MARTIAN CHRONOLOGY: TOWARD RESOLUTION OF THE 2005 "CONTROVERSY" AND EVIDENCE FOR OBLIQUITY-DRIVEN RESURFACING PROCESSES. William K. Hartmann, Planetary Science Institute, 1700 E. Ft. Lowell Rd., Ste 106, Tucson AZ 85719-2395 USA; hartmann@psi.edu

Direct Observations of New Crater Formation Confirm Our Isochrons: Malin et al. [1] recently reported discovery of 20 Martian impact sites where new craters, of diameter D = 2 m to 125 m, formed in a seven-year period. The craters formed at different times and appear to mark primary impacts, not secondaries. The Malin et al. results match their earlier result (MGS web site www.msss.com), proposing a small crater formation rate for the last 100 years. As seen in Fig. 1, their two data sets both match the crater formation rates I have used [2] in estimating crater retention ages of surfaces on Mars. Even if only half their detections are correct, their rate is still within about an order of magnitude of the rate I have used to construct the isochrons in Fig. 1. My more complete report is in press in *Icarus*.

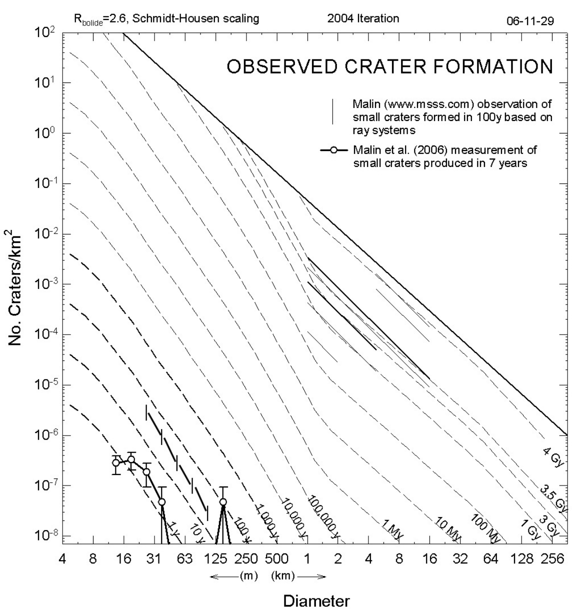


Fig. 1. Isochron diagram showing measurements of current crater production by Malin et al. [1, and www.msss.com]. The reports of new craters forming Mars in 100 y (vertical tick marks) and 7 years (data points with error bars) fall about a factor 2 to 3 below our isochrons for 100 and 7 years, based on [2].

Ending the So-called Crater Controversy: The new observations, if correct, help resolve a widely-publicized controversy about the Martian timescale and the origins of small decameter-scale craters on Mars, aired at earlier 6th International Conference on Mars [3]. Some of the controversial issues are now moot, and others can be answered.

First, many authors have repeated a statement that crater counting yields useful ages only if the craters used are all primaries [3-6], and have indicated that my isochrons plot my estimates of the number of primaries [5]. This is incorrect. I have consistently attempted since ~ 1967 to measure the background buildup of primaries plus scattered distant secondaries as a function of time (outside obvious clusters and rays) on various geologic formations [7]. This approach was also recommended in the multi-author 1981 Basaltic Volcanism Study Project volume [8].

Much of the "controversy" was framed around the ratio of secondary (S) to primary (P) craters [3,5,6]. The implication was that crater counters try to sort P's from S's, so that if they mistake S's for P's, the method fails. This is wrong in my case, because I do not sort P's from S's, but count the total of scattered "field craters,", as noted above. Neukum's work [9], in particular, was criticized because he argued that nearly all small craters are P's. There is an important subtlety: because Neukum assumes that most craters are primaries, he and his co-workers count essentially the same total number of craters that I do. Thus, whatever Neukum, Hartmann, or others happen to suspect about the P/S ratio makes negligible difference in the actual counts; both of our systems are based on the total number of "field craters" outside obvious clusters and rays. Hence, the question is not the P/S ratio, but rather the total production rate of craters – which has now been measured by Malin et al., and is consistent with our system.

A second critique [6,10], in response to the above, was that secondary craters are non-randomly clustered, according to statistical tests, and if they are non-random, the mix of field craters cannot be used for dating. The assertion of non-randomness may be true at some level of detail, but the practical effect on our chronology has not been demonstrated. We generally make multiple counts of small-scale "field craters" on different hi-res images within a larger province that has been mapped as homogeneous, and the counts are generally repeatable within the error bars we quote. An example is shown in Fig. 2. Also, Quantin studied more than 40 landslides in Valles Marineris, and in every case the crater density on the landslide was ≤ the crater density on the background, indicating that non-random clustering does not overwhelm the chronologic signal [11].

