CRATERING AGE CONSIDERATIONS FOR YOUNG TERRANES IN THE INNER SOLAR SYSTEM.

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Introduction: Pristine-looking terrains on Mars with few impact craters have generated considerable interest as they suggest that the planet is still active in a geologic sense. These terrains include lava flows, flood channels, glacial moraines, mid-latitude gullies and debris mantles, as well as polar and eolian deposits. However, attempts to quantitatively date such terrains from the statistics of small craters has been controversial. McEwen et al. [1] argued that the great majority of small Martian craters (smaller than a few hundred meters diameter) are secondaries rather than primaries, and that the production functions or isochrons used in dozens of recent publications are suspect. Studies of Europa [2,3] and the Moon [4,5] have also supported the view that secondaries dominate the statistics of small craters on these large moons. The importance of secondary cratering to chronology is reviewed in [6].

Meanwhile, a much more radical challenge to the chronology of Mars has come from Bouvier et al. [7], who argue that the basaltic shergottites have crystallization ages of ~4 Ga rather than ~180 Ma, and that the lithosphere of Mars is extremely old. Study of the rayed crater Zunil helps to address this issue as well as that of age constraints from small craters.

Zunil: The rays and secondaries of the 10-km Martian crater Zunil have been mapped and counted in detail by Preblich et al. [8,9]. Zunil provides a wonderful opportunity to study secondary cratering because it is such a young primary impact and the secondaries are distinctive, even those with a spatially random distribution in individual images, and because Mars is well imaged (unlike Europa). Preblich et al. estimate that the total number of secondaries ($\geq$ 10 m) produced by Zunil is of order 10^8 rather than 10^7 as reported by [1]. The size-frequency distribution (SFD) of the secondaries is much steeper in the rays and in distal reaches beyond well-defined rays than in regions between the rays. The great majority of Zunil secondaries appear to be spatially random and could be misinterpreted as primaries (e.g., ref. [10]). We find no evidence at most locations for a rollover in the abundance of secondary craters down to 15 m diameter, below which the imaging data is limiting, contrary to a conclusion of [10] from study of a small area near Zunil.

To account for all of the small craters one might expect from the Neukum or Hartmann production functions [11], only ~10% of the primary craters can be as prolific as Zunil in secondary production. Moderately oblique impacts like Zunil produce more high-velocity ejecta and secondaries than vertical impacts, but few impacts are vertical. Impacts into Amazonian lava plains are also likely to produce more high-velocity ejecta [12]. However, note that the lunar crater Tycho produced at least 10^6 secondaries in spite of impact into the heavily damaged lunar highlands [5].

An important new result is measurement of the size-mass relation of Zunil ejecta out to ejection velocities as high as 7 km/s [8,9]. A dozen previous studies, both laboratory experiments and from secondary craters, have demonstrated such a relation up to 1 km/s ejection velocity (see references in [6]). (Note that the escape velocity of Mars is 5 km/s but we can measure higher ejection velocities for small fragments that are decelerated by the atmosphere so they do fall back to make craters.) These results are consistent with the spallation model of Melosh [13].

Why Secondaries Usually Dominate the Numbers of Small Craters: The mass-velocity relation of high-velocity impact ejecta is key to understanding why secondaries must dominate the statistics of small craters [6]. If one starts by assuming that ejecta from asteroid impacts has the same SFD as ejecta from a primary impact event on the Moon or Mars [14,15], then it is simple to demonstrate that the secondary craters must have a much steeper SFD than small primaries. The mass-velocity relation (small fragments are ejected at higher velocities on average) steepens the SFD substantially. This implies that the SFD of the fragments cannot be much steeper than cumulative power-law index –2, in order to match the secondary SFD index of –5 seen at Zunil. Because the SFD of the ejecta is not so steep, there is no mass requirement that the abundances of secondary craters must roll over after just one or two orders of magnitude decrease in size.

