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Do young martian ray craters have ages consistent with the crater count system?

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ABSTRACT

McEwen et al. (McEwen, A.S., Preblich, B.S., Turtle, E.P., Artemieva, N.A., Golombek, M.P., Hurst, M., Kirk, R.L., Burr, D.M., Christensen, P. [2005]. Icarus 176, 351–381) developed a useful test for the internal consistency of crater-count chronometry systems. They argued that certain multi-kilometer, fresh-looking martian craters with prominent rays should be the youngest or near-youngest craters in their size range. The "McEwen et al. test" is that the ages determined from crater densities of the smallest superimposed craters (typically diameter $D \sim 5$–20 m) should thus be comparable to the expected formation intervals of the host primary. McEwen et al. concluded from MOC data that crater chronometry failed this test by factors of 700–2000. We apply HiRISE and other imagery to eight different young craters in order to re-evaluate their arguments. We use existing crater chronology systems as well as the reported observed production rate of 16 m craters (Malin, M.C., Edgett, K., Posiolova, L., McColley, S., Noe Dobrea, E. [2006]. Science 314, 1573–1557; Hartmann, W.K., Quantin, C., Mangold, N. [2007]. Icarus 186, 11–23; Kreslavsky [2007]. Seventh International Conference on Mars, 3325). Every case passes the McEwen et al. test. We conclude that the huge inconsistencies suggested by McEwen et al. are spurious. Many of these craters show evidence of impact into ice-rich material, and appear to have ice-flow features and sublimation pits on their floors. As production rate data improve, decameter-scale craters will provide a valuable way of dating these young martian geological formations and the processes that modify them.

1. Background

McEwen et al. (2005) and Tornabene et al. (2005) pointed out several sharply defined, young-looking, multi-kilometer primary martian craters, including Zunil, with ray systems detectable in THEMIS infrared night-time imagery. McEwen et al. noted that because martian ray systems quickly disappear due to winds and erosion, these craters are likely to be among the youngest examples of their size class. Using impact rate models (Neukum et al., 2001; Ivanov, 2001; Hartmann and Neukum, 2001; Hartmann, 2005), one can estimate intervals between impacts that form craters in any given size bin. If the craters are among the youngest of their size, plausible expected ages can thus be derived for each, namely the order of magnitude of the formation interval. A plausible age might extend to a few times that value (if the crater is, say, the 2nd, 3rd, 4th ... youngest in its diameter bin). Superposition arguments may also constrain the expected age; for example, with craters on polar layered terrains.

McEwen et al. (2005) used such craters to develop an interesting test of validity for crater chronometry systems – namely that the numbers of small ($D \lesssim 50$ m) craters superimposed on such "host craters" should be consistent with their expected age. They studied two of the ray craters and one other crater (McMurdo) at MOC image resolution and stated that the numbers of small craters in their interiors and on their ejecta blankets are grossly deficient and inconsistent with the likely ages of the craters themselves, based on "isochron" or crater production-rate curves used at that time by Hartmann et al. (1999), and Neukum et al. (2001), and as discussed further by Ivanov (2001), Ivanov et al. (2002) and Hartmann and Neukum (2001). The McEwen results would also be inconsistent with the current iterations of the crater count system by Hartmann (2005) and by Neukum and the HRSC Imaging Team (2004).

The three host primary craters discussed by McEwen et al. were Zunil ($D = 10$ km), Tooting (then unnamed, $D = 29$ km), and McMurdo ($D = 23$ km). From estimated production rates for craters of these sizes, they inferred probabilistically that the host crater should have an age around 1 Myr for Zunil, around 5 Myr for Tooting, and as much as 180 Myr old for a McMurdo-sized crater superposed on the southern polar layered deposits.

To give more specific details, in the case of host-crater Zunil, they found no MOC imaged craters of $D > 24$ m inside the crater or on its continuous ejecta blanket out to 2.7 Zunil radii, for which

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they gave a total area of ~600 km^2. From this they inferred a post-Zunil crater density of <1 crater/600 km^2 (crater interior + blanket), or <1.7(10^{-3}) craters/km^2. They applied this to the Hartmann isochrons (1999–2001 iterations) for craters of $D > 24$ m, and found a Zunil model age of $\lesssim$10,000 y – very unlikely for craters that form only roughly once per 1 Myr. (Our current "2004 iteration," from Hartmann (2005), would also give an age $\lesssim$10,000 y from this datum.) Hence, they argued that the crater count system is seriously internally flawed, in that the decameter craters do not give the same result as the 10-km scale craters.

For their other two host craters they also concluded that the crater chronometry systems again gave ages far too young to be realistic on the basis of the above production rates for the host craters themselves. They suggested that the probability of the Hartmann and Neukum systems giving even roughly correct ages is only around 0.1–1.4%.

Based on the alleged inconsistency in ages, McEwen et al. (2005, p. 375) suggested that the crater counts systems "predict too many small primary craters." They inferred that Hartmann's production rates and isochrons give 2000× too many primaries, and that the Neukum production function gives 700× too many. In other words, McEwen et al. implied a production rate for ~24-m primary craters, ~1/2000 the rate shown by the Hartmann isochrons and ~1/700 of the Neukum rates.

One year later, Malin et al. (2006) detected formation of small primaries on Mars (typically 10–20 m scale), a best value being ~9(10^{-8}) craters/km^2 y for $D \geqslant 16$ m. This is about 325–575 times the rate McEwen et al. predicted for primaries, but less than a factor 3 or 4 below values used by in the Hartmann and Neukum systems, depending on the analysis of the Malin et al. data. (cf. Hartmann, 2007; Kreslavsky, 2007, gets even closer agreement, within a factor of two.)

A conceptual complication must be noted. The McEwen et al. (2005) discussion implied that Hartmann attempted to avoid counting *any* secondaries, and that Hartmann's isochrons were intended to represent primaries alone: McEwen et al. erred in inferring this. Hartmann counts the total mix of primaries plus an unknown fraction of semi-randomly scattered "field secondaries" (Field secondaries are defined, even if somewhat fuzzily, as those outside rays and obvious clusters). Given the factors mentioned above, both the Hartmann and Neukum isochrons thus still allow for some fraction of craters being secondaries. For example, if the observed formation rate of 20 m primaries is 60% of the level plotted on the isochron, that leaves the other 40% as a possible fraction which are secondaries, though error bars are critical factor in such a measurement. (The fraction of field secondaries is presently uncertain, but it may be <50% at many diameters; it probably varies with D.)

McEwen et al. do propose a useful test of the crater count system: Are the small crater densities superimposed on the youngest martian ray host craters consistent with inferred ages of the host craters? In this paper we will apply this useful "McEwen et al. test" to see whether the existing chronometric systems perform satisfactorily.

Many observers have emphasized potential problems in using decameter-scale craters to derive chronologic information. Such problems include the role of secondaries and the rapid erosive loss of such craters (McEwen, 2003; Chapman, 2004; Bierhaus et al., 2005; Plescia, 2005; McEwen et al., 2005; McEwen and Bierhaus, 2006; Mouginis-Mark et al., 2003). We concur that some problems of this type exist when interpreting densities of such small craters. However, these problems were somewhat offset when Malin et al. (2006) observed ~10–20-m-scale primaries actually forming on Mars at nearly the rates we have used. In some ways, this makes dating of small, very young formations from decameter-scale craters *more* secure than dating of larger units from larger craters, because we have a direct measure of decameter crater formation rates which will indeed improve with more observations in the next few years. At $D \gtrsim 500$ m, however, the production rates are determined primarily from measurement of crater production rates on the Moon from dated Apollo/Luna landing sites and model-dependent transfer of those rates to Mars (after model-dependent scaling corrections for gravity, impact velocity, etc.). To summarize, decameter-scale craters should soon have great value in chronometry.

Let us consider briefly the effects of "distant" or "field" secondaries on these ideas. These are the somewhat randomly scattered ones outside a few radii from a primary, and outside obvious rays and clusters. We note that craters larger than 3–10 km are believed necessary to launch fragments large enough to ascend through the atmosphere at near-escape velocity and thus be scattered essentially all over Mars. Three-kilometer craters form roughly once every 200,000 y, and 10 km craters about once per Myr. Thus, roughly speaking, one expects no global scattering of distant, field secondaries on Mars on surfaces younger than about 10^5 y. In the case of a formation of age roughly 2×10^5–10^6 y, however, there could well be one or a few 3–10 km craters on Mars (such as Zunil) that launched martian meteorite-sized debris around Mars. Such a formation could thus have scatter of 10 m secondary craters, especially if the formation is not too far from one of the source craters. Surfaces of this age are thus most subject to stochastic additions, since they might be affected by 0, 1, 2, 3 or more distant sources of secondaries. On surfaces older than a few $\times 10^7$ y (most of the surface of Mars, representing >99% of martian history), we would expect at least tens of "Zunils" to have formed somewhere on Mars, so that the distribution of distant field secondaries begins to be more randomized, and the ratio of primaries to secondaries at each size begins to become more stable. Thus, the total mix of primaries plus field secondaries begins to be more reliable as a chronometer. If the long-term average fraction of secondaries in the total mix of decameter-scale craters is <0.5, all these issues are minimized because the primaries dominate in any case; but if the fraction is >0.5, the possible effects of stochastic addition of secondaries become more important, especially on surfaces in the narrow age range of 200,000 y to 2 Myr in age. These effects are discussed in additional detail by Werner et al. (2009).

How do these considerations affect the McEwen et al. test? The original problem was that McEwen et al. found no craters smaller than 24 m in their test cases, and concluded that Zunil gave ages <10,000 y, at least two orders of magnitude below the expected age for Zunil. We will argue on the basis of the measured Malin et al. (2006) production that finding even a few primary impact craters in the 16–24 m size range on flat floor areas inside Zunil (area ~20 km^2) would suggest an age of more like a few hundred thousand years – which begins to be much more plausible for craters expected to form once per Myr. On the other hand, if one wants to argue that these small craters are secondaries, then detection of a few 16–24 m craters inside Zunil again suggests it is >200,000 y old, simply because major showers of distant secondaries are unlikely in a much shorter time period. And a mix of primaries and secondaries produces the same result. In short, the detection of essentially any population of decameter-scale craters superimposed on the host craters in this study virtually assures that the host crater is far older than the ~10,000–20,000-year figure attributed to our technique by McEwen et al. (2005) – regardless of whether the decameters craters are regarded as primaries or secondaries.

2. New evaluation of the ages of seven young ray craters and McMurdo: crater densities on floor deposits and ejecta

Several of us (WKH, CQ, SCW) independently examined MOC, HiRISE, and other images of various young craters (see Fig. 1) and made counts of the small craters detected inside the host craters and/or on their ejecta blankets. As will be discussed in more detail below, the images at HiRISE resolution do show populations of small craters that the McEwen et al. team could not detect. Our approach to each primary host crater depends somewhat on its specific situation. Ideally, we preferred counts of small craters inside the fresh primaries, but these interiors, unexpectedly, are some of the most complex area to obtain and interpret crater counts.

