PROGRESS IN MARTIAN CHRONOLOGICAL STUDIES FROM CRATER COUNTS: ACCUMULATION OF THE SMALLEST CRATERS

William K. Hartmann
1700 E. Fort Lowell Road, Suite 106, Tucson, Arizona 85719-2395 USA
hartmann@psi.edu

ABSTRACT

Nature's process of cratering the worlds of the solar system offers many opportunities for understanding geologic characteristics of planetary surfaces far beyond the cratering process itself. These include assessment of ages, geological processes of modification, and rates of such processes. Recent critiques of this method, and concerns about secondary craters, are overwrought. Remaining issues revolve around use of small craters (diameter $D \lesssim 200$ m). I propose that under any of the suggested models, km-scale surfaces lacking craters of $D \lesssim 50$ m are unlikely to have ages > few 10s My.

1. BACKGROUND: THE CRATERING OPPORTUNITY

On various worlds, nature creates symmetric circular craters with fairly well-known size frequency distributions (SFDs) and crudely known formation rates. Each primary impact (by an interplanetary body) scatters numbers of secondary impactors, which produce "distant secondary craters" (secondaries outside obvious clusters and rays, far removed from their parent primary crater). The total SFD of such craters, prior to any erosional or depositional losses, is called the "production function." An example is shown in Fig. 1, based on counts on the relatively young lava-covered surface of the volcano, Arsia Mons. Studies of the SFDs on different stratigraphic units, and measurements of losses of the smaller craters relative to the "production function" SFD, provide a wealth of information about surface ages and erosional/depositional processes [1]. The total accumulated densities of well-preserved craters – i.e., the total number/km^2 of primaries plus distant secondaries – give a datum for measuring the crater retention age of the surface. This may give the formation age of the underlying rock unit under ideal conditions, but there is an analogy to radiometric gas retention ages. In ideal conditions, the gas retention age of a rock gives its formation age, but in the presence of disturbances, such as an impact or heating event, the gas retention age may give the date of the disturbance. In the same way, in an erosive or depositional environment, the crater retention age may measure the retention time, i.e., survival time, of craters and other topographic features of the characteristic scale being considered. In areas of complex history, the combination of the shape of the SFD and morphologies of craters in different diameter ranges gives a valuable tool for estimating the nature and rate of geological processes of obliteration.

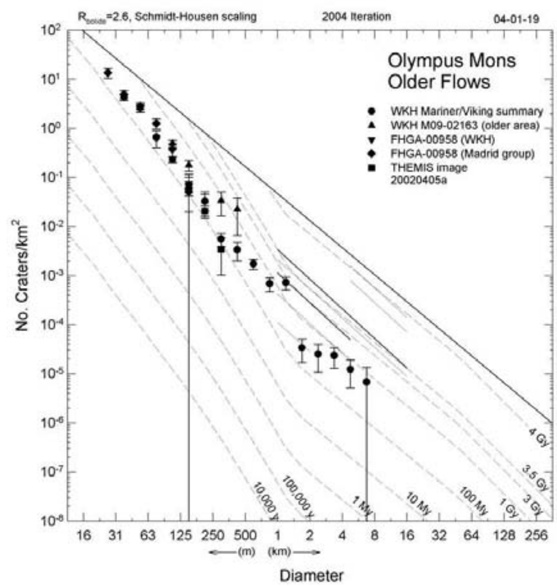

Fig. 1. Data points show size-frequency distribution of total size-frequency distribution (primaries + secondaries) derived from Mars Global Surveyor and other imagery of Olympus Mons. Lava flow surfaces were divided into an older group and a younger group, based on superposition criteria; this plot shows data from the older flows. Images used are listed. Curved lines are isochrons for various ages, and upper solid line is empirically measured saturation equilibrium curve. The counts suggest a good fit to she shape of the isochrons, i.e., "production function" curves, and suggest a characteristic age of a few hundred My for the older surface lavas.

2. BRIEF REVIEW OF RECENT CRITIQUES

Such techniques have recently come under fire, but some of the criticisms are seeing the glass as half empty, instead of recognizing the "glass-half-full" value of the information supplied by craters. I address some of these issues here.

Malin and Edgett stated that "...it is impossible to date Martian surfaces from impact craters...given the problems of burial and exhumation," and that a Mars with young volcanism "is not the planet we think we see...." [2] This ignores that the present techniques made a correct pre-Apollo 1965 prediction of "about 3.6" Gy for typical lunar mare ages [3], and also correctly predicted from Mariner 9 data in the 1970s that widespread areas of Martian lavas are only a few hundred My old [4], as evidently confirmed a decade later by basaltic and other igneous meteorites from all but one of 5 to 9 Martian launch sites. The technique can even characterize the date of the exhumation episodes, because typical exhumed surfaces (documented by Malin and Edgett [2]) have a low density of sharp, small craters, and the numbers of those craters give a measurement of the exposure time since exhumation. Furthermore, the SFD contains information on the rate of the exhumation process. If the small sharp craters fit the proposed production function or isochron shape, it means that the exhumation event was short-lived relative to the time since exhumation, because the production function SFD as been preserved ever since. On the other hand, if the SFD is flattened, indicating continuing losses of small craters, it means that the exhumation process has continued over an extended period, such that the surface is still being eroded even as new craters are forming. Morever, Malin and Edgett proposed no new, revised chronology for Mars. Order-of-magnitude revisions of proposed crater count chronologies would bring them into conflict with the Martian meteorite evidence.

