INVESTIGATIONS AND REGRESSION ANALYSES OF SIZE-FREQUENCY DISTRIBUTIONS OF SUB-KILOMETER IMPACT CRATERS ON VESTA

A. Neesemann[1], T. Kneissl[1], N. Schmedemann[1], S.H.G. Walter[1], G.G. Michael[1], S. van Gasselt[1], H. Hiesinger[2], R. Jaumann[3], C. Raymond[4], C.T. Russell[5] [1]Freie Universität Berlin, Inst. of Geological Sciences, Planetary Sciences and Remote Sensing Group, Malteserstr. 74-100, 12249 Berlin, (Germany); adrian.neesemann@fu-berlin.de; [2]Inst. für Planetologie, Westfälische Wilhelms-Universität, Münster, Germany; [3]German Aerospace Center (DLR), Inst. of Planetary Research, Berlin, Germany; [4]JPL, Caltech, Pasadena, CA, USA; [5]Inst. of Geophysics and Planetary Physics, Dept. of Earth and Space Sciences, University of California, Los Angeles, CA, USA

Introduction: Between July 2011 and September 2012 several instruments onboard the Dawn spacecraft [1-2] have delivered a large amount of data of the third largest and second most massive body in the asteroid belt, Vesta. While Dawn is en route to Ceres we have extensively investigated size-frequency distributions (SFDs) of sub-kilometer impact craters accumulated on fresh surface units on Vesta. Up to now, only few investigations of SFDs of small craters mainly measured on ejecta blankets and interior deposits of larger, fresh impact craters on Vesta have been published i.a. by [3-8]. The objective of these investigations were both to verify one of the two already published production functions (PFs), the asteroid-flux model production function (MPF) of [5, 9] and the lunar-like PF of [10], and to use them to derive extrapolated $N(1)$ values for relative and absolute model age (AMA) estimates. Based on the small amount of published investigations often performed on small areas, it is possibly still too early to draw universally valid conclusions. Moreover, since the two PFs considerably differ in shape and thus contradict each other, derived $N(1)$ values and hence AMAs vary as well. In order to improve our knowledge about the statistics of small craters, we expanded our crater catalogue of investigated fresh <40 km primary craters respectively their ejecta blankets, which represent some of the youngest surface units on Vesta.

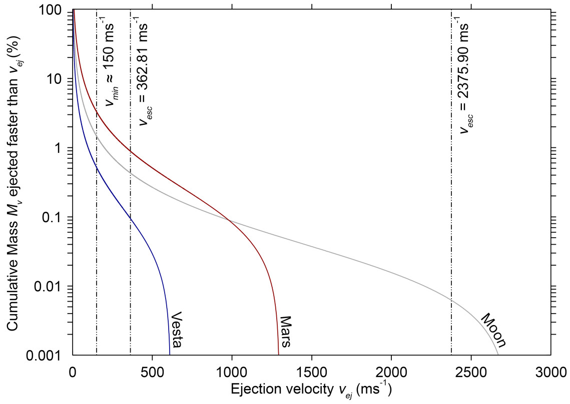

Figure 1: Cumulative Mass M_v (%) ejected faster than v_ej plotted versus the ejection velocity v_ej (ms^{-1}) for a Vibidia sized impact (rim diameter D_r = 6.39 km) on various planetary bodies (Vesta, Mars and the Moon). Note that different sized impactors are necessary to form craters of the same size on the three bodies primarily due to differences in impactor velocity, target density and gravitational conditions.

Background: SFDs of small craters, under some circumstances, can be very susceptible to change because small craters are the first ones to be affected by subsequent modification [11-13]. This includes (among other processes) an admixture of secondary craters which, due to the specific shape of the SFD of ejected projectiles and the inverse relation between the spall size and ejection velocity [14-19], can considerably increase the numbers of small craters. On the other hand, degradation processes on Vesta, primarily caused by impact-induced seismic shaking, which destabilizes slopes and triggers mass wastings, will reduce the numbers of small craters when compared to larger ones. Since the influence of both processes largely depends on the age (the older a surface, the higher the probability that modification has occurred), we investigate especially young/fresh surface units whose superposed