For example, we tended to avoid counting craters on steep inner walls of fresh craters, which are affected by mass wasting and may be some of the more unstable surfaces on the planet, in view of downslope motions of loose wall materials (see Fig. 2). Crater retention ages on such walls would measure the survival time against mass wasting, not the age of the host crater itself. As examples, the wall of Zunil constitutes about 34% of the crater area, and for Zumba the number is more like 40%, so the removal of wall area is significant. If smooth level areas could be found on the floors *inside* the fresh craters, as shown in Fig. 3, we favored those surfaces, since the small craters on such an area must have accumulated after the primary host crater formed. Thus, as long as we can avoid swarms of secondaries, these surfaces give a minimum model age for the host crater. In such areas we did not find clusters or rays typical of secondary swarms, but rather we were usually counting very sparsely scattered, individual sharp, or occasionally moderately degraded bowl-shaped craters that appeared to mark primary impacts. In general, we believe that most of the craters we count here are probably primaries (although, as noted above, this belief is not essential to our final conclusions).

Even the floors of fresh craters, however, are not as ideal counting surfaces as we expected. As shown in Fig. 4, we found that several of the host primaries' floors, contrary to expectation, had flow features or fans coming off the central peak, or were pocked by innumerable round to irregular pits somewhat reminiscent of the pitting in polar and other ice-rich terrains, usually attributed to sublimation (for an early discussion, see Thomas et al., 1992, pp. 778, 782, 788). We suspect that these features, along with the common rampart ejecta blankets, may be evidence that the impact tapped into underground ice deposits or ice-rich soil. Such deep ice has long been recognized, and mapping of rampart ejecta craters suggests depths of ~400 m at equatorial latitudes, decreasing to surface ice at high latitudes (Squyres et al., 1992). Spectroscopic observations of lunar craters have indicated that central peaks bring up deep-seated material (Pieters, 1982). In the martian cases, these materials may include muddy slurries of regolith granular debris and melted ice. The floors may have filled with ice-rich deposits, subsequently eaten away by sublimation.

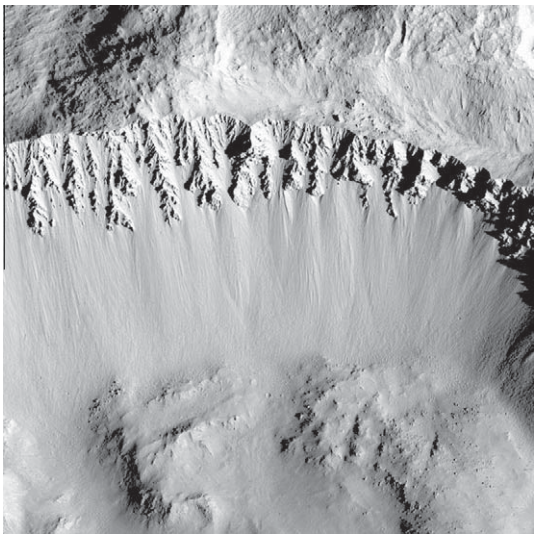

Fig. 2. Interior S wall of Gratteri, showing mass wasting that makes the wall unsuitable for crater counting (HiRISE PSP_001367_1620).

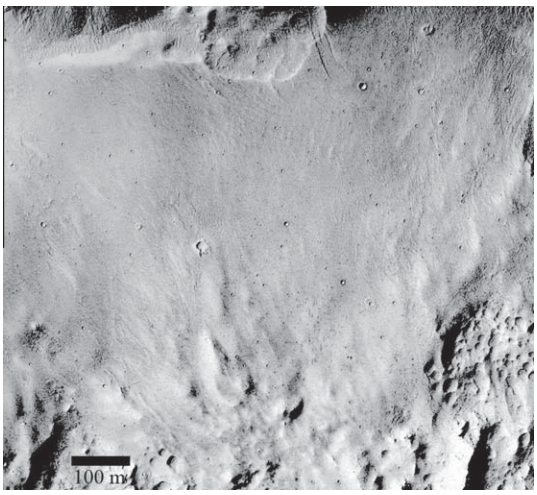

Fig. 3. Smooth, cratered plain unit of N floor of Gratteri. The host crater Gratteri must be at least as old as this unit, and the small-crater population gives a minimum age for Gratteri itself. The SE corner gives a good example of pitted terrain similar to that in Zunil (cf. Fig. 4d) (HiRISE PSP_001367_1620).

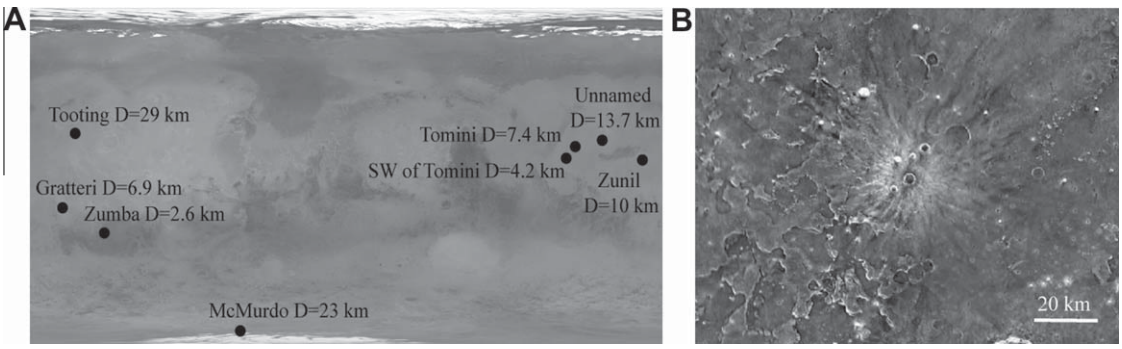

Fig. 1. (A) Global map of Mars showing the test craters studied here. Seven are young rayed craters and the eighth is McMurdo. (B) Regional view of 6.9-km young ray crater Gratteri. Rays show up as dark, being cooler than background, due to fine-grained textures (THEMIS night IR mosaic).

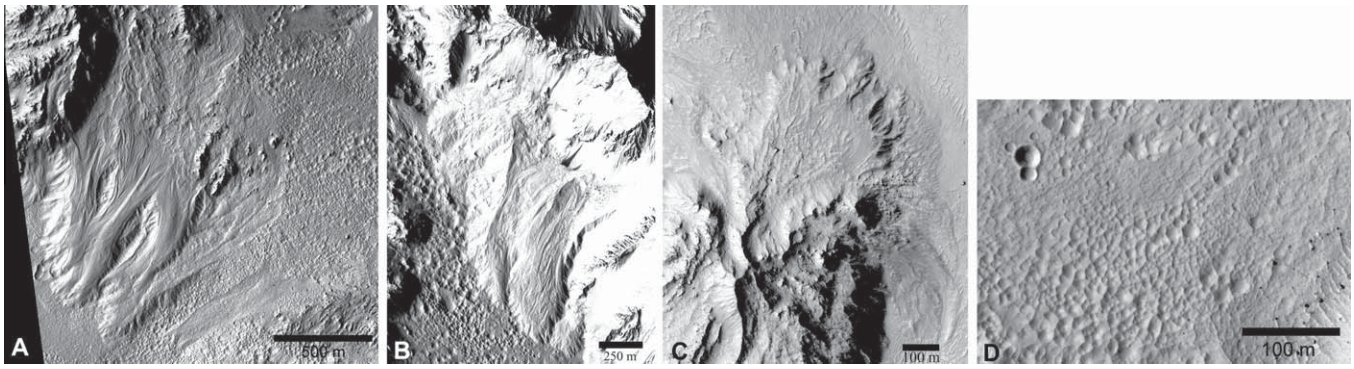

Fig. 4. Examples of lobate flows and pitting in young ray craters. (A) Flow feature coming off central peak of Zunil. To the east is typical pitted terrain (HiRISE PSP_001764_1880). (B) Similar flow feature off SW side of central peak of Tooting. On the floor, to the SE, similar strongly pitted terrain is seen (HiRISE PSP_002158_2035). (C) Similar flow feature off NE side of central peak of Tomini (HiRISE PSP_001660_1950). (D) Pitted terrain in Zunil, contrasting with a small cluster of impact craters (upper left), believed to mark breakup of a primary meteoritic body (HiRISE PSP_001764_1880). The pitting in all images is suggested to be related to sublimation processes.

The flows off central peaks, shown in Fig. 4A–C, are particularly remarkable in this context. They have apparent lobate flow fronts and are dissimilar to debris aprons, which more typically surround isolated mountains and may be mobilized in their upper layers by repeated ice-rich dust mantling associated with high obliquity periods. We cannot tell from the morphology or crater counts whether they coincide with, or postdate, crater formation. However, as per the remarks above, we assume they are formed at about the time of impact, as the melted ice interacts with upheaved central peak material. The important point here is that they prove that the morphology among most of the youngest ray craters is not pure deposition of dry rubble or impact melt produced by explosion, which might be called "dry impact morphology." Rather, it involves flow phenomena, rampart ejecta, and probable deposition of muddy slurries that subsequently freeze and produce sublimation pitting – processes not seen on the Moon.

The presence of the pits, sometimes made counts of small craters on the interior very uncertain (cf. Fig. 4D). However, we believe the necessarily young impact craters on these relatively fresh surfaces were usually distinguishable from sublimation pits by sharp circular rims and bowl-shaped interiors of the former.

In cases where the floor was too complex for reliable counts of small craters, we attempted counts on the ejecta blankets. These had their own problems. We noted frequent smooth eolian bedforms, such as dunes and ripples in some of the low areas on some of these blankets (e.g., Zunil, cf. Fig. 5). These could be depositions from global dust transport. However, ejecta blankets in general, if emplaced as loose pulverized material, may have intrinsically mobile surface layers, and may not retain 10–20-m-scale craters long enough to be useful. Plausibly, ejecta blankets of loose dry materials may tend to be altered or partially removed by winds. In support of this, older martian craters tend to have more poorly preserved ejecta blankets. Assuming no showers of secondaries on such young primaries, the densities of visible decameter-scale impact craters on a blanket would thus give a minimum age for the blanket and the host crater.

Recall that McEwen et al. (2005) concluded that the small craters, applied to our isochron system, give ages orders of magnitude younger than expected for the host crater. Thus, if our counting techniques find *minimum* ages within even an order of magnitude of the expected formation ages, they would refute the McEwen et al. conclusion.

Next we discuss several examples of young craters, one at a time. We discuss first the three examples considered by McEwen et al., then four more examples, including examples found by Tornabene et al. (2005) and by us. Table 1 gives a summary of the results, in order of crater size.

