SECONDARY CRATERING AND AGE DETERMINATION ON MARS.

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Introduction: The discovery of a secondary-crater strewn field generated by the 10-km crater Zunil [1] stirred up a discussion of what is the real shape of the primary production crater size-frequency distribution and if age determination based on craters in the smaller-crater size range is possible. The main point of the discussion is whether or not the steep branch (below about 1 km diameter) is due to secondary or primary cratering. Here, we present crater counts inside and outside the Zunil strewn field as well as a discussion based on empirical data of the implications on the crater size-frequency distribution if secondary cratering occurs.

Crater Size-Frequency Measurements at Zunil: Based on HRSC and MOC imaging data we were able to measure the size-frequency distributions (SFD) of Zunil's secondaries and the underlying primary crater distribution. The secondary crater field around Zunil shows typical secondary crater characteristics, e.g. clustering, and appearing as dark-haloed pits. Other craters not showing these features and appearing randomly distributed are considered as primaries. The resulting distribution for the primary crater population follows the predicted shape of the crater SFD for Mars [2, 3], which has been observed also in the asteroid belt, the projectile source region [e.g. 8]. The cumulative distribution is close to a $N \sim D^{-3}$ distribution, while the secondary distribution clearly shows a steeper distribution behavior ($N \sim D^{-5}$) for the larger secondary crater range, and which has been observed elsewhere [4, 5]. 640 secondary craters of the Zunil strewn field have been counted in the HRSC image (orbit 1152) in an area of 5900 km^2 at a distance of 300 km from Zunil. The SFD of counted craters is shown in cumulative form in Fig. 1 (primaries-left, secondaries-right) and as an R-plot in Fig. 2. In Fig. 1 we compare the measured SFDs with the crater production function derived in [2, 3, 6] for a best-fit model crater age of about 14 Ma. The secondary crater SFD is obviously dissimilar from the assumed production function. The flattening of the SFD, observed below $D_2 \sim 70$ m, is not due to unresolved craters being well above the HRSC image resolution of 12.5 m/pixel; cratering equilibrium is not reached either. The computer model of McEwen et al. [1] also predicts flattening of the SFD for secondary craters being shifted to 10 times smaller diameters. Fig. 2 shows the R-plot for the Zunil secondaries and three measurements of close secondary crater fields [9] on Mars. For comparison, R-plot isochrones for 10 Ma and 1 Ma are given [2, 3]. The age of the Cerberus plains, commonly interpreted as very young, is found to be 14 Ma when applying the Hartmann/Neukum cratering chronology model [6] to the primary crater count. The misinterpretation in age, if unwittingly counting all craters, would be less than a factor of two. Even such an error that might occur if no caution is taken and one measured in the middle of a strewn field of secondaries is not an argument against the method of age determination using crater counts.

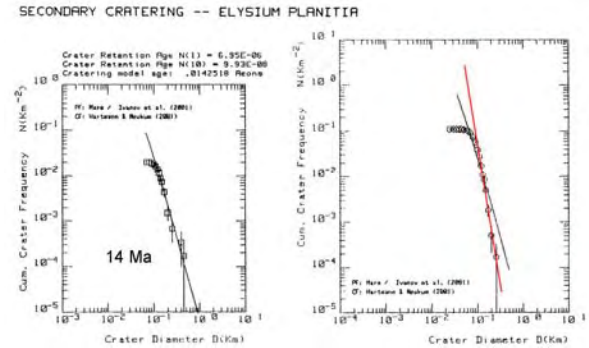

Fig. 1: Crater size-frequency measurements in the Cerberus plains. The primary crater distribution yields a surface age of about 14 Ma (left), the distribution of craters belonging to Zunil's secondary strewn field shows a much steeper distribution for the larger crater-size range and a flattening in the smaller size range, compare Fig.2.

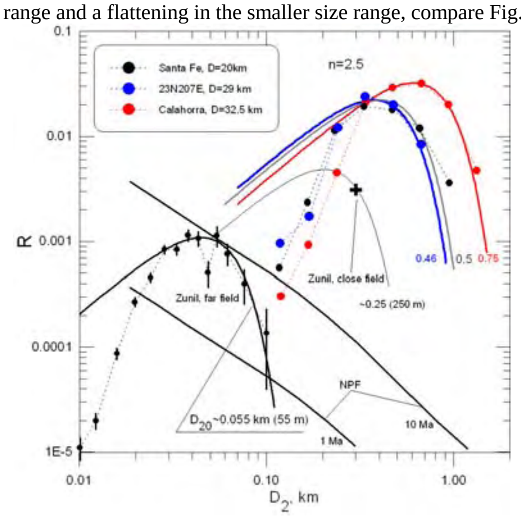

Fig. 2: R-plot for Zunil secondaries (cp. Fig.1 right) measured in the far field (at a distance of 300 km) in comparison with close secondaries for 3 other craters, counted in [10] within 6 crater radii and the R-plot of the crater production function (NPF) derived by [2, 3] for 1 and 10 Ma. The largest close-secondaries of Zunil (250m<D_2<400 m) were measured SE of the crater and give a single R-plot point. All R-SFD are fitted with the Weibull function $R \sim (D_2/D_{20})^{n-1}\exp(-(D_2/D_{20})^n)$ for n=2.5. This Weibull fit represents well the rollover of SFDs for small secondary craters.

