MODELING SMALL IMPACT CRATERS ON EJECTA BLANKETS: SELF-SECONDARIES VERSUS UNRECOGNISABLE PRIMARIES. N. A. Artemieva[1,2] and M. Zanetti[3], [1]Planetary Science Institute (Tucson, AZ 85719, artemeva@psi.edu; [2]Institute for Dynamics of Geospheres (Moscow, Russia); [3]University of Western Ontario, Canada.

Introduction: Measuring crater size-frequency distributions (CSFDs) on the continuous ejecta blankets of impact craters is a widely used technique allowing estimates of projectile flux, and the derivation of absolute model ages (AMAs) of parent crater formation [1-2]. However, recent studies using high-resolution crater counts [3-5] revealed that the basic assumption of total resurfacing during ejecta emplacement could be wrong (Fig. 1). In particular, so-called self-secondary craters (SSCs) could be formed by late-arriving ejecta fragments on the continuous blanket, shortly after ejecta deposition, but before impact melt units are emplaced. If a population of unrecognized self-secondary craters has been included in lunar cratering chronology calibration counts, like those done at Tycho, North Ray, and Cone Craters, then estimates for the flux of impactors in the inner solar system may be over-estimated (by as much as a factor of 4). Understanding the flux of incoming projectiles recorded on ejecta blankets is critical to the underpinnings of comparative size-frequency measurements between terrestrial planets, and our ability to model absolute ages for planetary surfaces.

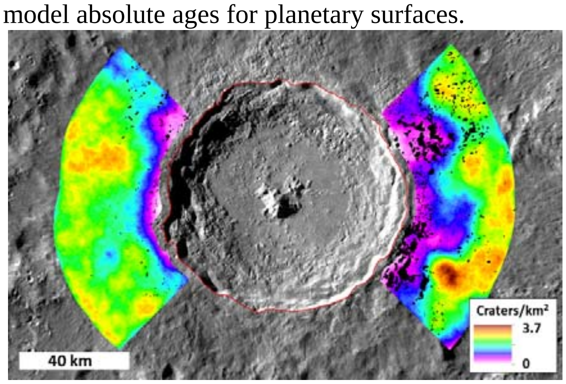

Fig. 1. Crater population density at Tycho crater [5]. Population of crater >50 m in diameter, irrespective of crater diameter, increases with radial distance from the crater rim, and is highly correlated with the distribution of impact melt ponds (black units).

Using the size-frequency distribution of small (<500 m diameter craters) and numerical modelling we are interested in determining if crater density patterns observed on ejecta blankets [5] can be caused by 1) near-rim primary craters that cannot be easily identified due to impacts into rough (blocky) surface; or 2) Self-secondary craters that are formed by high-angle solid ejecta deposited with substantial delay in comparison with continuous ejecta blanket emplacement.

Numerical model and initial conditions: We use the 3D hydrocode SOVA [6] complemented by the ANEOS equation of state for non-porous quartzite and dunite [7-8]. The code takes into account the influence of dry friction (K=0.65) on the motion of disrupted rocks [9]. To check the first hypothesis we model a vertical impact of a projectile with radius r (5-20 m) into a bumpy surface (Fig. 2) at 18 km/s. The size of each hemispherical boulder R is equal to 5r, i.e., comparable with the size of a future crater as derived from standard scaling laws [10]; the distance between the impact point O and the boulder centre B varies from 0 (impact into the boulder centre) to 2R. The resolution is rather low, 10 cells per projectile radius (cppr).

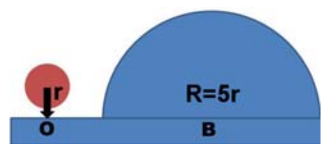

Fig. 2. Initial conditions for an impact into a bumpy surface. A projectile with radius r impacts vertically a flat surface with a hemispherical boulder R.

To model high-velocity high-angle ejecta (second hypothesis) we model oblique impacts (15-90° degree to horizon) of a km-sized projectile into a flat surface to reproduce 20-80-km-diameter complex lunar craters, such as Aristarchus or Tycho. Tracer particles are used to calculate ejection angles, velocities, and shock pressures. The computational resolution is 20-40 cppr.

Results: *Impacts into a rough surface.* Images of shock compression within the target for various distances OB are shown in Fig. 3. Obviously, presence of boulders changes the crater size and its morphology. If an impact occurs into the boulder center, it totally destroys and disperses the boulder; the transient crater (TC) is smaller than expected and extremely shallow. If impacts occur between boulders, the resulting TCs tend to be of the same size as the crater on a flat surface. However, the presence of boulders prevents formation of regular near-crater ejecta; remnants of boulders fill the crater with numerous fragments making it shallow and, may be, irregular (as fragments of a weakly shocked boulder could be large).

High-velocity high-angle ejecta. Models of 30-90° impacts reveal a zone of high-angle high-velocity ejecta that is sourced from the spallation zone (i.e., close to the surface and to the impact point); and its azimuth from the impact point is ~90°. Ejection angles are >80°, ejection velocities are in the range of 0.8-1.2 km/s. Maximum shock compression of these ejecta does not exceed 20 GPa, i.e., ejecta are solid and moderately shocked. Estimated travel distances are in the range of 80-200 km; estimated travel time exceeds 20 minutes, i.e., is far longer than the time interval required for regular ejecta emplacement. As the final crater center is shifted downrange relative to the impact point, azimuths of final deposits are > 150° (Fig. 4). Similar ejecta patterns are produces after an impact at 60°, while vertical or highly oblique (≤30°) impacts do not produce these high angle ejecta.

