Structural rim uplift and ejecta thickness measurements of complex martian and lunar impact craters.

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Introduction: Complex impact craters in the solar system show elevated craters rims like their simple counterparts. Comparing complex and simple craters, the raised crater rim in simple craters is built up to roughly one half by the structural rim uplift of pre-impact target material near the transient crater cavity and to another half by the deposition of a coherent proximal ejecta blanket at the edge of the transient crater [1, 2, 3]. As complex craters show a considerable widening of their diameter with respect to the transient cavity, the thick, proximal ejecta is situated to some degree inside the final crater [2, 3, 4]. The final crater rim of complex craters can be situated up to 1.5-2.0 transient crater radii from the crater center. Taking this into account, at such distances the thickness of the ejecta material represents only a fraction of that occurring at the rim of their simple counterparts [5]. Nevertheless, complex martian and lunar impact craters do show elevated crater rims, but the cause of final crater rim is less obvious [6]. We analyzed twelve martian (8.2 – 49.2 km diameter) and five lunar (15.8 – 44.8 km diameter) complex impact craters regarding their structural rim uplift and ejecta thickness along their final crater rims. Additionaly, we reconstructed the transient crater cavity sizes of these craters to determine the relationship between the transient (r_t) and the final crater rim (r). By analyzing these craters we want to investigate the crater formation process, expecially to quantify the components that together build-up the total amount of the elevated crater rim. The comparative study of lunar and martian craters is intended to study effects of atmosphere and target volatiles on crater rim kinematics.

Methods: For our crater parameter analyses we combined different martian (HiRISE and CTX, resolutions of 1 m and 6.2 m, respectively) and lunar (WAC, Kaguya, and LROC, resolutions of 100m, 10m, and 1m, respectively) high-resolution images and digital elevation models to analyze the crater walls. In a first step, we calculated the elevation of the paleo-surface (***Fig. 1, red dashed line***) of the crater that enables us to determine the so-called structural rim uplift amount "h_u" of the exposed and uplifted bedrocks. The paleo-surface was calculated as a linear interpolation between two points that are situated beyond the continuous ejecta blanket, going through the crater center and the boundary point between the uplifted bedrock and the superposed ejecta. Using this method, we could exactly calculate the paleo-surface elevation for the exposed boundary location point "*P*" (***Fig. 1, green dot***). After that we measured the thickness of the overlying ejecta deposits "h_e" (***Fig. 1***). In a final step, we calculated the specific percentage of the structural rim uplift and ejecta content that together build-up the total amount of the elevated crater rim. To constrain the size of the transient crater cavity and hence the radial distance between transient cavity and final crater rim (i) accumulated horizontal distance measurements (AHD) of the exposed terrace width for the lunar craters and (ii) balanced profile reconstructions (BPR) along the terraced zones for the martian craters were carried out.

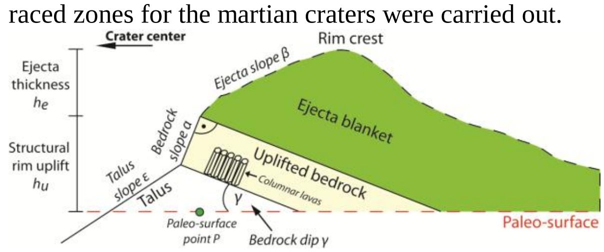

Fig. 1: *Schematic sketch of the crater wall region.*

Results: Our study of the martian complex impact craters indicates that averaging the data obtain from different craters the structural rim uplift at the final crater rim makes 77.6% (±8.4%) of the total rim elevation while the ejecta thickness only contributes 22.4% (±8.4%) (***Tab. 1***). The structural rim uplift of lunar complex crater makes 70.6% (±2.5%) of the elevated crater rim, whereas the ejecta thickness amounts to 29.4% (±2.5%) of the total crater rim elevation (***Tab. 2***). For the martian impact craters the transient crater cavity size calculations (BPR) delivered final (r) to transient crater (r_t) size relations between 1.21 and 1.51 (r/r_t) and values between 1.10 and 1.40 (r/r_t) for the lunar craters (AHD) (***Tab. 1, 2***). The transient crater size calculations for the martian and the lunar craters suggest smaller transient crater sizes than previously assumed literature datasets [7, 8, 9].

Discussion and Conclusion: Our complex martian and lunar impact crater analyses show that the structural rim uplift is a more dominant effect than the ejcta emplacement to build-up the total amount of the final crater rim. Similar results were previously derived for several lunar craters [10] and for one martian impact crater (Pangboche crater) [11]. The question is how such a large structural rim uplift occurs outside the transient cavity? It seems unlikely that dike emplacement or the injection of interthrust wedges - important processes in crater rim uplift in simple craters - contribute to the total amount of the structural rim uplift at this distances beyond the transient crater cavity. Results of numerical models of crater formation suggest that the final crater rim uplift of complex craters could be the remnant of plastic thickening that occurs during excavation near the target surface at the cavity rim. This zone may reach ~1.5 transient crater radii. Additional mechanisms, such as reverse faulting during the excavation stage, could alternatively explain structural rim uplift at this distances.