2.1. Zunil (7.7°N, 166°E, D = 10 km)

As discussed above, McEwen et al. (2005) stated that with Mars Global Surveyor images, they could find no craters of $D > 24$ m in the interior of 10-km primary crater Zunil *and on its ejecta blanket*. As noted above, they divided by the total area out to the outskirts

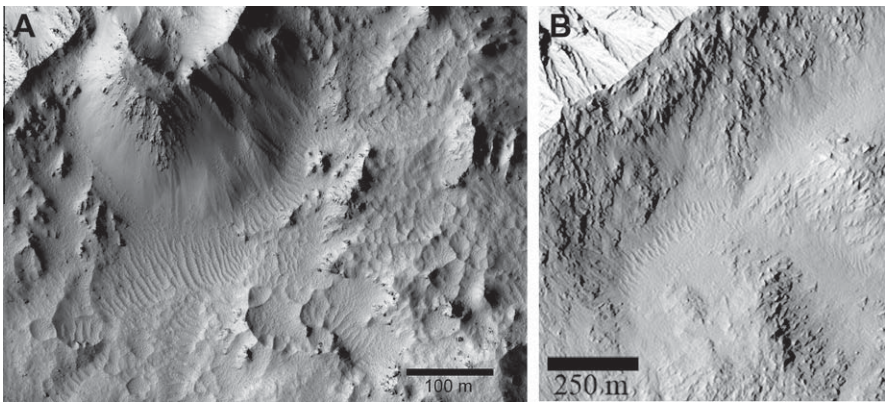

Fig. 5. Dune-like eolian bedforms, indicating post-impact reworking of surfaces of Zunil. (A) Dunes at the SE foot of the central peak (HiRISE PSP_001764_1880). (B) Dunes (L center) on ejecta blanket, just outside SE rim of Zunil. Bright surface in upper left is inner SE wall of the crater. These features suggest that the ejecta blankets have locally or globally derived deposits of loose material, which have been mobile since the crater's formation (HiRISE PSP_002252_1880).

Table 1
Ages estimated for young martian ray craters (listed in order of size).

Crater	Diam. (km)	"Problematic age" suggested from small craters by McEwen et al. (2005) (Myr)	Expected interval between formation events on Mars (Myr)	Age est. from Hartmann isochrons (Myr)	Age est. from least-square fit to Neukum isochrons (Myr)	Age. est. from Malin data at $D = 16$ m*
Zumba	2.6		0.1	0.2–0.8	0.1	0.5–1
SW of Tomini	4.2		0.4	4–30	4–8	17–31
Gratteri	6.9		0.8	0.7–2	0.5–5	3–20
Tomini	7.4		0.9	2–20	1–4	7–30
Zunil	10	0.01	1	0.1–1	0.06	0.7
Unnamed	13.7		3	5–8		2
McMurdo	23	0.1	[7]**	2–30	2–9	7–16
Tooting	29	0.02–0.07	9	2–10	0.8–4	7

* Using production rate of $9(10^{-8})$ craters/km^2 y for cumulative craters of $D > 16$ meters.
** Although the expected formation interval is ~7 Myr somewhere on Mars, McEwen et al. argued noted that McMurdo is superposed on the south polar layered deposits (SPLD) and that the formation interval on an area as small as the SPLD is 180 Myr. They cite Schaller et al. (2003) as arguing that the SPLD have a crater retention age on the order of 0.1 Myr and thus McMurdo is younger than that.

of the blanket, and the resulting low crater density, combined with our isochrons, gave a very low maximum model age of ~10,000 y for Zunil, inconsistent with an expected crater formation interval of about 1 Myr for a 10 km Zunil-sized crater.

More recent HiRISE images, however, show that a sparse population of decameter-scale impact craters does exist inside Zunil (Fig. 4D), including examples up to $D \sim 26$ m. We sought the best way to analyze this population. Much of the interior of Zunil is of questionable stability and quality for counting small craters. Zunil's floor is dominated by tracts of intensely pitted terrain with many features that might be mistaken for impact craters (Figs. 4D and 5a). As shown in Fig. 4A, a massive flow with layered units extends off the south side of the central peak. As mentioned above, these features may indicate that muddy material was brought up from depth, flowed onto the floor over a period during and after crater formation, and then froze and produced sublimation pits. McEwen et al. (2005, p. 357) noted the flow lobes of Zunil's ejecta blanket, and estimated that the excavation tapped ice-rich layers 400–700 m deep; their 2005 interpretation is consistent with the subsequent HiRISE indications of ice-related modification inside Zunil, discussed above.

Contrary to the conclusion of McEwen et al. (2005) from MOC images, and in spite of the problems of surface reworking, Zunil does contain a population of small craters, reaching sizes slightly above their cutoff as $D = 24$ m. Fig. 4D exemplifies what appears to be a small cluster of clear impact craters on Zunil's floor, noted independently by WKH and CQ during a search for impact craters on the main floor. They are distinct from the pits (i.e., the possible sublimation pits). We interpret the closely spaced grouping of sharp, symmetric craters in Fig. 4D as a cluster produced by atmospheric breakup of a single primary impactor; it fits the general dimensions for a weak meteoroid breakup, predicted by Popova et al. (2003), and also by Ivanov et al. (2008, 2009). The largest of these craters has diameter ~26 m. The others have diameters ~15 m, ~9 m, and ~7 m. The equivalent diameter of the single crater that would have been produced by the meteoroid, had it not fragmented, can be estimated by utilizing the relation of the kinetic energy of the impactor. Let D_{crater} refer to the diameter of the single crater that would have been made if the impactor had not fragmented. Neglecting drag on the smallest pieces, the kinetic energy of the unfragmented meteoroid would equal the total kinetic energy of all the fragments. Using an approximate scaling exponent between energy and D, we have

$$D_{\text{crater}}^{3.1} \sim \sum D_1^{3.1} + D_2^{3.1} + \cdots$$

The scaling exponent is an average from published values (e.g., Ivanov et al., 2008). Summing over the individual craters to cumulate the energy into one meteoritic impactor, or one crater, we can find the diameter of the "equivalent single crater." We thus reconstruct an "equivalent single crater" of $D_{\text{crater}} \sim 28$ m. Because the largest fragment in a meteoroid breakup is often an appreciable fraction of the size of the original body, we suggest that often the equivalent single crater would not be a great deal bigger than the largest crater in most observed clusters.

Zunil itself has an area of only 78 km^2, and the floor, which is most suitable for crater detection, has an area more like 20 km^2. Thus a density of one crater on Zunil's floor amounts to 2×10^{-2} craters/km^2. According to our isochron diagrams (Fig. 6C and D), this density at $D = 28$ m already implies an age of several hundred thousand years, not 10,000 y. If other, smaller craters "hide" among the proposed sublimation pits, a better measurement could be made, but the detections are difficult on the pitted floor of Zunil.

As a second test of Zunil, because of the above difficulty, CQ and SCW counted craters on the ejecta blanket. Here, other problems arose, as the blanket at HiRISE scale is complex, as discussed above and shown in Fig. 6B. Fig. 6B shows a clustering of small craters that may represent secondaries or a cluster from primary fragmentation. The counts involve a much broader area. Again, however, detection of *any* scattered primary impact craters probably gives a minimum age for the blanket, and hence Zunil. As shown in Fig. 6C and D, the measured densities were consistent with ages more nearly in the range 0.1–1 Myr. This is a plausible age, and just below the expected formation interval. This in turn suggests, as did McEwen et al. (2005), that Zunil is perhaps the youngest martian crater in its size bin. These results indicate that Zunil passes the McEwen et al. test. Kreslavsky (2008a,b) has reported similar findings for Zunil at two meetings, noting a population of small craters on the Zunil ejecta in HiRISE images.

As a third test of Zunil, one other formation inside the crater was counted separately. The flow feature coming off the SW central peak is a single unit with an unusually smooth surface and appeared suitable for crater counting. WKH made counts there, but detected what appeared to be an anomalously high density of small craters on this unit. These might mark breakup of a weak primary meteoroid, or a scattering of secondary debris (although secondaries in Zunil may be unlikely, as it is perhaps the youngest large source of distant secondaries, and fall-back of discrete secondaries directly into the crater is believed to be unlikely based on impact modeling). CQ suspected that some of the pits were sublimation pits just beginning to form on the flow, not impact features. The crater density and model age derived from these counts is about an order of magnitude above the other counts, or about a few Myr. This would still pass the McEwen et al. test, although we are inclined to discount these data as an unreliable measurement of Zunil's age.

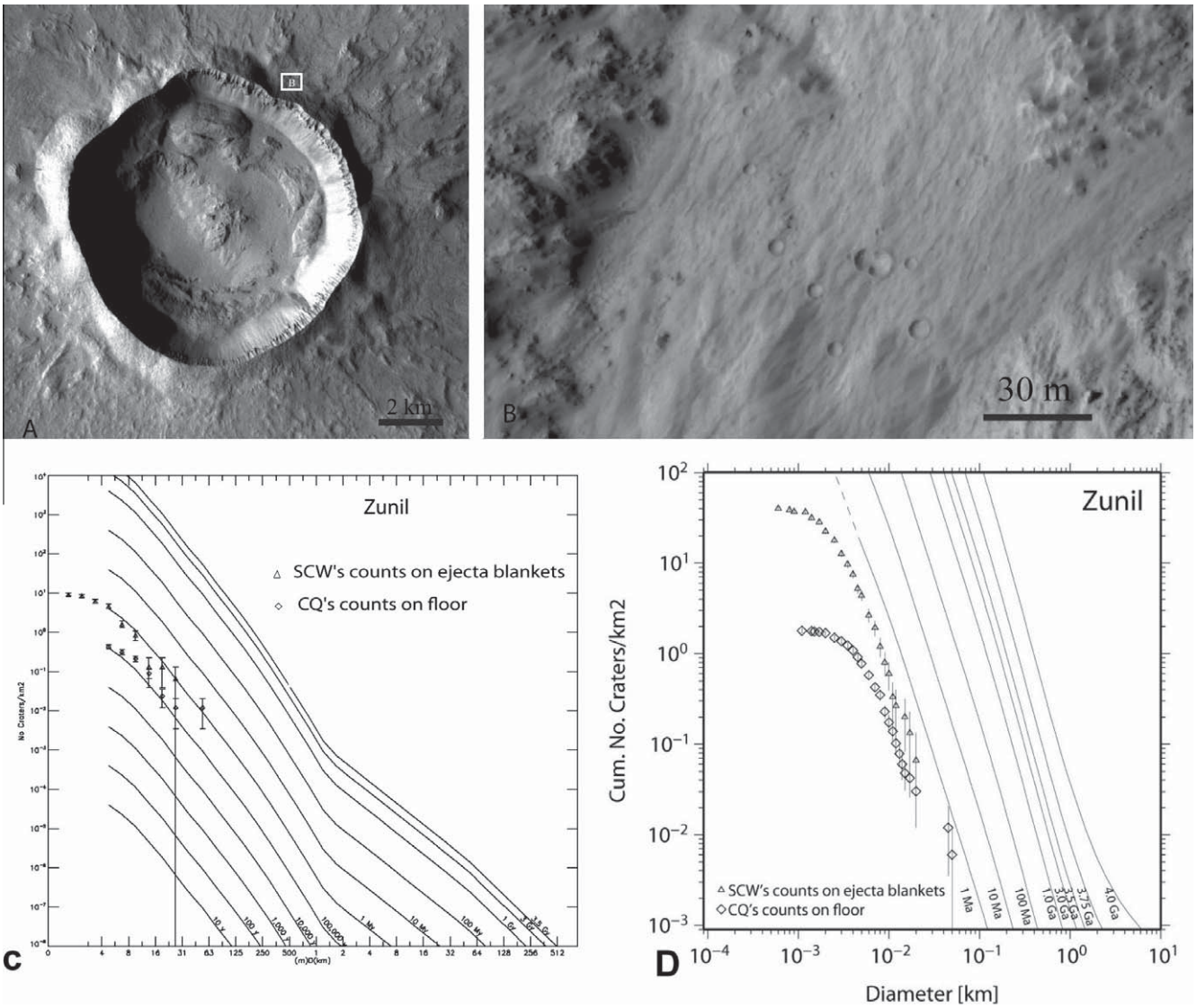

Fig. 6. Zunil. (A) View of crater and near-rim ejecta (THEMIS VIS V09818024). Box shows location of segment (B) of this figure. (B) Ejecta blanket, showing impact craters (HiRISE PSP_1764_1880. (C) Log differential plot of crater counts. (D) Cumulative plot of same crater counts.