A third critique was that in many Martian areas, the crater counts do not fit the isochrons, but cross them at a lower slope, and that this implies the system is faulty [12]. The observation is correct, but the conclusion is not. For years, crater counters have observed this effect, but have repeatedly affirmed that in the youngest, best-preserved surfaces (apparently lava plains), crater counts converge toward a repeatable "production function" size-frequency distribution (PFSFD) – the SFD used in my isochrons [2,8,9,13]. To respond to this critique, I made new counts in a very young lava area suggested to us by Ken Tanaka in 2006; the counts show a particularly good fit to the PFSFD isochron shape I have used (Fig. 2), reaffirming that the PFSFD is verifiable.

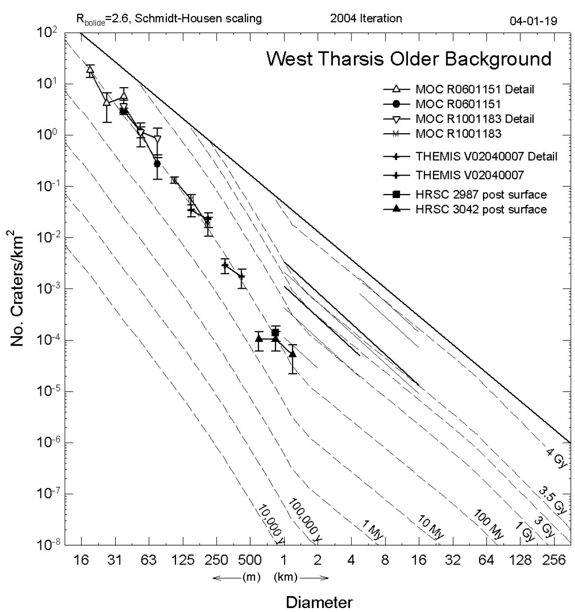


Fig 2. Confirming the production function SFD on lavas in in east Amazonis Planitia/west Tharsis. (a) Formation was suggested by Ken Tanaka as good area for testing PFSFD. Counts from MOC, THEMIS, and HRSC show excellent confirmation of isochron SFD shape. Note that counts from each image are plotted separately and show excellent repeatability in fitting the 100 My isochrons.

Support for the Overall Crater Chronology: Contrary to the various criticisms and claims of "controversy," all the direct empirical lines of evidence, including lunar mare ages measured by Apollo, the cratering rate observed by Malin et al. [1], and the ages of the Martian basaltic lava meteorites, are now internally consistent with the published crater count chronologies. No critics have suggested an alternative chronology. Another support is that the independent Neukum and Hartmann systems derive essentially the same ages. Also, in the case of the broad Martian lava plains, which are thought to be the source of basaltic lava Martian the meteorites, the crater count ages are consistent with the meteorite ages – typically a few hundred My.

What does this chronology say about Mars? The current chronology, as developed by Neukum, myself, and various coworkers [7-9, 11,13,15-18], suggests that Noachian geologic processes of cratering, volcanism, fluvial activity, and probably glaciation before about 3.0-3.5 Gy, were about 2 orders of magnitude higher than the Amazonian rate [13]. The Noachian activity was followed by dwindling but continuing sporadic volcanism, fluvial activity, and glaciation into modern geologic time, with some sporadic examples of all four of the above processes dated within the last 50 My (last 1% of Martian history). Neukum [9,13], Hartmann [2,8,13,15], Werner [19], McEwen et al. [5], Burr et al. [20], Quantin [11], and others find substantial geologic activity, including lava flows, fluvial activity, glaciation, mantling, and numerous landslides, within the last 5 to 100 My.

Toward Synthesis of Observations by Malin and McEwen Groups: If Malin et al. are right about P crater production, it does not necessarily mean that McEwen et al. are wrong in emphasizing the role of S's. In the current view by McEwen, myself, and others, secondaries are not expected on a random surface in first 10^5 to 10^6 y because we have to wait for a parent P crater of D ~ 3-10 km [5,16,17] to form somewhere on Mars. For those surfaces, we can use the newly discovered Malin et al. rates to measure crater retention ages, but on older surfaces we have to consider combined effects of P's+S's. The "worst case scenario" occurs on surfaces around 1 My old, because we don't know if small craters are mostly Malin et al. P's, or P's + a flock of McEwen et al. S's from a single Zunil-like P. However, as I've pointed out [16,17], if we look at surfaces older than 10 My-100 My, then S's from ~ 10 to ~ 100 of Zunil-sized P's have accumulated. At that point, the distant S's themselves become part of the noisy but quasi-random accumulating background. One more distant Zunil adds only ~ 1% to the total number of small S's.