Most other recent critiques have focused on small craters (typically 10m < D < 250 m), suggesting that they do not convey useful information on ages or geologic processes [5]. These critiques raise interesting and useful issues, but they all erroneously state that crater chronology systems depend fundamentally on an assumption that all the counted craters are primaries. This is incorrect in my case, since I count not just primaries, but the total mix of primaries plus distant secondaries. It is true that my isochron derivation (converting to Mars from the "calibration SFD" found in lunar maria) involves a velocity ratio more appropriate to primaries than secondaries, but this is a 2nd order correction compared to the errors proposed by the critical authors. An example of the problem is found in the McEwen et al. (2005) paper on Zunil (cf. [5]), which reads numbers off my isochrons and represents them as primary crater numbers, then concludes that they are off by a factor 2000 – the error being that my isochrons don't give primary crater numbers, but rather primary + secondary totals. The internal inconsistency in the McEwen et al. (2005) work is shown by the fact that they apply their new understanding to derive a new age for the Athabasca Vallis channel system, but their result (1.5 My to 200 My) is virtually identical to a result for Athabasca Vallis based on my isochron system (few My to <200 My), published three years earlier by Berman and Hartmann [6].

Do my current isochrons really represent the production rate of small craters? Malin et al. have observed a new 25 m crater on Mars, with dramatic ray system of ejecta, which faded in a few years, presumably due to winds and sand mobility. They used their observations of several rapidly-fading ray systems to estimate a production rate for craters of 25m-100m (www.msss.com). As shown in Fig. 1, their rate is within about a factor 3 of my isochrons at that size. Issues may be raised about whether the Malin et al. estimate is correct, but if it is, then the isochrons appear likely to be within an order of magnitude of the correct production rate for small craters of 25m $\lesssim$ D $\lesssim$ 100m.

Another critique, by Bierhaus [5], based on his good work on Europa cratering, argues that secondaries are so hopelessly dominated by non-random clustering that age information would be wiped out among small craters. This ignores that crater counters generally avoid obvious clusters and rays, in an attempt to count the relatively randomly distributed craters. Empirical evidence also obviates this criticism. For example, in recent work on some 45 Martian landslides, Quantin et al. [7] showed that in every case the stratigraphically younger landslides have the same or (usually) measurably lower crater density than the older ones or background, which counters the assertion that statistical clustering of secondaries wipes out chronometric information among small craters. It seems clear that crater SFD's, even at small sizes in small areas, generally do preserve chronographic information.

3. A SIMPLE MODEL OF SMALL CRATER PRODUCTION

In my system, I have made no judgement whether small craters (D $\lesssim$ 200m) are dominated by primaries or secondaries. The literature is divided on this. However, it is valuable to think through the consequences of either end-member model. If most small craters are primaries, they accumulate randomly but relatively uniformly with time, so that my existing "2004 iteration" isochrons [1] would be correct.

If most such craters are completely dominated by secondaries, they would accumulate not gradually but in showers, each shower caused by an "offstage" primary impact crater some distance away. Head et al. [8] concluded that craters at least 3 km across are needed to eject Martian meteorites from Mars, which means that craters of D > 3 km are needed to thrown decameter-scale secondary craters over much of Mars. Thus, as a thought experiment, we may consider Zunil-sized (10 km) craters as a test case for understanding the accumulation of secondaries. (Note that larger craters produce more secondaries, but 20 km craters would be ~1/4 as frequent as "Zunils.") McEwen et al. (2005, Table 3; cf. [5]), give model results on secondary crater SFDs at different distances from a Zunil-sized crater. McEwen et al. and my isochrons agree that the timescale between formation of Zunil-sized craters is of order 1 My. Therefore, if 20m-scale craters are virtually all secondaries, we would have to wait an average of 1 My for "a Zunil" to cast a sizeable population of 20m secondaries onto randomly chosen fresh surfaces, such as new lava flows. This model can be made more specific. For example, the models of McEwen et al. indicate that Zunil covers only 1/6 of Mars with secondary crater densities comparable to my 1 My isochrons. Thus, as shown in Fig. 1, we would actually have to wait for some 6-10 Zunils (allowing for overlap of secondary fields), or ~ 6-10 My for secondaries to being to appear on a newly-formed geologic formation. McEwen et al., invoking a model by co-author Artemieva, use a size distribution for secondaries that appears steeper than I would expect, but after 10 My, a few larger primaries would begin to fill in secondaries at larger sizes. The point is that the McEwen et al. model predicts that on surfaces older than about 10 My years, the accumulated number of craters begins to straddle my isochron for 10 My – indicating a gross consistency between McEwen et al. [5] and my isochrons.