Note that in Fig. 6 and other isochron figures, the first data plot shows the differential counts plotted (histogram style) in logarithmic bins, as in the isochron diagram developed in iterations (Hartmann et al., 1999; Hartmann, 2005). The second plot in each case shows the same counts in cumulative style, with a least-squares fit of the data points (the ones selected by us as best), to the Neukum isochron shape, in a program using techniques discussed by Neukum and Hiller (1981) and Werner (2005). Historically, these Hartmann and Neukum isochron systems were developed essentially independently, with separate methods for using scaling relations (which convert the data from the lunar calibration to Mars), although the curve *shape* (not position) in the latest (Hartmann, 2005) iteration, in the interval 20–250 m, is based on the curvature given by Neukum. Below 20 m, Hartmann introduced greater curvature (less steep slope) to allow for meteoroid losses in the martian atmosphere, based on Popova et al. (2003). The similarity of result by these two methods indicates the robustness of the system, and also gives the reader some sense of the uncertainties in the overall method (cf. Hartmann and Neukum, 2001; Hartmann, 2005, for further discussion).

To summarize the case of Zunil, we find a likely age of about 0.1–1 Myr in the Hartmann and Neukum systems. Using the Malin et al. (2006) direct measurement for formation of craters of $D > 16$ m, we estimate a Zunil age of 0.7 Myr. All three of these methods give results far higher than the 10,000-y age that McEwen et al. (2005, p. 375) estimated from our graphs. Our results are satisfyingly consistent with the expected age of about 1 Myr, given the uncertainties, and we infer that the McEwen et al. assertion of a Zunil age with a large discrepancy by a factor of a thousand is no longer valid.

2.2. McMurdo (84.5°S, 0°W, D = 23 km)

The second crater discussed by McEwen et al. (2005) is the south polar crater McMurdo. McEwen et al. developed an argument that McMurdo has a probability of only 0.1% of being consistent with the crater chronology system. This case does not involve a young ray system. Rather, the argument is that McMurdo's age is constrained by its secondaries, forming on top the south polar layered deposits (SPLD). McEwen et al. (2005) cited an abstract by Schaller et al. (2003) who in turn cited estimates that the SPLD have a general surface age of 10–100 Myr, but have experienced a veneer of resurfacing as recently as 100,000 y. McEwen's probability statement is derived by stating that in an area as small as the

SPLD, a McMurdo-sized crater should form about every 90–180 Myr, but that McMurdo itself supposedly postdates the 100,000 y-old veneer of last resurfacing. They thus estimate a probability of $10^5/10^8$, or 0.1%, and imply that something is wrong with the formation rate statistics by a factor of a thousand.

This argument is flawed. First, the quoted probabilities and expected ages are the result of McEwen et al. choosing an arbitrary small area (the SPLD) around the crater being tested. While the likely interval between McMurdo-sized craters forming on the SPLD might be 90–180 Myr, the formation interval on all of Mars in the diameter bin centered on McMurdo's size (~19–27 km) is more like 7 or 8 Myr. Obviously, the formation probability goes down if the specified area goes down. Second, Schaller et al. (2005, p. 375) made a more complete analysis and found a "complete lack of secondary craters" of $D < 300$ m from both McMurdo and another recent 15-km crater on the SPLD, which they said implies that "at least 30 m of the deposits" have been added or resurfaced since McMurdo was formed. Third, in agreement with this, HiRISE images of McMurdo show very major structural modification of the crater, including what seem to be significant mantling deposits subduing much of the *N* rim (Fig. 7). Fourth, and most important, while McEwen et al. (2005) speak generally of "the paucity" and "the lack" of primary craters on the SPLD, we do see examples of probable primary impacts on McMurdo in MOC data, as shown in Fig. 7C.

In our view, the data about McMurdo are not inconsistent with the McEwen et al. test. There are several consistency arguments, all satisfactory. (1) If the general SPLD upper layers are 10–100 Myr old, and if the formation interval of a McMurdo on the SPLD is 90–180 Myr, then it is reasonable that we have one "fresh-looking McMurdo" with its larger secondaries still visible on the SPLD. (2) If the last resurfacing occurred 100,000 y ago, it is also reasonable that it postdates McMurdo, and that many smaller secondaries, but not all secondaries, have been lost, as noted by Schaller et al. (2005).

As shown in Fig. 7C, we see a few examples of apparent single, primary impact craters as large as 50–60 m on the south inner wall of McMurdo, suggesting that the McMurdo is at least as old as that

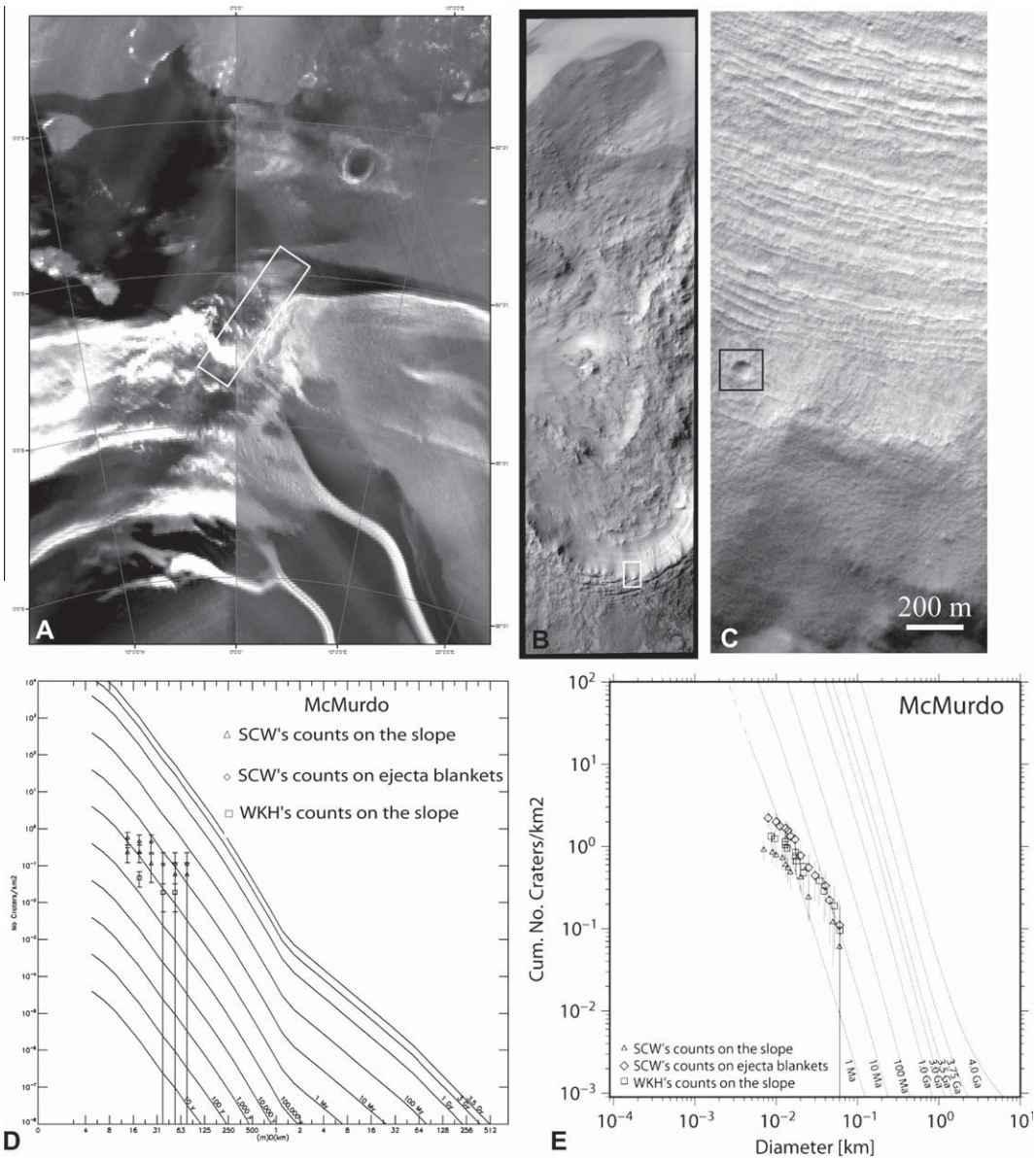

Fig. 7. McMurdo. (A) Regional view (THEMIS IR day time mosaic). (B) Higher resolution view of the crater, showing obliteration of north half of the rim (THEMIS VIS V09424010). (C) Detail of layered terrain near S rim, showing small impact crater (MOC R1304287). (D) Log differential plot of crater counts. (E) Cumulative plot of same crater counts.

population. Our counts of that population $D \sim 10$–60 m give crater retention ages (survival times) typically around roughly 1–20 Myr for craters of this size; this is the age characteristic of the last one or few of the highest obliquity excursions (typically 50–70°), hence it may be a dating of the last major climate excursions and mantling layers, if not of McMurdo itself. If the McMurdo region is undergoing substantial polar mantling, the interpretation of the small-crater statistics is complicated by small-crater loss processes. Our sparse crater statistics suggest that the size distribution of the decameter-scale craters is quite flat, as would be expected from a population subject to repeated cycles of deposition and crater infill by dust mantling associated with obliquity cycles (Mustard et al., 2001; Costard et al., 2001; Head et al., 2003; Levrard et al., 2004). Such flattening of the size distribution curve is well documented observationally and theoretically among larger craters on various older surfaces affected by deposition and erosion (Chapman et al., 1969; Hartmann, 1971, 2005). In keeping with the original definition of crater retention age (Hartmann, 1966), note that the crater density at any diameter D and depth d in the SPLD thus dates only survival time of craters *of that diameter and depth*. In the polar terrains especially, smaller craters are constantly being lost as the layered deposits accumulate, sublime, and/or erode. The largest craters we detected inside McMurdo, in the areas where we could make counts, suggest that McMurdo has probably existed for at least 10 Myr, and could be considerably older if the south inner "wall" (the best area for our counts) is not the original wall, but is an area where layered deposits have formed and been eaten away or exposed by insolation-dependent and slope-dependent erosive effects.