Testing secondaries against primaries responsible for the steep branch of the SFD: Following the claim that the smaller-crater distribution is generated due to secondary cratering, we refer to previously published considerations [7, 8, 10] and construct an artificial crater distribution based on the assumptions outlined by [1]. We start with a flat primary crater distribution ($N \sim D^{-2}$). The largest possible secondary crater generated, has a diameter of a factor of 0.05 of the largest primary [5]. The steep branch is now assumed to be due to secondaries. Grinding and fragmentation experiments indicate lower frequencies in the smaller-size range. Such distributions are known statistically as Weibull distribution [7]. Such behaviour has been observed for lunar secondary crater distributions [4] and is found in the Zunil cratering record (Fig.2). Steep SFDs for the largest secondaries cannot be extrapolated to small crater diameters (below ~ 0.7 of the largest secondary crater diameter) [4] as found for the Zunil case. Unrecognized global background secondaries responsible for the smaller-crater range may be given bydistributions between $N \sim D^{-3}$ and D^{-4}, following the arguments discussed above. This construction implies certain consequences outlined here.

Surface age dependence: Artificial crater SFDs are constructed for various surface ages. Fig. 3 shows three examples of crater distributions as well as the measured crater SFDs (according to the observed shape [2, 3]) for various-aged surfaces. The onset point for the secondary distribution is shifted toward larger craters for older surfaces, which is a change of the SFD shape with time, whereas no change in shape of the distributions on the moon and Mars is observed.

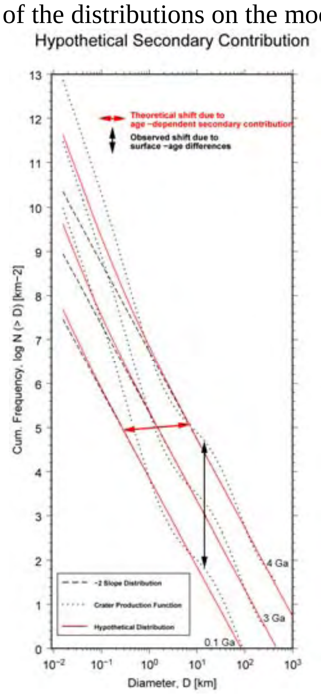

Fig. 3: Comparison of the hypothetical crater distribution and the observed crater production function [2, 3] for three different surface ages. The surface age effects the shape of the hypothetical crater SFD (red solid line) and the observed crater SFD (black dotted) differently.
While the hypothetical curve varies in shape with time, the observed distribution is just shifted to higher frequencies with time, but keeps the shape.

Percentage of Secondaries contributing: Hypothetical secondary crater contribution for two possible different slope indices (-3.0 and -3.5) can be compared to the predicted/observed crater size-frequency distribution given as a function of surface age. For a -3slope the contribution of secondaries to any measurement could be up to 10 %, while for a -3.5-slope the hypothetical secondary crater contribution would exceed the measured one by more than 100 %. The strongest effect is not observed for the smaller size range as commonly expected but for the crater range around 1 km in diameter. This would imply that the shape of the distribution would vary with surface age; this is not observed on the surface of the moon and Mars.

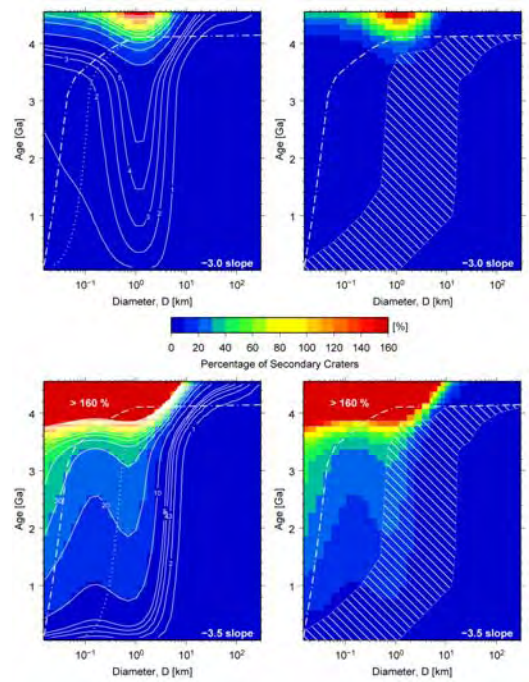

Fig. 4: Percentage of secondary craters contributing to the observed crater SFD, given for surface ages between 0 Ga and 4.5 Ga. The hatched area (right) marks the crater diameters and surface ages, where measurements were performed.

Conclusion: Detailed measurements of the Martian crater SFD for surfaces reflecting a variety of ages confirm the stability of the shape in time. This has previously been shown for the Moon [3, 8]. The steep branch of the crater distribution is not dominated by secondaries, but might include up to 10 % craters formed through secondary cratering. The applicability of simple power laws to describe secondary cratering is not valid.

References: [1]McEwen et al.(2005)Icarus, 176, 351-381. [2] Ivanov(2001)*SSR*., 96, 87-104. [3]Neukum(1983)habilitation dissertation, Munich. [4]Koenig(1977)*PhD-thesis*. Heidelberg. [5] Vickery (1986)*Icarus*, 67, 224-236. [6]Hartmann & Neukum (2001)SSR, 96, 165-194. [7]Weibull(1951)*J. Appl. Mech.* 18, 293-297. [8]Neukum & Ivanov(1994)In: Hazards, p. 359.[9] Block & Barlow (2005) LPSC 36, #1816. [10] Hartmann (2005) Icarus 174, 294-320.