Figure 3 shows a preliminary combined "Malin + McEwen" model. I used the reported Malin et al. flux [1] for 10 My and 100 My, and then added the widely scattered secondaries predicted by McEwen et al. [5] from 10 and 100 Zunils, respectively. The total numbers in the decameter size range actually straddle my 10 My and 100 My isochrons. The model is crude. It does not take into account the full size range of P's, and the size distributions need to be refined – but the overall principle is clear: on surfaces older than 100 My, the Malin data on P's, the McEwen estimates of S's, and my isochrons may all be consistent. This is supported by a conclusion of McEwen et al. [5]. After they indicated (incorrectly) that my isochrons reflect only P's, and that my isochrons are off by 2000, they presented their own new estimate of the age of surfaces in Athabasca Vallis – which agreed with age estimates we published three years earlier for the Athabasca-Marte Valles complex [19] (and with ages by Burr et al. [20]) also published three years earlier. Thus, in spite of a widely perceived "controversy," we are actually consistent, and the reason is that the McEwen et al. [5] estimate of S's more or less matches our isochrons (as well as the accumulation of Malin P's [1]). Interestingly, this result may suggest that the P/S ratio is in the range of 1/10 to 10, among the 10-20 m "field craters," although it is too early to reach conclusions about this ratio.

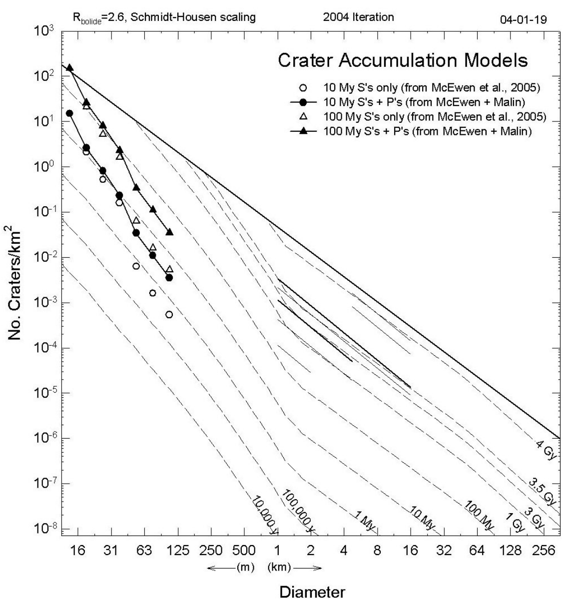
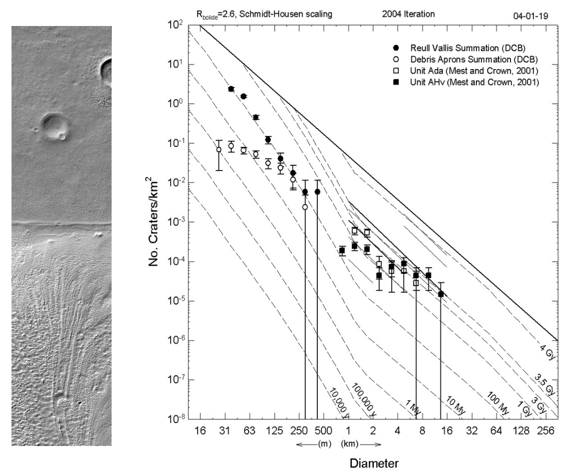


Fig. 3. Isochron diagram showing calculated size distributions of "Malin P + McEwen S" craters, scattered over most of Mars. Although the assumed SFD shapes are different from what I have used, the general curves are close to my isochron values, 10 and 100 My after surface formation

Obliquity-driven Climate and Resurfacing Cycles: Example of the Opportunity in Crater Dating: The Malin et al. report of crater formation rate opens the door to direct dating of Martian small formations. Among the most interesting Martian formations are glacier-like features and debris aprons that give a strong suggestion of ice-related flow. An example of the new potential for chronologic study appears in Fig. 4, showing that the debris apron surface is strongly deficient in small craters relative to nearby surfaces. An age derived from the isochrons for small craters, D = ~ 20 m, is about 1-8 My. For craters larger than 16 m, the crater production rate from the Malin et al. data is $9(10^{-8})$ craters/km^2-y, and the age derived from counts divided by Malin production rate is ~1-3 My. In a variety of additional glacier-like and possible ice-flow terrains and mantling terrains, I have repeatedly derived ages in the general range of a few My to a few tens of My, and this is order of magnitude is supported by the direct Malin et al. observation [1].



(a) **(b)**

Fig. 4. (a) Edge of debris apron (bottom) and surrounding plain (top; MOC E0101294, 2 km wide). (b) Crater counts by Crown, Berman, and Hartmann on a nearby plain show production function size distribution matching an age of 100 My, but counts on the apron show that small craters are being lost. Craters of D ~ 20 m last only ~ 1-8 My, probably due to losses by sublimation or deformation during ice flow.