To summarize, the McEwen et al. (2005) argument that McMurdo should have formed "within the past 100 Ka," or represents a discrepancy in the crater chronology system by a factor of 1000, is refuted by the available evidence. McMurdo is not superposed on the last mantling or resurfacing of the SPLD. The cratering and superposition evidence related to McMurdo is satisfyingly consistent with an age of McMurdo in the range of >10 Myr to as much as 100 Myr or more. It formed on the SPLD and has been modified since by mantling and other processes, which produces the observed, flattened size distribution.

2.3. Tooting (23.4°N; 207.5°E, D = 29 km)

The third crater considered by McEwen et al. (2005) is Tooting (which was unnamed at the time of the McEwen et al. work). McEwen et al., working from an argument by Mouginis-Mark et al. (2003), concluded that Tooting is very young, and that there are "few or no superposed impact craters" at $D > 24$ m. McEwen et al. inferred an age of less than 17,000–68,000 y, according to our crater chronology systems, whereas the expected formation interval is about 5 Myr. They inferred from this that the chronometric systems are internally inconsistent by a factor >71. Mouginis-Mark and Garbeil (2007) restudied Tooting, however. They found superposed craters, and derived an age of 0.4–1.7 Myr, undercutting the McEwen et al. conclusion.

Like Zunil, the mid-latitude crater Tooting shows signs of ice interactions that affect the morphology and the crater counting. It has a well-defined rampart ejecta blanket, as shown in Fig. 8A. Interior morphology suggests fluvial modification during or since formation (Fig. 8C, upper right). As with Zunil, there is a major flow feature off the central peak, on the SW side (Fig. 4B) plausibly suggesting upthrust of ice-rich material. The floor is mostly covered by a heavily pitted formation. As with Zunil, we suggest the Tooting impact brought up melted icy material, which may have flowed and refrozen, subsequently producing sublimation pits. Tooting is located just off the W flank of Olympus Mons, a region found to be one of the two mid-latitude maxima in ice deposition rates at high latitude, according to climatic models of ice deposition by Forget et al. (2006).

The morphologic features make counting of impact craters on the main floor very difficult. In spite of the difficulties, we have detected substantial populations of craters (Fig. 8). Our counts were based on HiRISE coverage of the floor, including several relatively smooth surfaces off the sides of the central peak (Fig. 8C). Fig. 8C shows several isolated impact craters of D = tens of meters, with sharp raised rims, on flow or landslide surfaces just off the W side of the central peak. The population of craters we have measured ranges from ~ 3 m $< D \sim 100$ m. They give good evidence that surfaces inside Tooting and on its ejecta blanket fit close to our isochrons, giving model ages of at least a few Myr, refuting the discussions by McEwen et al. (2005). The isochron diagram suggests an expected formation interval of about 9 Myr and we conclude that the available evidence is consistent with this.

2.4. Gratteri (17.7°S, 160.1°W, D = 6.9 km)

Gratteri represents an example similar to Zunil. It was recognized with THEMIS nighttime IR images as having a spectacular ray system, in much the way Zunil was found (Tornabene et al., 2005). The interior of Gratteri presents similar interpretive problems. Although the crater is located at a relatively low latitude of $\sim 18°$, much of the floor is covered by a smooth layer that suggests a later mantle, perhaps like those described by Mustard et al. (2001). In several places, such as the west central floor, this layer appears to have been removed, exhuming an older, rougher surface. This can be seen in Fig. 9A, west of the central peak near the shadow.

On the one hand, the smooth layer is ideal for counting craters. The impact craters are clearly defined, with sharp rims (Fig. 3). If they are all primaries, they give only a minimum age for Gratteri, because the layer may have been deposited inside Gratteri at some unknown time after the crater formed. However, there is visible clustering with higher densities among the smallest craters in some parts of the smooth area, suggesting a sprinkling of very small secondaries (Fig. 3, south center). In that case, Gratteri is probably older than Zunil and/or other young primary craters that may have scattered such secondaries around Mars. Still, it is useful for our test, because McEwen et al. (2005) assert that ages derived from our isochrons are typically far too young.

For craters on the smooth floor deposit inside Gratteri, we accumulated counts in the diameter bins 4 m $< D <$ 45 m. The isochrons appear to give a consistent age of around 1–20 Myr (Fig. 9C and D). A best order-of-magnitude estimate would be 5 Myr for the mantle surface. Gratteri should be at least this old or older. The isochron system suggests that a formation interval for Gratteri-sized crater should be ~ 0.8 Myr. We suggest that Gratteri may not be the youngest ray crater in its diameter bin, and that the counts of small craters give an plausible consistent age for Gratteri, thus satisfying the McEwen et al. test.

2.5. Zumba (28.7°S, 133.1°W, D = 2.6 km)

Zumba, only 2.6 km across, is a smaller crater than the others and is useful in extending the probable age range of our examples. The isochron system suggests that craters in this size bin would form only ~ 0.1 Myr apart, on average. We would thus expect a very low crater density.

The actual density is hard to measure. The interior is occupied by steep walls with bouldery rubble at their bases, and by a floor that is very heavily pitted, as with Zunil, Tooting, and Gratteri. However, some small, clear impact craters, with sharp raised circular rims, can be seen, as in Fig. 10B, which shows the part of the ejecta blanket. Zumba has rampart ejecta, although it may not be the fully fluidized ejecta type that has been most often suggested

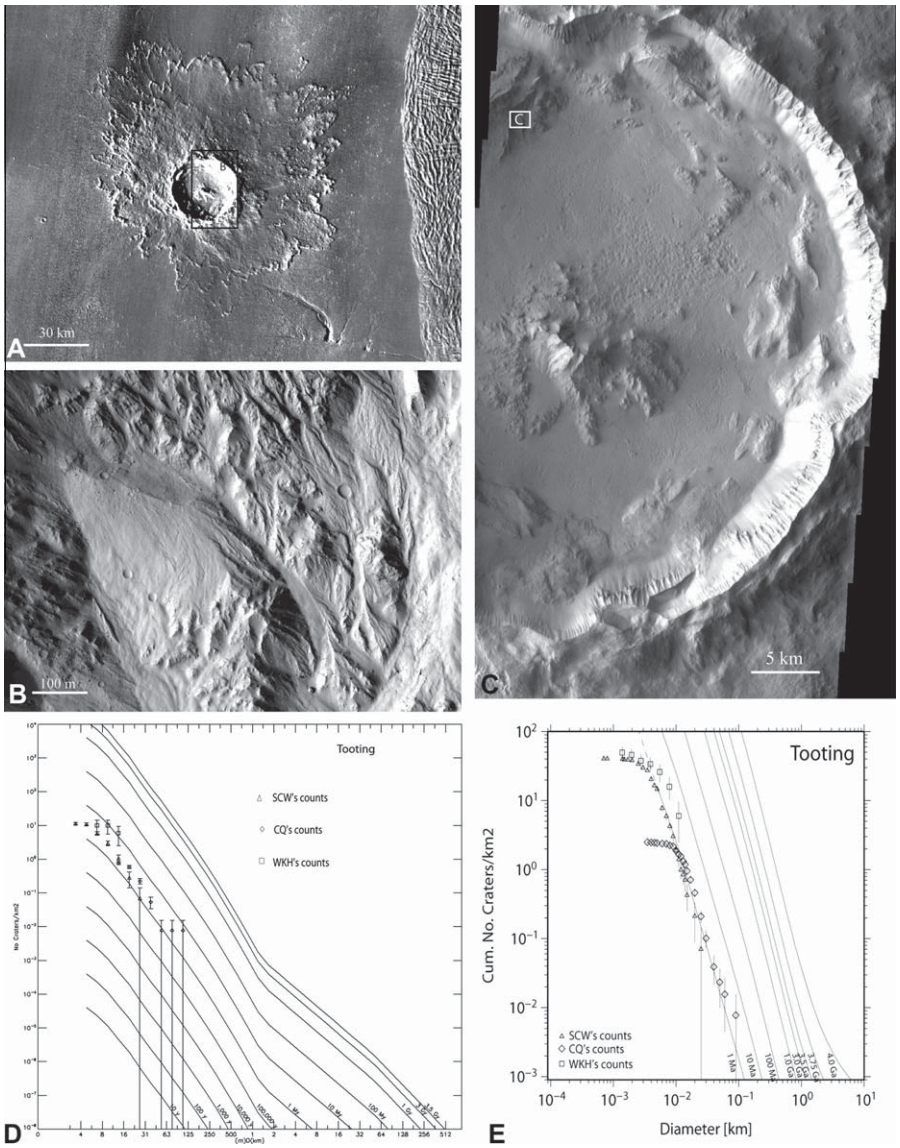

Fig. 8. Tooting. (A) Regional view showing rampart ejecta (THEMIS IR day time mosaic). (B) Part of crater and interior, showing floor deposits (THEMIS VIS V11439007). (C) Floor deposits near N wall, showing decameter-scale craters (HiRISE PSP_002158_2035). (D) Log differential plot of crater counts. (E) Cumulative plot of same crater counts.

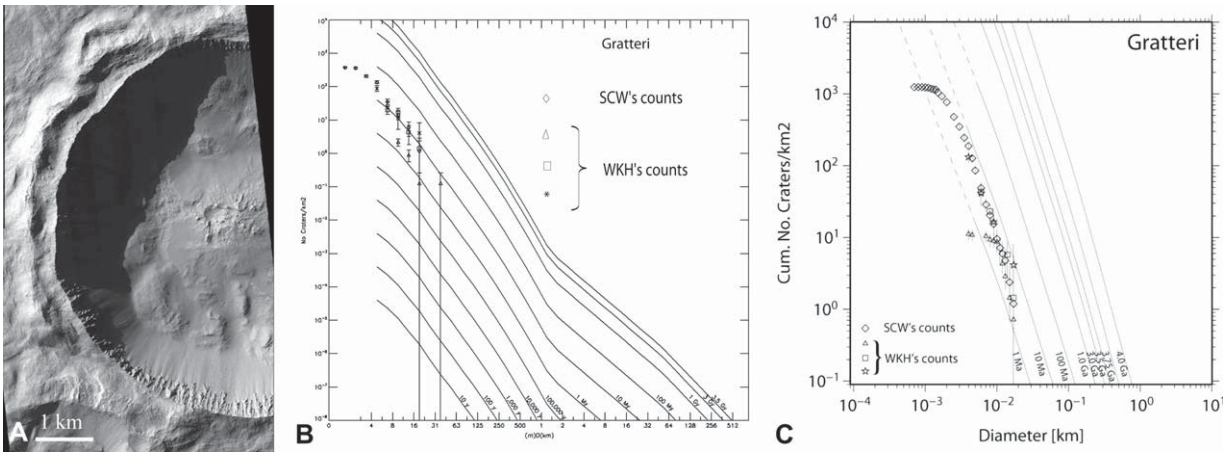

Fig. 9. Gratteri. (A) General view of crater showing rampart ejecta blanket (HiRISE PSP_001367_1620). (B) Log differential plot of crater counts. (C) Cumulative plot of same crater counts.