A Sanity Check on Martian Ages: There is a population of large young craters on Mars that can be dated from their own statistics as well as from superimposed small craters, as a consistency check on the Neukum/Hartmann production functions or isochrons. Young primary craters larger than 10 km diameter are best identified on Late Amazonian terrains where large craters are rare and where they have been well sampled with high-resolution MOC images. Late Amazonian terrains cover ~7% of Mars, and there are at least 4 primary craters larger than 10 km diameter that appear remarkably young from the paucity of superimposed small craters: Zunil (7.7 N, 166 E; 10 km), Tooting (23 N, 207 E; 29 km), McMurdo (84 S, 0 E; 23 km), and a 11-km crater just south of the summit caldera of

Olympus Mons. From the few small craters that can be identified and using Neukum's production function, all of these craters should be younger than 100 Ka (and < 10 Ka in the case of Zunil). However, according to the same Neukum production function we should expect 4 craters > 10 km every ~60 Ma and 2 craters > 20 km in ~70 Ma over 7% of Mars. Crater age dating with large craters is reasonably well established, with uncertainties of a factor of a few, so it appears that the small-crater end of the Neukum production function underestimates the ages of these sparsely-cratered surfaces by 2-3 orders of magnitude. Likewise the Hartmann "isochrons" when applied only to small craters may also predict ages that are 2-3 orders of magnitude too young. Assuming that these craters are younger than ~100 Ma, it is reasonable that they could have been spared a significant number of secondary craters larger than ~20 m diameter. The secondary cratering of the past ~100 Ma is instead highly concentrated over a small fraction of Mars, around the recent large primary craters themselves such as Zunil. In contrast, the rate of formation of small (less than a few hundred meters) primary craters is much less than predicted by the Neukum and Hartmann production functions. The recent "Martian Ice Ages" [16] cannot be reliably tied to recent obliquity cycles.

Is there Hope For Age Dating with Small Craters?: Yes, at least for the inner Solar System (excluding Earth and Venus) where significant numbers of small primary craters must form. A basic tenant of dating from craters is that each crater is an independent random event. Secondary craters form by the millions essentially simultaneously and represent an extreme violation of that tenant. Certainly a terrain with more secondaries is likely to be older than one with fewer, especially if the two terrains are near each other. But a rationale for quantitative dating from secondaries has never appeared in a peer-reviewed publication.

We can date surfaces with small primary craters provided that we know the primary production function and we are able to distinguish primaries from secondaries, or at least demonstrate that primaries must dominate the statistics. See [1,6] for further discussion. Future work is needed to determine the primary production function for small craters and to determine how to distinguish primaries from secondaries.

Are Basaltic Shergottites ~4 Ga Old?: The hypothesis of [7] is that the lithosphere of Mars is extremely old but most mineral ages have been reset recently by acidic aqueous solutions percolating through the Martian surface. This is an extrapolation of results from MER Opportunity [17], except that there is no evidence that the acidic mineralization was recent. Also, the acidic mineralization is associated with sulfate-rich deposits that cover a small percentage of Mars [18]. There are large regions of Mars with fewer large craters than the lunar maria, in spite of Mars residing closer to the asteroid belt than the Moon, and these regions must be considerably younger than 4 Ga. Zunil is superimposed over a large expanse (~10^5 km^2) of flood lavas on which the statistics of primary craters (larger than 500 m) indicates a surface age of less than ~100 Ma [19]. There are older lavas (~200 Ma and probably older at depth) nearby and below the uppermost lava flows. Zunil impacted into this stack of lavas and must have ejected millions of rocks from Mars, as shown by the calculated ejection velocities [8,9] and modeling [20]. Bouvier et al. [7] wrote: "Most notably, the ~180 Ma ages conflict with the apparent rarity of uncratered surface young enough that it would allow for voluminous volcanic activity ~180 My ago." This statement is contradicted by studies of the Cerberus Plains, and Zunil provides direct evidence that millions of potential Martian meteorites with young crystallization ages were ejected from the planet.

Conclusions: The basic crater chronology of the Moon and Mars based on craters larger than 1 km diameter [21,22] is probably sound, to within a factor of a few. However, attempts to date especially young terrains where only small craters are present are meaningful only when primary craters can be identified or shown to be statistically dominant and their SFD is compared to an accurate production function for primaries.

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