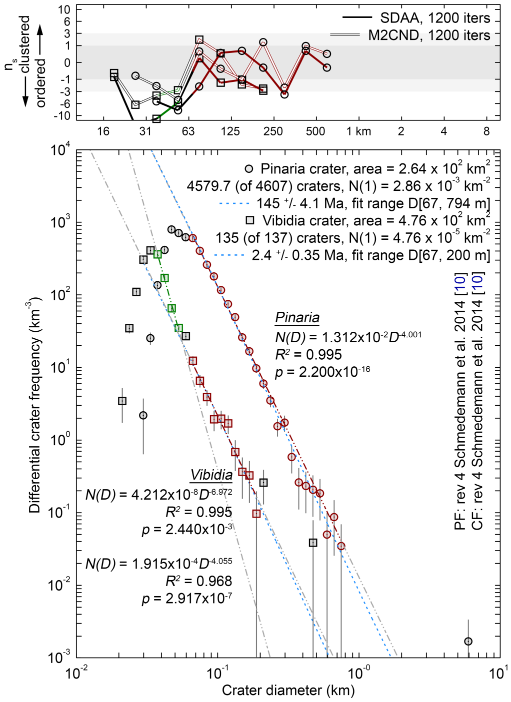

Figure 2: CFSDs obtained on ejecta blankets of one of the youngest (Vibidia) and one of the oldest (Pinaria) investigated craters in differential presentation. The upper plot shows the results of two individual randomness analyses methods namely a *standard deviation of adjacent area* (SDAA) and a *mean 2nd closest neighbor distance* (M2CND) [25-26] to gain insight into the spatial distribution of craters within the measurement area.

CSFDs should most likely reflect the mass-velocity distribution of impacting meteorites.

Methodology: Till now, we have investigated CSFDs superposed on ejecta blankets and sometimes also on the interior deposits of 42 fresh craters on Vesta. Primary craters have been classified as fresh provided that they exhibit two of the following properties: (1) a distinct, sharp crater rim and/or fresh exposed crater walls with "spur-and-gully" morphology, (2) a relatively low density of small craters superposed on the corresponding surface units (ejecta blankets) and (3) a conspicuous spectral signature in Framing Camera (FC) color ratio data.

In order to measure CSFDs we performed crater counts within ESRI's ArcGIS by using the *CraterTools* [20] extension which allows comfortable and most accurate measuring of areas and impact crater diameters by automatically solving the problem of map-projection related distortions. Additionally, its newer version [21] also allows for automated correction of topography-related crater and area distortions, which occur when the actual shape of the investigated body deviates from the used reference ellipsoid used for the map projection. For the analyses of CSFDs and the derivation of absolute model formation ages, we used the software *Craterstats* by [22-23]. Additionally, we have estimated the amount of mass ejected for certain crater sizes on Vesta in comparison to Mars and the Moon (**Fig. 1**) using the most recent version of the widely accepted cratering model of [24]. In this way, under consideration of spallation models of [14-19] and impactor-crater scaling laws by [25-26], we are able to make at least a rough estimate of the SFD of ejected fragments that are capable of forming secondary craters.

Results: CSFDs over a limited diameter range generally follow a power-law of the form $N \sim D^a$ with N as the number of craters of diameter D and a as the power-law exponent. It appears from the various analyses, which we performed that SFDs of craters between D(80 m, 1 km) exhibit power-law exponents between -4.0 to -4.4 (differential), (see **Fig. 2** and **Tab. 1**) or -3.0 to -3.2 (cumulative). For comparison, the lunar-like PF of [10] exhibits a mean differential power-law exponent of -4.21 between D(80 m, 1 km). The consequence that arises from this is that most CSFDs investigated on relatively fresh surface units run significantly steeper than the asteroid-flux derived MPF of [5, 9], which has an average power-law exponent of approx. -3.54 (differential) between D(80 m, 1 km). As modeling results show (**Fig. 1**), the mass ejected at velocities at which traditional secondary craters form (~150 ms^{-1} < $v_{\text{sec}} < v_{\text{esc}}$) is much smaller on Vesta when compared, for example, to Mars or the Moon, owing to their higher escape and impact velocities. Thus we expect fewer secondary craters on Vesta. However, the increase in negative power-law exponents of CSFDs towards smaller diameters is one of the characteristics of an admixture of secondary craters [27]. Moreover, the increase in power-law exponents is accompanied by spatial clustering of probably secondary craters. The crossover diameter in our measurements at which the steep secondary SFD exceeds the primary SFD seems to be somewhere around 70-100 m.