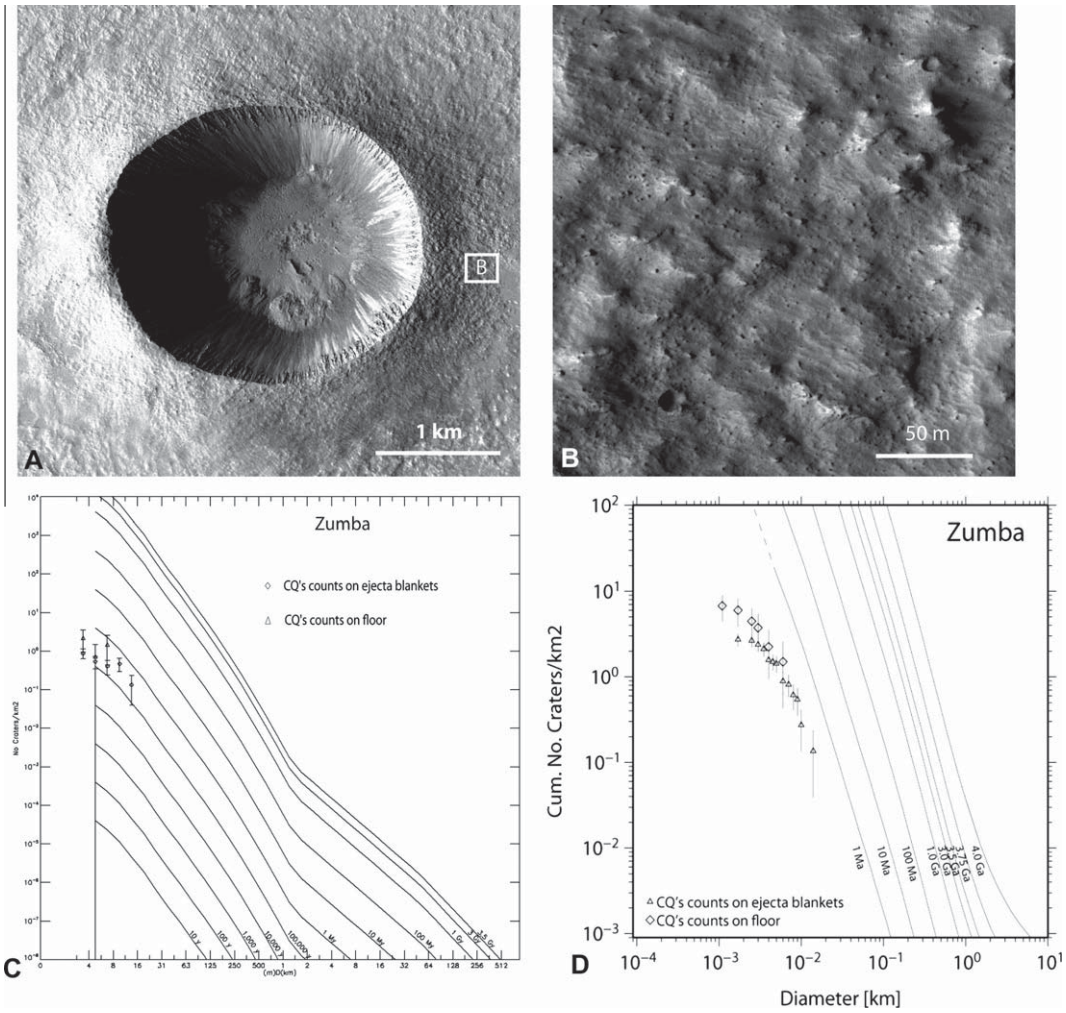

Fig. 10. Zumba. (A) General view of crater (HiRISE PSP_003608_1510). (B) Ejecta blanket, showing several craters (e.g., upper right, lower left) (HiRISE PSP_003608_1510). (C) Log differential plot of crater counts. (D) Cumulative plot of same crater counts.

to be evidence of volatiles in the subsurface. However, the floor has pitting that is suggestive of sublimation of ice.

Zumba, as the smallest crater studied here, should have one of the youngest crater retention ages reported here, if it is one of the youngest craters in its size bin. Counts were made by CQ both on the floor of the crater and on the ejecta blanket. These did give some of the youngest ages that we recorded, about 0.1–0.8 Myr.

We conclude that Zumba satisfies the McEwen et al. test.

2.6. Unnamed crater SW of Tomini (14.9°N, 123.3°E, D = 4.2 km)

This crater and its surroundings are shown in Fig. 11. An ejecta blanket exists but is not strongly lobate. For this relatively small crater, the formation interval is estimated to be about 0.4 Myr.

As plotted in Fig. 11, WKH made counts on several areas of the floor, giving a consistently much higher model age of a few Myr to 20 Myr. Even the youngest estimates would imply that the crater is more like the 10th youngest in its size bin than the youngest. The higher crater densities would imply that this crater is far from the youngest, and that the ray systems of even such a small crater can survive for as much as 20 Myr, at least in particularly favorable circumstances of target material.

If the crater is more than ~1 Myr old, it is possible that some of the small craterlets on the floor are secondaries from distant Zunil-like craters, but (by this hypothesis itself) the crater would have an age somewhat older than the estimated few hundred thousand years formation age and thus would satisfy the McEwen test. In fact, "SW Tomini" is completely enclosed in the ray field of Tomini (at around middle distance of the rays), but on night-time images, we do not see evidence of the Tomini rays overlapping "SW Tomini." The ray evidence we have seen seems not decisive as to which crater formed first. The question of near simultaneous formation by an asteroid and satellite might be considered.

In any case, this crater appears to avoid the problem advanced by McEwen et al. (2005), in which the isochrons allegedly gave ages hundreds of times too small. It is our single example of a crater count age that strains the bounds of acceptability, vis-à-vis the McEwen et al. test, but in the direction of being older than expected, not younger. Therefore, we conclude the test is not violated.

2.7. Tomini (16.3°N, 125.9°E, D = 7.4 km)

Tomini (Fig. 12), like Zunil and Tooting, shows signs of impact into ice-rich target material. It has a massive flow feature off its central peak, shown in Fig. 4C. Relative to the crater dimensions, this one appears even larger than the ones in Zunil or Tooting. The formation interval, or youngest crater in this size bin, is expected to be ~0.9 Myr.

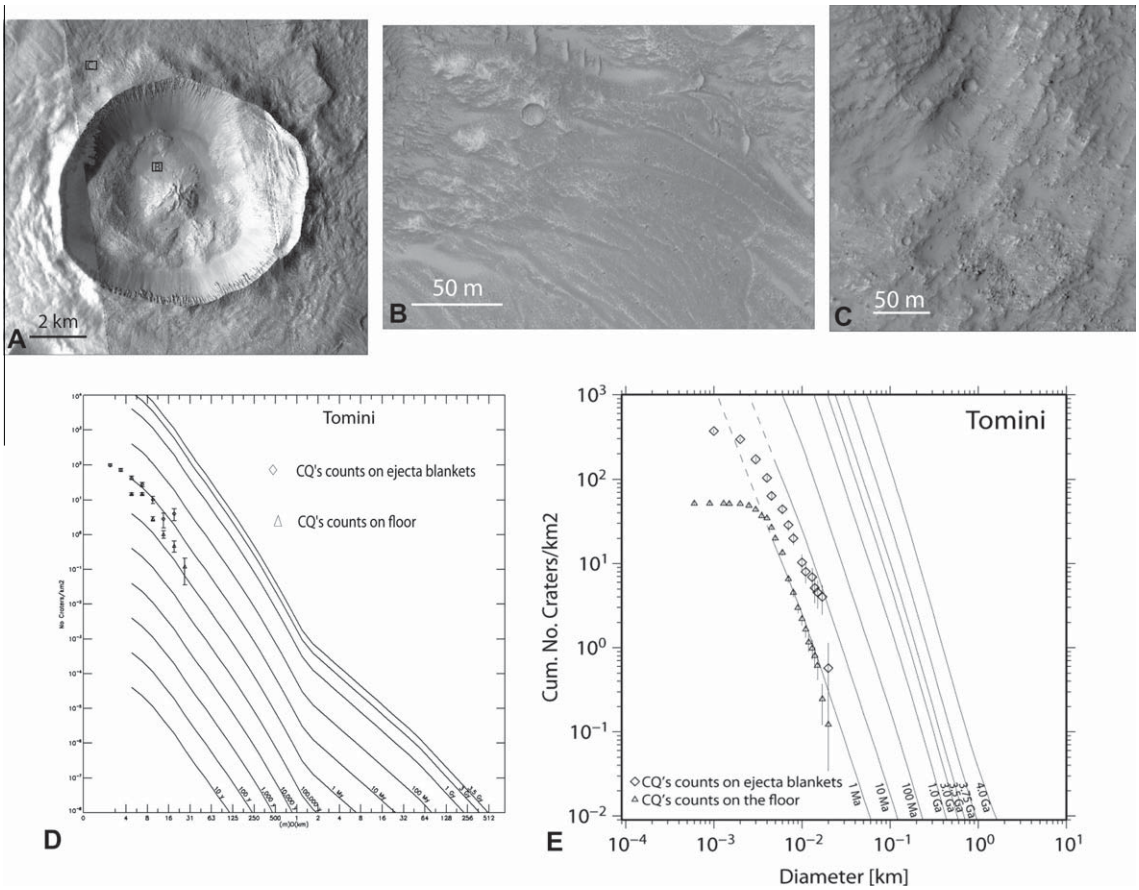

Fig. 11. Tomini. (A) Regional view (HiRISE PSP_001871_1975 on THEMIS VIS V14387010). (B) Examples of craters on N central floor (HiRISE PSP_001871_1975). (C) Example of craters on ejecta blanket (HiRISE PSP_001871_1975). (D) Log differential plot of crater counts. (E) Cumulative plot of same crater counts.