This age range is exactly the range of the last few periods of high obliquity (> 45°) [20, 21,22], as suggested by Costard and coworkers [21]. Estimates of sublimation rates on Mars also imply it would be hard to defend ages ≥ 100 My for ice flow features.

These data support the idea that we are seeing an array of ice-flow, glacier-related, and mantling features on Mars associated with ice deposition and cyclic deposition during climate changes caused by the last few cycles of high obliquity on Mars with in the last tens of My.

Summary: Contrary to recent perceptions, the discovery of ongoing production of decameter craters means that researchers can date crater retention ages (i.e., rock formation events, exhumation events, and other generalized resurfacing events), even on small and young formations. Table 1 summarizes some internally consistent, direct observational data on the Martian chronology. Further opportunities abound, and we must continue trying to learn how to read the record of accumulating small craters.

References: [1] Malin M. C. et al. (2006) *Science, 314,* 1573-1557. [2] Hartmann W. K. (2005) *Icarus, 174,* 294-320. [3] McEwen A. S. (2003) 6th Intl. Conf. on Mars, Abstract #3268. [4] Chapman C. R. (2004) 2nd Conf. on Early Mars, Abstract #8028. [5] McEwen A. S. et al. (2005) *Icarus, 176,* 351-381. [6] McEwen A. S. and Bierhaus E. B. (2006) *Ann. Rev. Earth Planet. Sci., 34,* 535. [7] Hartmann W. K. (1967) *Lunar Planet. Lab. Comm., 6,* 31-38. [8] Hartmann W. K. et al. (1981) in Report of Basaltic Volcanism Study Project, Pergamon Press, Elmsford. [9] Neukum, G. and B. Ivanov (1994) in *Hazards due to Comets and Asteroids (T. Gehrels, Ed.*), pp. 359-416, Univ. Arizona Press, Tucson. [10] Bierhaus, E. B. et al. (1995) *Nature*, *437,* 1125-1127. [11] Quantin, C. et al. (2004) *Icarus, 172,* 555-72. [12] Plescia, J. (2005) *LPS XXVI,* Abstract #2171. [13] Hartmann W. and Neukum G. (2001) in *Chronology and Evolution of Mars*, Eds. R. Kallenbach, J. Geiss, and W. K. Hartmann. (Bern: International Space Science Institute; also *Space Sci. Rev., 96,*165-194.) [14] Hartmann, W. (1965) *Icarus, 4,* 157-165. [15] Hartmann, W. (1973) *J. Geophys. Res*., *78,* 4096-4116. [16] Hartmann, W. (2006) Bull. Amer. Astron. Soc., Abstract. [17] Hartmann, W. (2007) *Icarus,* in press. [18] Werner, S. (2005), Ph.D. thesis. [19] Berman D. C. and Hartmann W. (2002) *Icarus, 159,* 1-17. [20] Burr, D. et al. (2002) *Icarus, 159,* 53-73. [21] Costard F. et al. (2001). *Science, 295,* 110-113. [22] Laskar, J. et al. (2004) *LPS XXXV*, Abstract #1600.

TABLE:
TOWARD A MARTIAN CHRONOLOGY
See more detailed table, discussion, and additional references in [2]

< 5-50 My	Most recent high obliquity cycles, glaciation, mantling & younger landslides. Youngest lavas in Cerberus, Amazonis, Olympus Mons [2,5,8,11,13,15,20]
Few Ma to 200 Ma	Unusually young major outflow channel (Marte/Athabasca Vallis) [5,18,19]
170 Ma	Basaltic lava flow in unknown locations (most basaltic shergottites)
100-1000 Ma	Lavas in Elysium, Amazonis, Cerberus, Olympus Mons [2,8,13,15]
300-500 Ma	Lava flows (2 basaltic shergottites)
≤ 670 Ma	Transient water exposure in nakhlite Lafayette, unknown location
1.3 Ga	Igneous rock-forming episodes, unknown location (Nakhlites)
~2-3.2 Ga	**Amazonis/Hesperian boundary (poorly constrained [13])**
~3-3.5 Ga	Many outflow channels [2,8,13,15]
~3-3.5 Ga	Sulfate sediments common
~3.5-3.7 Ga	**Hesperian/Noachian boundary [13]**
3.5 Ga?	Phyllosilicate mineralogy common
~3.7-4.5 Ga	Resurfacing rates 10-100× higher than in Amazonian [13; WKH in preparation]
3.97 Ga	Carbonates in ALH 84001
4.51 Ga	Formation of Martian crust and ALH84001