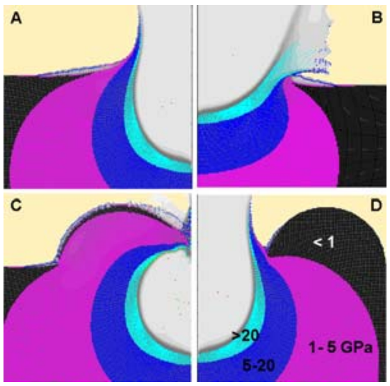

Fig. 3. Initial stage of impacts into a bumpy surface. Tracer colors show maximum shock compression. A: flat surface; B: impact into a boulder, OB=0; C and D: impacts between boulders, OB=6r and OB=12r.

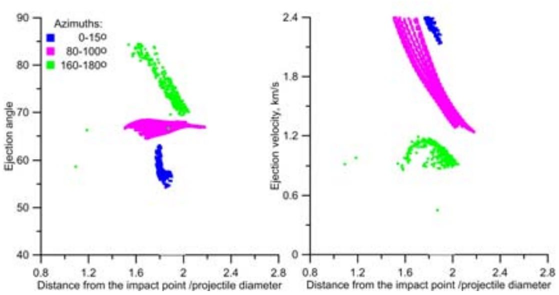

Fig. 4. Tracers corresponding to early spall ejecta after a 45° impact. Various colors correspond to various azimuths from the crater center (see legend, blue is for downrange ejecta, green – for uprange). Left plate shows ejection angles, right plate – ejection velocities.

Self-similarity of ejection process. Neither strength nor gravity affects early ejecta, and for a given projectile size, ejection angles and velocities are the same if the ejection position is measured in projectile radii. This implies that we cannot expect self-secondary craters on ejecta blankets of much smaller craters (i.e., <10 km diameter; they will be far away from the crater and its ejecta blanket) or much bigger craters (> 150 km diameter; they will be inside the crater). Based on our new modelling results, craters of 40-100 km are the best candidates to produce self-secondaries.

Discussion and future work: Deficiency of small craters on rough surfaces has been observed on asteroids [11-12], on the rim of G.Bruno crater [13] and has been partially reproduced in impact experiments [14-15]. In this work we confirm these observations with shock physics models. According to [16] large, hundreds of m in size boulders are common near the rim of large craters.

Moderate high-angle uprange ejecta have been observed in laboratory experiments of oblique impacts into sand [17]. However, these ejecta are part of the regular ejecta curtain and cannot produce SSCs. More dramatic vertical ejection of spall low-velocity fragments has been documented in MEMIN experiments [18]. Seems this process is also not relevant to self-secondaries and could be explained by a small size of the target block and by the “wrong” gravity direction.

Interaction of shock waves with a free surface (spallation zone) strongly depends on the structure of this surface and, unfortunately, on the computational parameters (resolution, artificial viscosity in use). We plan to model impacts into various targets with the highest resolution available in 3D models in order to confirm (or to reject) our preliminary findings. Models of impacts into a rough surface have to include a variety of boulders in accordance with those observed around lunar craters. New counts of impact craters on ejecta blankets as well as the analysis of boulders distribution will provide crucial data for future models.

Conclusions: Numerical models show that both hypotheses could work: 1) impacts into a rough, boulder filled surface produce fewer and smaller craters than impacts into more uniform surfaces, and these surfaces would therefore have a different SFD of craters. 2) Contrary to longstanding modelling results, high velocity high angle ejecta do exist and may produce self-secondary craters mainly uprange.

References: [1] Hartmann W.K. et al. 1981. *Basaltic Volcanism on the terrestrial planets*. [2] Neukum G. et al. 2001. *Space Sci Rev* 96: 55–86. [3] Plescia J.B. and Robinson M.S. 2011. *LPSC-42*: Abstract 1839. [4] Hiesinger H. et al. 2012. *JGR* 117. Doi: 10.1029/2011JE003935. [5] Zanetti M. et al. 2015. *LPI Contribution* 1841. Abstract 9041. [6] Shuvalov V.V. (1999) *Shock Waves 9*, 381–390. [7] Thompson S. L. and Lauson H .S. (1972) *Report SC-RR-71 0714.* 119 p. [8] Melosh H. J. (2007) *Meteoritics & Plan. Sci. 42,* 2079-2098. [9] Ivanov B.A. and Melosh H.J. (1999) *Annu. Rev. Earth Planet. Sci., 27*, 385-415. [10] Holsapple K.A. and Housen K.R. 2007. Icarus 187: 345-356. [11] Chapman C.R. et al. 2002. *Icarus* 155:104-118. [12] Michel P. et al. 2009. *Icarus* 200:503-513. [13] Williams J.-P. et al. 2014. *LPSC-45*: Abstract 2882. [14] Güttler C. et al. 2012. *Icarus* 220:1040-1049. [15] Durda D.D. et al. *M&PS* 46:149-155. [16] Bart G.D. and Melosh H.J. 2010. *Icarus* 209:337-357. [17] Anderson J.L.B. et al. 2003. *JGR* 108. Doi: 10.1029/2003JE002075. [18] Sommer F. et al. 2013. *M&PS* 48: 33–49.