Crater populations are found on both the floor and the ejecta blanket (Fig. 12B and C). CQ made separate counts on each area. The CQ counts show an older age for the ejecta blanket than for the floor, perhaps 4–10 Myr for the former and 1–3 Myr for the latter (based on both the Hartmann isochrons in Fig. 12D and the Werner/Neukum isochrons in Fig. 12E). The CQ counts on the floor were on a relatively smooth area close to the central peak (see box in Fig. 12A). A flow off the central peak (possibly contemporaneous with peak formation) is superposed on the floor (Fig. 4C), and so it appears questionable whether the floor deposits would be much younger than the crater itself and its ejecta blanket.

We conclude that Tomini is one of the younger craters in its size bin and that it passes the McEwen et al. test.

2.8. Unnamed crater, SW flank of Elysium Mons (16.9°N, 141.7°E, D = 13.7 km)

This young-looking crater (Fig. 13) was first noted by the HiRISE team and reported on their web site. The formation interval is expected to be ~3 Myr. It has a rampart ejecta blanket and the floor is very pitted, supporting that the target material may have been ice-rich. A crater population is visible on the ejecta blanket (Fig. 13B).

CQ made counts on the ejecta blanket, using a THEMIS visible image and on a HiRISE image. These counts do not fit the isochrons as well as the counts of most of the other craters, but rather have a systematically flatter slope than the isochrons (Fig. 13C and D). Such flattening is typical of long-term, gradual losses (see discussion under McMurdo). Possibly, mantling or dust deposition has been acting to obliterate the smaller craters. In this case, the largest craters are most useful in setting at least a lower limit on the age of the crater. Interpreting the data, we ignore the single large crater ($D \sim 900$ m) because it is so far off the curve defined by the others. We assume it is a statistics-of-one fluke, an unusually recent impact for its size. The remaining population suggests that the larger craters approach an isochron and model age around 2–9 Myr (cf. Table 1).

3. Time dependence of cratering rate: effect on absolute ages

Both the Neukum and Hartmann crater chronometry systems assumed (consistent with other researchers of the time), for lack of better data, that the cratering rate after about 3 Gyr ago has been more or less constant. Some data suggested a slight decrease, and some a slight increase. Hartmann (1972) and Neukum (1983) used Apollo/Luna data to detect a steeply declining rate around 3.9–3.0 Gyr ago. Hartmann's "2004 iteration" (Hartmann, 2005) isochrons assumed a near-constant rate after that, and Neukum (1983) gave a curve of cratering rate vs. time that declined by only <10% after about 2.8 Gyr ago.

Quantin et al. (2007) and Hartmann et al. (2007), however, in a linked pair of papers, proposed evidence that the cratering rate on Mars and the Moon has decreased by as much as a factor three since ~3 Gyr ago. This suggestion came from martian landslide crater counts, and also from lunar impact melts and impact glasses. If this suggestion is correct, all our crater count model ages and formation intervals in the last 100 Myr or so would be increased by about a factor three. This correction factor would decline for older ages.

However, the issue of cratering rate vs. time is still more complex. Dating of L chondrites has suggested a major asteroid

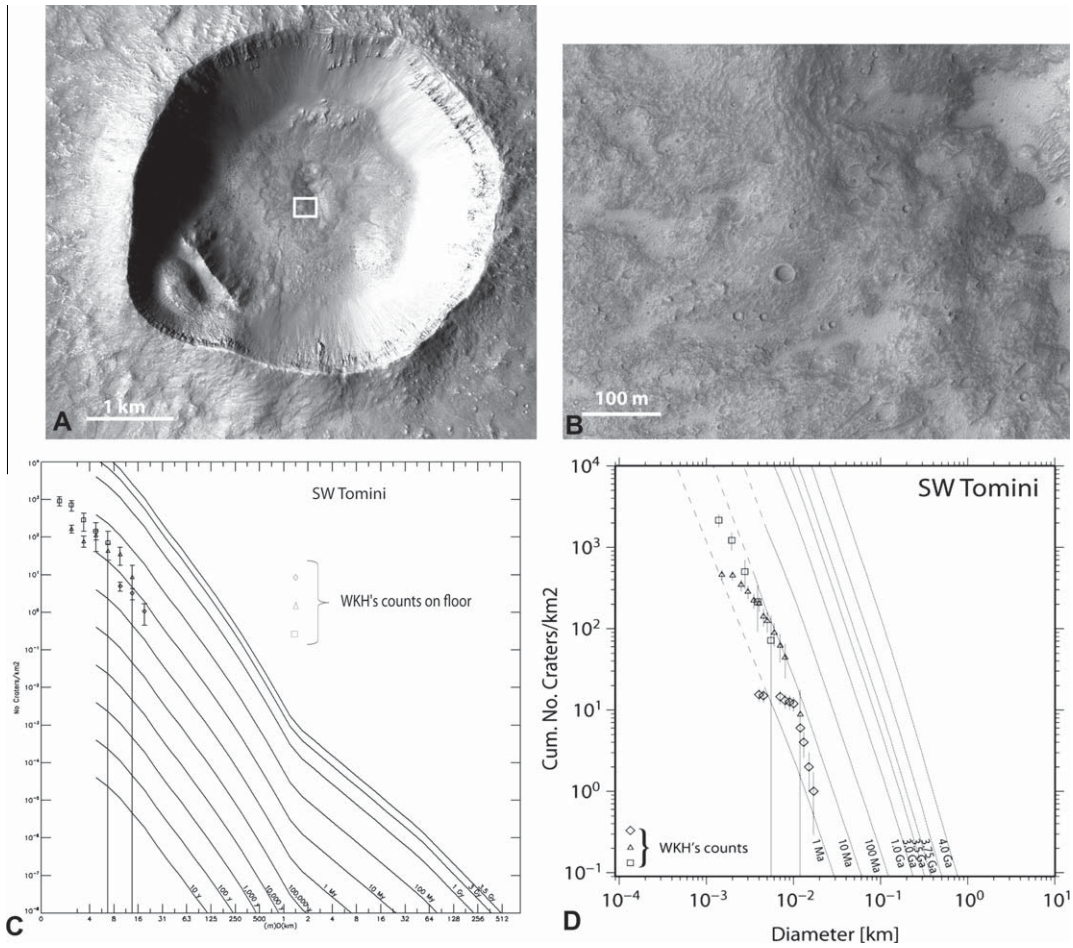

Fig. 12. Unnamed crater SW of Tomini. (A) General view of crater (HiRISE PSP_001660_1950). (B) Detail of hills NW of center, showing several decameter-scale craters (HiRISE PSP_001660_1950). (C) Log differential plot of crater counts. (D) Cumulative plot of same crater counts.

breakup event around 470 Myr ago (Bogard, 1995; Trieloff et al., 2006), and excavations of "fossil L chondrites" in Swedish limestones dramatically confirmed a shower of L chondrites at about 470 Myr ago (Schmitz et al., 1997, 2003). The large spike in lunar glasses at this time suggests that the Moon and inner Solar System, generally, may have experienced a strong wave of these impactors (cf. Hartmann et al., 2007). The impact rate at larger sizes may not have been affected, since a given asteroid collision can produce fragments only up to a specific cutoff size. The survival half-life to sweep up Earth-crossing fragments from main belt asteroids, governed by belt resonances and collision lifetimes with inner Solar System planets, is about 5–50 Myr (Wasson, 1985, pp. 59–61), so the L chondrite spike should have ended on that timescale. The wave of impacts, however, could have affected the recent average cratering rate, relative to the long-term decline. This event shows that the decameter-scale cratering rate is, to some extent, decoupled from the cratering rate for larger craters. The smaller the crater size, the more dependence of swarms of impacts from individual asteroid breakups. Thus, it is possible that decameter craters on Mars experienced at least one significant short-term peak during the last few hundred Myr, without the larger craters being affected.

Hence, we must be cautious about whether the production rate of decameter-scale craters, as a function of time, is so spiky on timescales of a few Myr that the ages we derive from decameter-scale craters, for young km-scale host craters, is grossly unreliable.

On the positive side, the L chondrite event seems to have been the largest even in the last 1 Gyr. Events of this size apparently do not happen within the last few Myr (nor are they expected from asteroid collision models). Thus, although the curve of cratering rate vs. time surely has some spikiness on a timescale of tens or hundreds of Myr (with 5–50 Myr decay times), the spikiness becomes akin to a constant noise level for surfaces older than a few hundred Myr, so that the model ages for features older than a few hundred Myr (~90% of the age of Mars) may not be grossly affected by the sporadic events. If smaller-scale asteroid breakup events happened in the last few Myr, then the main problem in the context of this paper is that we live in the time coinciding with an anomalously high, short-term impact flux. In that case, model ages from decameter-scale craters, within the last few Myr, should be decreased. This effect thus acts against the possible effect of a long-term increase. It is even possible that two effects, long-term decline vs. an anomalous short-term spike, may somewhat cancel for model ages derived from small craters in the last few Myr. Note that in this paragraph, we are assuming asteroid belt collisions that affect only the decameter-scale martian craters, without being major enough to affect the production rate of the 2–29 km "host craters" discussed here.

To summarize, in spite of the spiky nature of the cratering rate at small sizes, we so far have no strong empirical or theoretical evidence that the cratering rate during the lifetime of the young ray craters studies here has been anomalously high or low. In any case,