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Name	r [km]	N	h_u [m]	h_e [m]	h_r [m]	h_u [%]	h_e [%]	r_t [m] (r/r_t)
MC1	4.1	564	**77.9** ± 21.6	**30.7** ± 15.2	**108.6** ± 23.5	**71.7** ± 12.6	**28.3** ± 12.6	*No visible terraces*
MC2	4.1	232	**183.8** ± 35.3	**64.3** ± 51.4	**248.0** ± 67.5	**77.1** ± 14.7	**23.0** ± 14.7	**2604** ± 19 (1.57)
MC3	5.7	369	**172.5** ± 63.6	**24.5** ± 19.8	**196.9** ± 59.1	**86.6** ± 11.8	**13.4** ± 11.8	**3773** ± 31 (1.51)
MC4	6.0	462	**210.2** ± 20.1	**48.3** ± 18.4	**258.5** ± 22.1	**81.5** ± 6.6	**18.5** ± 6.6	**4414** ± 227 (1.35)
MC5	7.3	1014	**282.3** ± 47.6	**66.6** ± 29.4	**349.0** ± 57.0	**81.2** ± 7.3	**18.8** ± 7.3	**5570** ± 253 (1.31)
MC6	7.8	303	**157.3** ± 32.6	**46.0** ± 43.6	**203.0** ± 59.3	**80.6** ± 15.1	**19.4** ± 15.1	**6017** ± 51 (1.30)
MC7	9.0	*No visible outcrops*						**7407** ± 140 (1.22)
MC8 (SantaFe)	9.9	83	**107.9** ± 34.7	**14.0** ± 8.3	**121.8** ± 36.7	**88.3** ± 6.1	**11.7** ± 6.1	**7959** ± 229 (1.24)
MC9 (Tooting)	13.4	78	**220.7** ± 73.3	**216.2** ± 162.2	**436.9** ± 90.6	**55.8** ± 25.8	**44.2** ± 25.8	**10178** ± 42 (1.32)
MC10	16.7	343	**464.7** ± 78.8	**148.5** ± 67.8	**613.2** ± 96.7	**76.3** ± 9.3	**23.7** ± 9.3	**13766** ± 235 (1.21)
MC11	21.1	161	**424.8** ± 62.0	**153.8** ± 54.5	**578.6** ± 88.3	**73.9** ± 7.3	**26.1** ± 7.3	**17421** ± 31 (1.21)
MC12 (Bamberg)	24.6	67	**483.0** ± 44.3	**118.6** ± 55.1	**601.7** ± 77.0	**80.9** ± 6.9	**19.1** ± 6.9	**18972** ± 309 (1.30)
					Mean	**77.6** ± 8.4	**22.4** ± 8.4	

***Tab. 1*:** Calculation results of the complex martian impact craters (*r = crater radius, N = number of measurements,* h_u *= structural rim uplift,* h_e *= ejecta thickness,* h_r *= total rim height,* r_t *= transient crater radius (BPR).*

Name	r [km]	N	h_u [m]	h_e [m]	h_r [m]	h_u [%]	h_e [%]	r_t [m] (r/r_t)
Bessel	7.9	2241	**443.1** ± 115.7	**173.1** ± 51.7	**616.3** ± 93.8	**70.8** ± 10.2	**29.2** ± 10.2	*No visible terraces*
Euler	13.5	591	**533.4** ± 154.1	**220.3** ± 113.2	**753.7** ± 76.1	**70.0** ± 16.5	**30.0** ± 16.5	**11630** (1.16)
Kepler	15.1	1151	**551.2** ± 200.6	**251.6** ± 75.9	**802.8** ± 190.2	**66.1** ± 12.7	**33.9** ± 12.7	**12390** (1.21)
Harpalus	19.9	716	**706.2** ± 133.3	**251.4** ± 73.7	**957.6** ± 131.8	**73.2** ± 8.2	**26.8** ± 8.2	**14175** (1.40)
Bürg	22.4	582	**846.7** ± 220.6	**298.3** ± 79.9	**1145.0** ± 216.7	**72.7** ± 8.3	**27.3** ± 8.3	**20400** (1.10)
					Mean	**70.6** ± 2.5	**29.4** ± 2.5	

***Tab. 2*:** Calculation results of the complex lunar impact craters (*r = crater radius, N = number of measurements,* h_u *= structural rim uplift,* h_e *= ejecta thickness,* h_r *= total rim height,* r_t *= transient crater radius (AHD).*