Table 1: Results of weighted least squares linear regression.

Primary crater	D range (m)	# of craters	Regression function	R^2	p-value
Antonia	67 - 371	409.7	$3.601\text{x}10^{-4}D^{-4.177}$	0.979	$2.279\text{x}10^{-12}$
	47 - 67	1411.7	$1.028\text{x}10^{-5}D^{-5.523}$	0.980	$9.854\text{x}10^{-3}$
Arruntia	67 - 209	87.8	$1.586\text{x}10^{-4}D^{-3.958}$	0.925	$8.839\text{x}10^{-6}$
	42 - 67	601.9	$4.705\text{x}10^{-7}D^{-6.114}$	0.997	$6.630\text{x}10^{-5}$
Canuleia	59 - 265	287.9	$1.786\text{x}10^{-3}D^{-4.230}$	0.972	$6.879\text{x}10^{-10}$
Cornelia	67 - 251	287.9	$1.542\text{x}10^{-4}D^{-4.380}$	0.972	$4.349\text{x}10^{-9}$
	42 - 75	1337.5	$5.267\text{x}10^{-5}D^{-4.776}$	0.997	$5.573\text{x}10^{-5}$
Pinaria	67 - 794	4579.7	$1.312\text{x}10^{-2}D^{-4.001}$	0.995	$2.200\text{x}10^{-16}$
Vibidia	67 - 200	135.0	$1.915\text{x}10^{-4}D^{-4.055}$	0.968	$2.917\text{x}10^{-7}$
	38 - 56	1407.9	$4.212\text{x}10^{-8}D^{-6.972}$	0.995	$2.440\text{x}10^{-3}$

Here we have only picked crater size-frequency data measured around a few fresh primary craters which already demonstrate that CSFDs exhibit varying power-law exponents. Note that regression analyses of the same surface unit but when performed on smaller crater sizes yield higher negative power-law exponents.

References: [1] Russell et al. (2007) *Earth, Moon, and Planets **101***, 65-91. [2] Russell and Raymond (2011) *Space Sci. Rev. **163***, 3-23. [3] Kneissl et al. (2014) *Icarus **244***, 133-157. [4] Krohn et al. (2014) *Planet. Space Sci. **103***, 36-56. [5] Marchi et al. (2014) *Planet. Space Sci. **103***, 96-103. [6] Neesemann et al. (2014) *45th* LPSC (Abs. #1712). [7] Neesemann et al. (2015) *46th* LPSC (Abs. #2814). [8] Ruesch et al. (2014) *Icarus **244***, 41-59. [9] Marchi et al. (2012) *Science **336***, 690-694. [10] Schmedemann et al. (2014) *Planet. Space Sci. **103***, 104-130. [11] Chapman (1974) *Icarus **22***, 272-291. [12] Neukum et al. (1975) *Earth, Moon, and Planets **12***, 201-229. [13] Smith et al. (2008) *GRL **35** (L10202)*. [14] Melosh (1984) *Icarus* **59**, 234-260. [15] O'Keefe and Ahrens (1986) *Icarus **62***, 328-338. [16] Vickery (1986) *Icarus **67*** 224-236. [17] Vickery (1987) *GRL **14*** 726-729. [18] Melosh 1987 *Int. J. of Impact Engineering **5***, 483-492. [19] Vickery and Melosh (1987), *Science **237***, 738-743. [20] Kneissl et al. (2011) *Planet. Space Sci. **59***, 1243-1254. [21] Kneissl et al. (2014) *45th LPSC* (Abs. #2398). [22] Michael et al. (2010) *EPSL* **294**, 223-229. [23] Michael et al. (2012) *Icarus* **218**, 169-177. [24] Housen and Holsapple (2011) *Icarus* **211**, 856-875. [25] Ivanov (2001) *Space Sci. Rev. **96***, 87-104. [26] Ivanov (2008) in *Catastrophic Events Caused by Cosmic Objects, ch. 2*, 91-116. [27] König (1977) PhD Thesis, 67 +XIV.

Acknowledgements: This work was partly supported by the German Aerospace Center (DLR) on behalf ot the Federal Ministry of Economic Affairs and Energy, grant 50 OW 1101.