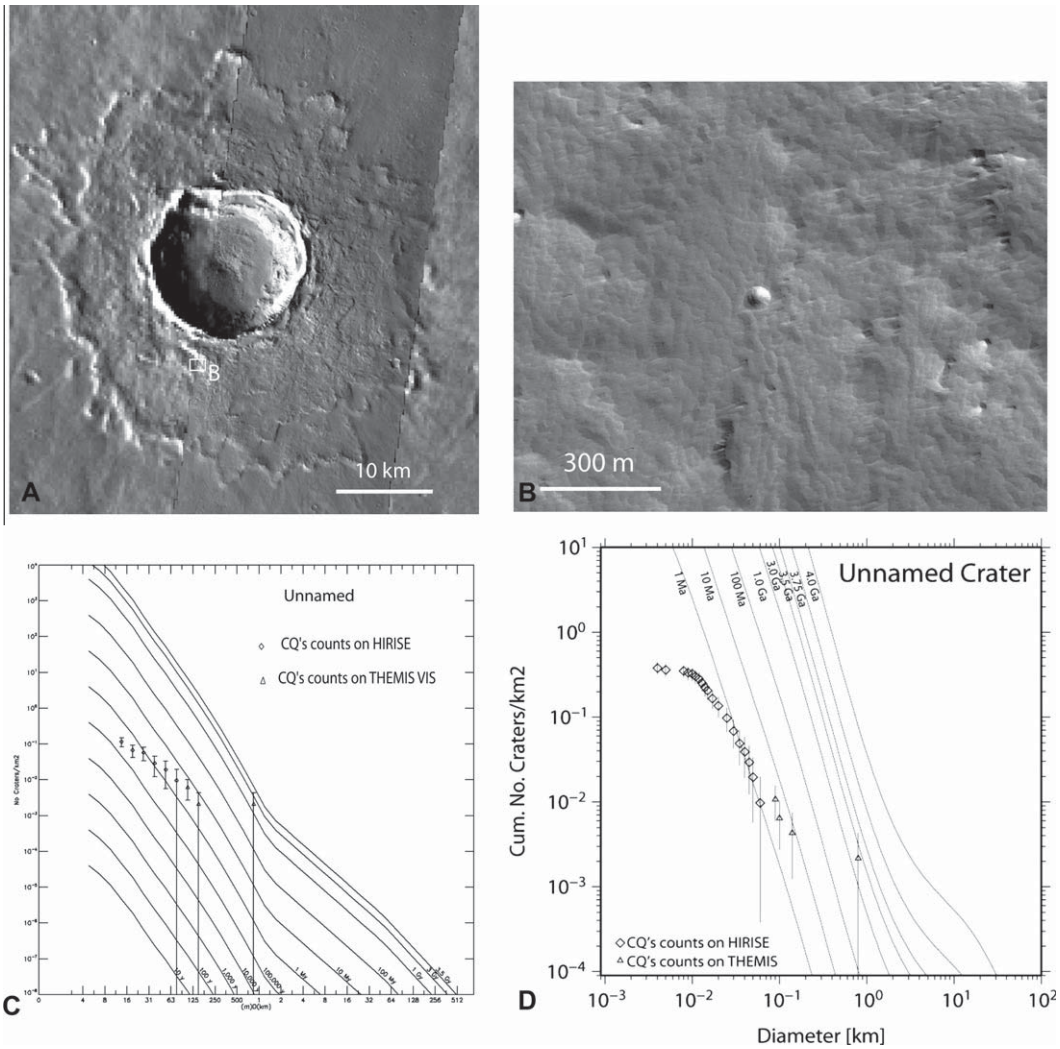

Fig. 13. Unnamed crater on SW flank of Elysium Mons. (A) Regional view showing rampart ejecta (THEMIS VIS V 08521012 on THEMIS IR day time mosaic). (B) Portion of ejecta blanket (HiRISE PSP_004244_1970). (C) Log differential plot of crater counts. (D) Cumulative plot of same crater counts. The largest (fluke) crater is considered to be a statistical fluke and is not considered to indicate the host crater's age.

both the Neukum and Hartmann isochron models attempt to average over the 10–20 Myr spikes due to asteroid collisions.

4. Example of older surfaces

The reader at this point may propose that since most of our measures of decameter-scale craters are producing ages in the range around 0.1–20 Myr, these ages have nothing to do with the craters themselves, but rather are simply a result of universal erosion at small scales all over Mars. This is not the case. Many martian areas exist in which decameter-scale crater densities are one or two orders of magnitude higher than the densities we have discussed, and in some cases are in saturation equilibrium (cf. Hartmann, 2005). As an example, we counted HiRISE-imaged craters in the summit calderas of Arsia Mons and Elysium Mons. These surfaces are much older than the craters we discuss here. Arsia Mons, averaging over slopes and summit caldera, was discussed by Hartmann (2005, pp. 311, 313) as having mean ages of 200–1000 Myr. Neukum and the HRSC team (2004) and Werner (2005) dated flows on the summit caldera floor of Arsia at about 130 Myr. Werner (2005) dated the Elysium caldera as having an overall age of 3.5 Gyr, with resurfacing at 1.6 Gyr. Werner (2009) reviews current evidence on the extended history of martian volcanism.

On a HiRISE image of Arsia Mons, WKH counted two small areas at highest resolution (one selected visually as appearing more densely cratered than the other), and CQ counted the whole frame at artificially reduced resolution. As shown in Fig. 14, the counts generally follow the isochron production shape, and are consistent with an average age for the surface lavas of a few hundred Myr, with the small craters at saturation levels below diameters ~32 m.

All our crater density measurements on older surfaces are much higher than densities on any of the young crater surfaces we have discussed. The conclusion of this section is that several large volcanoes display ages in the 10^8–10^9 y range, not inconsistent with the range of radiometric ages reported for many martian igneous meteorites. The correlation of low densities of decameter craters on suspected young host craters, and high densities on proposed older surfaces, supports our contention that the small crater densities, at least in some cases, do contain valuable age information, in spite of concerns about secondary cratering phenomena.

5. Conclusions

McEwen et al. (2005) proposed a useful test of crater-count methodologies, and we have applied it to the three craters they discussed, with higher resolution images than they used. We discuss five more young ray craters besides. In all eight cases, contrary

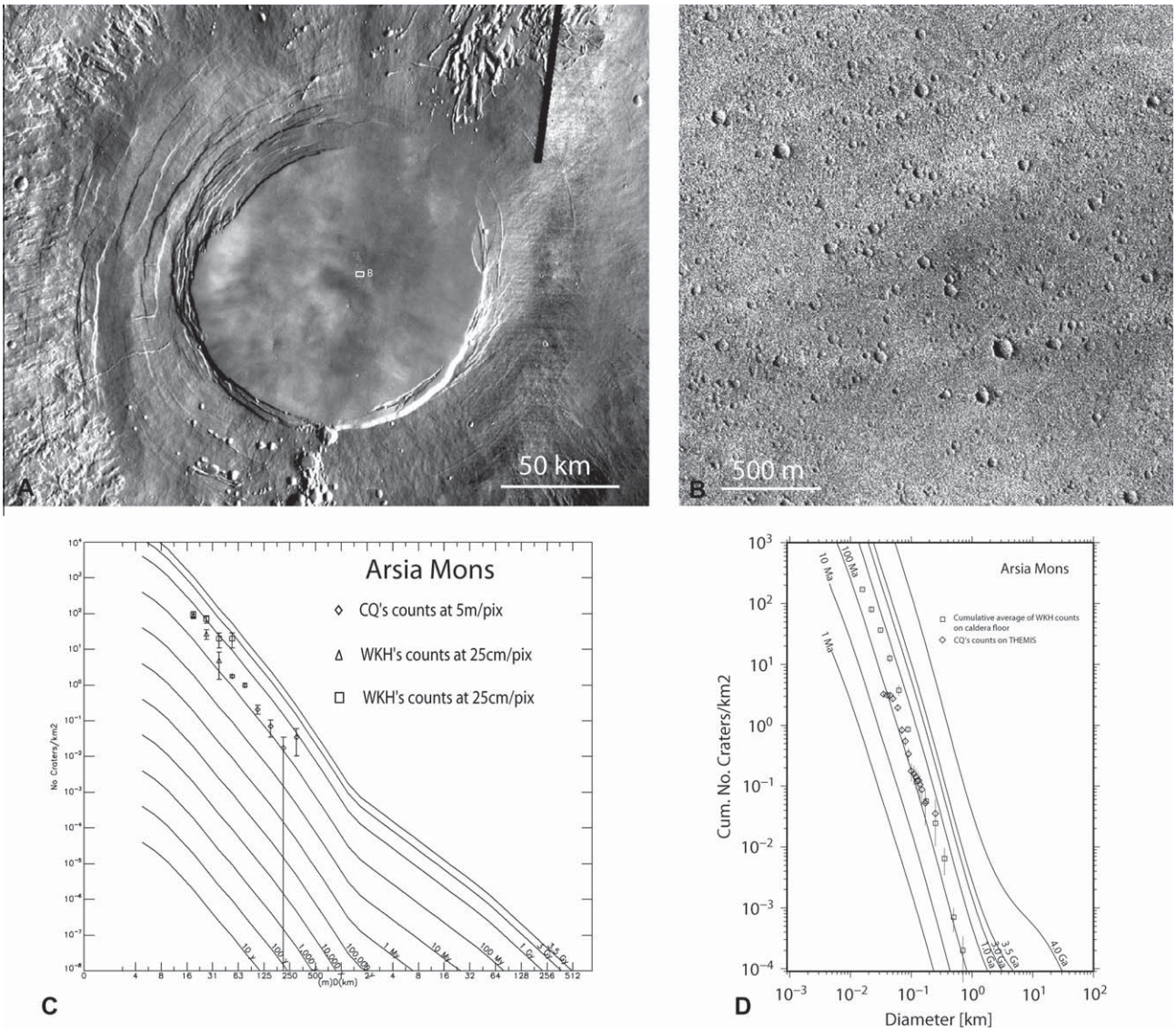

Fig. 14. Arsia Mons. (A) Caldera context image (THEMIS IR day time mosaic). (B) Example of craters on the floor of the caldera (HiRISE PSP_004702_1705). (C) Log differential plot of crater counts. (D) Cumulative plot of the same data.

to their results, we conclude that the decameter-scale crater populations, as interpreted by existing crater-count methodologies, give results consistent with the formation intervals expected from larger craters, and thus pass what we call the "McEwen et al. test." In our view, we have shown that the McEwen et al. (p. 378) conclusion, "Ages ... based on Hartmann-Neukum production functions for small craters suggest highly improbable events in the last 10–1000 Ka" is incorrect. The discrepancy in result arises mainly because the images they used in their pioneering work lacked the resolution necessary to detect the populations of decameter-scale craters necessary to perform the test, but arose also from a misunderstanding of what Hartmann was plotting. We conclude that the existing crater chronometry systems give results as good as can be expected, given the stochastic nature of the "youngest rayed host craters" that must be chosen for the test.

Contrary to our expectations, we found that the youngest ray craters' floors at decameter scale do not display "simple" excavational/depositional geology attributable to impact processes alone, but "complex" geology that appears to involve formation of lobate flows off the central peaks, heavily pitted floors and, in some cases, smooth mantle-like deposits. We suggest that these features, along with rampart ejecta, involve impact into ice-rich target substrates, even in equatorial regions. In these cases, central peaks may bring up melted ice, forming muddy slurry-like material that forms the observed lobate flows off the peak and then re-freezes. Some of these kinds of features are probably lost rapidly over millions of years due to sublimation of the ice, which destroys initial flow morphologies and may produce loose dust deposits removed or augmented by eolian processes. This would explain the rarity of such striking ice-related features in older craters. These conclusions support the McEwen et al. (2005) inference that Zunil tapped into ice-rich materials at depths of 400–700 m.

Further work is warranted in applying the McEwen et al. test to other craters. It may be possible to rank the youngest ray craters, in the different $\sqrt{2}$ diameter bins, according to age, and thus to characterize the timescale on which ray structures and the internal ice-related structures are lost. Because the formation rate of decameter-scale craters on Mars has actually been observed, the decameter-scale craters have great value in dating young, small (10-km scale) martian formations, but better understanding of

the formation rate of decameter scale primaries will be needed for surfaces older than a few 10^5 y. Refinements in crater chronometry can be made as the formation rate of decameter-scale and hectometer-scale craters, by both primary and secondary cratering processes, becomes better understood.

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