/b) for the majority of martian secondaries ranges from 1.0 to 1.4 when v_i < 1.0 km/s. An *along-range* elongation dominates the measured populations for impact velocities of up to ~0.7 km/s (Fig. 1A).

Prior experiments and our measurements find that rim height is typically larger in the downrange direction, with significantly smaller rim (or none at all) in the uprange direction [2,3,12,13]. Our measurements suggest that a marked downrange rim height asymmetry persists up to impact velocities of v_i ~ 1.0 km/s (Fig. 1B). In the iSALE-3D simulations, an asymmetry is observed in the opposite direction, and appears to arise from asymmetry in excavation flow: downrange ejecta are launched at higher velocities and at shallower angles, causing this material to spread out in the downrange direction, creating a shallower rim. Model crater rim height asymmetry is almost erased for v_i ~ 1.5 km/s.

The model crater d/D (using average diameter) ranges from 0.09 (0.5 km/s), to 0.14 (1.0 km/s) and 0.17 (1.5 km/s). In martian secondary populations, d/D ranges widely from a few percent to a maximum value (presumably formed by the most intact projectiles), which increases with v_i. At impact velocities of 1.2 km/s, a few craters in measured populations have d/D > 0.2. The vast majority, however, have d/D at or below the model crater d/D .

Future work. The interesting discrepancies between simulations and observations may result from a difference in impact parameters and target properties. We plan to explore this comparison further by running

iSALE-3D simulations with a larger range of impact velocities, a lower impact angle, as well as a weaker (regolith-like) target, and nonspherical projectile. With increasing stereo HiRISE coverage of secondary populations, the effects of target properties can be examined as well.

References: [1] Tornabene, L. et al., (2006) *JGR* 111 (E10), E10006; [2] Watters, WA & AC Radford (2014) *LPSC 45*, #2836, [3] Watters, WA et al. (2017) *JGR* (in revision); [4] Bierhaus et al. (2005) *Nature*, 437, pp. 1125-1127; [5] McEwen, A. et al., *Icarus* 176, pp. 351-381, 2005; [6] Calef, FJ et al. (2009) *JGR* 114 (E13), E10007; [7] Elbehausen, D. et al. (2009) *Icarus*, 204 (2) pp. 716-731; [8] Collins, GS et al., (2004) *MAPS*, 39 (2), pp. 217–231; [9] Ivanov et al., (2010) *GSA spec. pap*. 465, pp. 29-49; [10] Pierazzo et al., (2005) *GSA spec. pap.*, 384, pp. 443-457; [11] Moratto, Z., et al. (2010) *LPSC 41*, #2364; [12] Roberts, W. (1964) *Icarus* 3, pp. 348-364; [13] Moore, HG (1969) *USGS prof. paper* 658-B, pp. B107-B112.