In the same way, the model of McEwen et al. also predicts that after 100 My, the SFD would straddle my isochron for 100 My, and implies that after 100 My, some 100 different primaries would contribute to the population of secondaries at any given spot. This counters concerns about statistics-of-one effects of statistical clustering among spatial distributions of secondaries from single primaries. The same model shows that the small craters begin to reach saturation equilibrium densities (upper solid line on Fig. 2) in about 100 My, so that they become much less useful in dating surfaces.

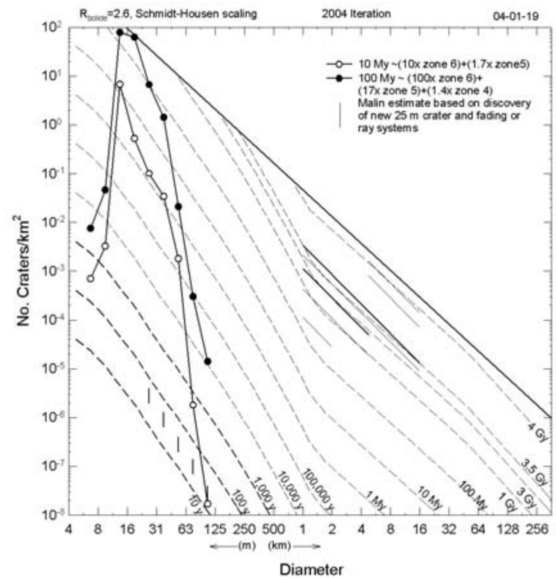

Fig. 2. McEwen predicted SFD's from Zunil secondaries after 10 and 100 My (see text). Tick marks (lower left) show Malin's proposed observed production of 25m-100m craters in 100 years (see text).

To put it another way, for surfaces formed over some 99.8% to 98% of Martian time (all but the last 10 to 100 My), the crater densities should roughly agree with the isochron system, even if the small craters are completely dominated by secondaries. In other words, a Martian lava flow, debris apron, glacier, or similar feature with virtually no 20m-scale craters must be < few My old, while such a surface with saturation density is > few hundred My old, contradicting the frequent assertion [5] that such craters give no chronologic information.

4. CONCLUSION

Existing crater chronology systems using craters of D ≥ 1 km have a track record of successful prediction of ages on the moon and Mars. Combination of crater density measurements with observations of crater morphologies gives valuable information about not only ages, but also geological processes affecting obliteration. Recent criticisms based on new observations of small crater populations, have been overwrought in their suggestions that impact crater chronology studies, and/or counts of small impact craters, are worthless. Impact crater counts, combined with crater morphology studies, are a valuable addition to the analytic toolkit of planetary geologists.

REFERENCES

1. Hartmann W.K., Martian cratering 8: Isochron refinement and the chronology of Mars, *ICARUS*, Vol. 174, 294-320, 2005.
2. Malin M.C. and Edgett K.S., Evidence for Persistent Flow and Aqueous Sedimentation on Early Mars, *SCIENCE*, Vol. 302, 1931-1934, 2003; Malin M.C. and Edgett K.S., *J. GEOPHYS. RES.*, Vol. 106, 23429-23570.
3. Hartmann W.K., Terrestrial and Lunar Flux of Large Meteorites in the Last Two Billion Years, *ICARUS*, Vol. 4, 157-165.
4. Hartmann W.K., Martian Cratering, IV: Mariner 9 Initial Analysis of Cratering Chronology, *J. GEOPHYS. RES.*, Vol. 78, 4096-4116, 1783. Hartmann W.K., Martian Cratering V: Toward an Empirical Martian Chronology, and Its Implications, *GEOPHYS. RES. LETT.* Vol. 5, 450-452, 1978.
5. McEwen A.S. et al., Discovery of a Large Rayed Crater on Mars: Implications for Recent Volcanic and Fluvial Activity and the Origin of Martian Meteorites, LPSC XXXIV, abstract #2040. McEwen A.S. et al., the Rayed Crater Zunil and Interpretations of Small Impact Craters on Mars, *ICARUS*, Vol. 176, 351-381, 2005. Bierhaus E.B. et al., Secondary Craters on Europa and Implications for Cratered Surfaces, *NATURE*, Vol. 437, 1125-1127, 2005. Chapman C.R., Mars Cratering Issues: Secondary Cratering and End-Noachian Degradation, Second Conf. on Early Mars, Abstract #8028, 2004.
6. Berman D.C. and Hartmann W.K., Recent Fluvial, Volcanic, and Tectonic Activity on the Cerberus Plains of Mars, ICARUS, Vol. 159, 1-17, 2002.
7. Quantin C. et al., Ages of Valles Marineris (Mars) Landslides and Implications for Canyon History, *ICARUS*, Vol. 172, 555-572, 2004.
8. Head J.N., Melosh H.J., and Ivanov, B.A., Martian Meteorite Launch: High-Speed Ejecta from Small Craters. *SCIENCE*, 298, 1752-1756, 2002.