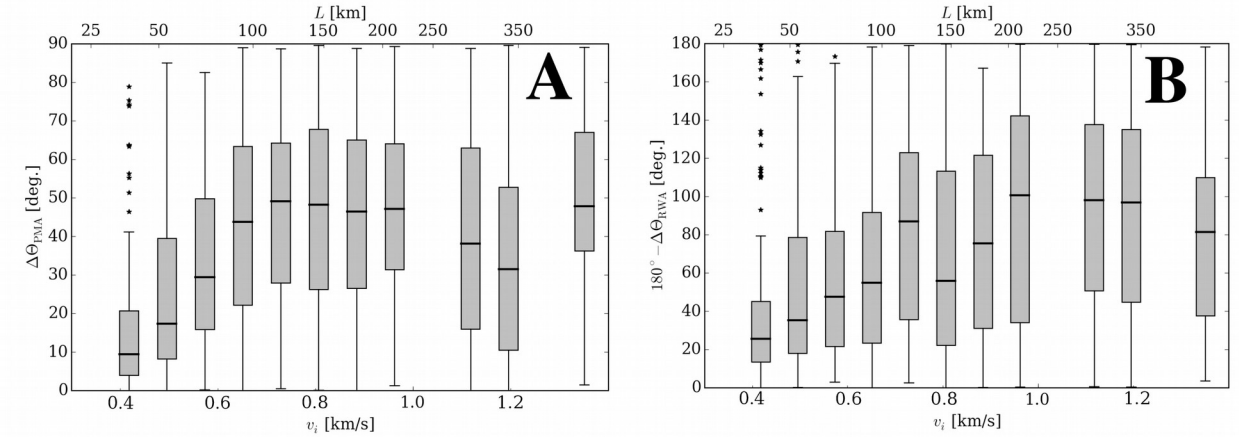

Figure 1: (A) Box plot of the offset between planform major axis orientation and the azimuth to source crater (i.e., 0° indicates perfect alignment) vs. impact velocity (v_i) and downrange distance (L); measurements are from secondary populations of four martian primary craters, replotted from [3]. Planform major axis is strongly aligned with source crater for $v_i < 0.5$ km/s, and is no longer aligned for $v_i \geq 0.7$ km/s. ($N = 1858$ craters); (B) Offset of "rim-weighted azimuth" from the azimuth to source crater (i.e., $180^\circ - \theta_{RWA} = 0^\circ$ indicates perfect alignment). The tallest rim heights are downrange for $v_i < 0.7$ km/s; this alignment largely disappears for $v_i \geq 1$ km/s [3]. ($N = 1868$ craters)

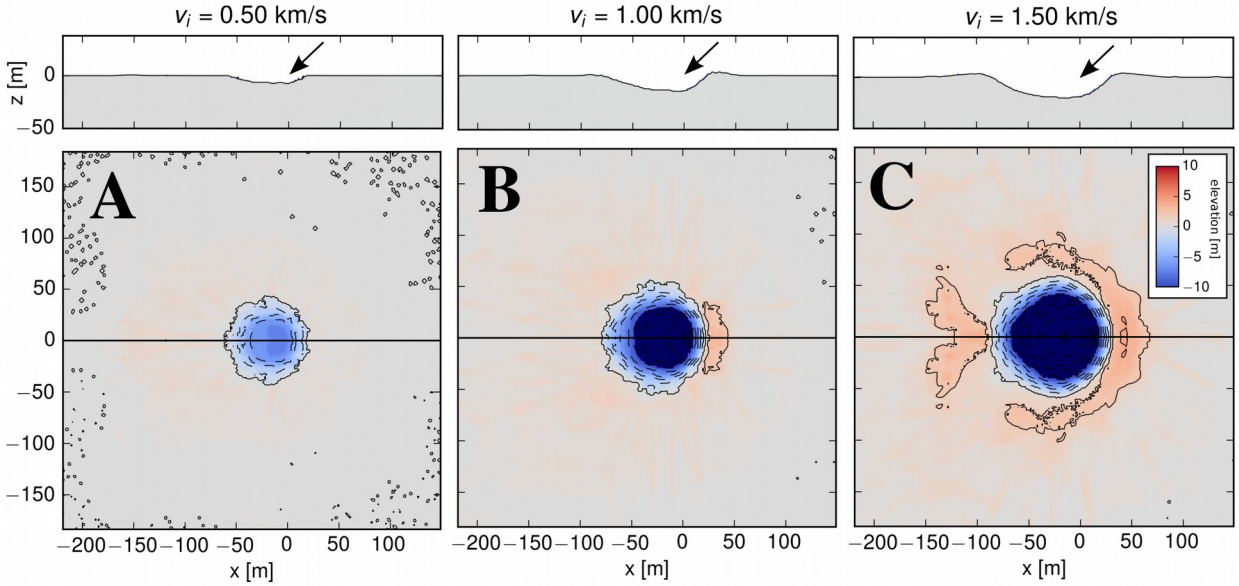

Figure 2: Results of iSALE-3D simulations of low-velocity cratering into a basaltic high-strength target at 0.5 km/s, 1.0 km/s, and 1.5 km/s after 18.5 seconds (impact site is at (0,0); impact angle was 45°; projectile velocity vector is marked with an arrow). In agreement with measurements, the lowest cavity elevation is located uprange of the planimetric center. The uprange rim is taller than the downrange rim for $v_i \geq 1.0$ km/s, as well as at earlier times for simulation A ($v_i = 0.5$ km/s).