NEW AGE MARS. A.S. McEwen, LPL, University of Arizona, Tucson, AZ 85721.

Recent Geologic Activity and Climate Change on Mars. Some of the most exciting results from MGS have come from images of terrains and deposits that are nearly devoid of small (10-100 m diameter) impact craters, interpreted as evidence for recent geologic activity and/or climate change. What are the constraints on absolute ages of the deposits or timing of the modification processes?

A key issue is whether impact craters smaller than a few hundred meters diameter are dominated by primary impacts or by the secondary impacts of larger primary craters. Many craters are obvious secondaries, closely associated with a primary crater and with distinctive morphologies, but there has been a longstanding controversy about the relative abundances of small primaries *versus* distant secondaries on the Moon [1]. McEwen et al. [2] have concluded that Martian impact craters smaller than at least ~250 m are most likely dominated by secondaries. I suggest here that the Hartmann and Neukum production functions [HNPF; ref. 3] predicts far too many small primary craters, thus changing the constraints on the ages of the youngest terrains.

The Origin of Martian Meteorites. The discoveries on Earth of meteorites from Mars make it apparent that distant secondary craters are abundant on Mars. The probability that a rock ejected from Mars will land on Earth and be discovered is 10^{-6} to 10^{-7} [4]. Fragments smaller than 10 cm diameter are decelerated efficiently by the current Martian atmosphere [5], so at least 10^6 fragments larger than 10 cm must be ejected by the impacts that delivered the known Mars rocks. The material that escapes Mars represents only a small fraction of the high-velocity ejecta; the majority falls back to create distant secondary craters (fragments larger than 10 cm ejected at >3 km/s will travel >10^3 km before impact).

Zunil. A 10.1-km diameter crater (recently named Zunil) in the Cerberus Plains of Mars created ~10^7 secondary craters 10 to 230 m in diameter within 800 km of the impact site [2]. Many of these secondary craters are concentrated in radial streaks that extend up to 1600 km west of the primary crater, analogous to lunar rays. The larger Zunil secondaries are distinctive in both visible and thermal infrared imaging as they have dark interiors with high thermal inertias and bright outer ejecta blankets with low thermal inertias. MOC images show fresh morphologies including sharp rims and well-preserved bright rays, but the craters are shallow and often noncircular, as expected for relatively low-velocity or clustered impacts. About 80% of the impact craters superimposed over the youngest surfaces in the Cerberus Plains have the distinctive characteristics of Zunil secondaries. We have not identified any other large (≥10 km diameter) impact crater on Mars with such distinctive rays of young secondary craters. Zunil is an excellent example of how spallation of a competent surface layer can produce high-velocity ejecta [6].

Is Zunil the Source Crater for some of the Basaltic Shergottites? Zunil is an excellent candidate for one of two main source craters for the known basaltic shergottites with lava emplacement ages of 165-177 Ma and ejection ages of ~1.5 and ~2.7 Ma [7]. The ~1.5 and ~2.7 Ma ejection ages are consistent with evidence that Zunil is one of the youngest Martian craters larger than 10 km. The youngest Cerberus Plains lavas are probably composed of basalt according to lava emplacement models and TES data. The near absence of craters larger than 500 m superimposed on the youngest lavas indicates they are less than ~100 Ma old [8], but there are older lavas only tens of meters below the young lavas [9]. The basaltic shergottites probably originated within 100 m of the surface [4-6], so ejection of 165-177 Ma lavas from Zunil is consistent with these constraints.

Models of Secondary Cratering. A 3D hydrodynamic simulation [5] of a 45° impact at 10 km/s, producing a 10-km crater like Zunil, ejects 10^8 to 10^9 rock fragments at velocities sufficient to make craters larger than 10 m diameter, although the actual number of countable craters will be reduced by several effects [2]. Nearly all of the modeled secondary craters larger than 50 m are within 800 km of the impact site but many smaller craters extend out to 3500 km. In fact, 70% of the secondary craters from 10-50 m diameter occur at ranges greater than 800 km!

The observations of Zunil and the hydrodynamic simulation were used to model the global average production function for secondary craters [2]. Better models are needed, but producing sufficient quantities of secondaries to account for the observed populations of small craters on Mars is not difficult.

Morphology and Morphometry of Small Craters. Examination of many MOC images of sparsely-cratered terrains shows that small craters are strongly clustered in space and time, and nearly all of the small craters are shallow and flat-floored. Depth/diameter ratios of 1300 small craters (10-500 m) in Isidis Planitia and Gusev crater have a mean value of 0.08; the freshest of these craters give a ratio of 0.11, identical to that of fresh secondary craters on the Moon and significantly less than the value of ~0.2 or more expected for fresh primary craters of this size range [2].

Upper Hesperian/Lower Amazonian Regolith. Hartmann et al. [10] applied an average of the Hartmann and Neukum production functions (i.e., the HNPF) to estimate regolith production from impact "gardening" as a function of terrain age. They concluded that late Hesperian/early Amazonian terrains such as the Pathfinder and the two Viking landing sites should have experienced cumulative gardening of 3-14 m depth. This conclusion conflicts with the interpretations of the science teams for all 3 landers [11-13]. There are two ways to reduce the model regolith depths: (1) if most of the small craters are indeed secondaries, they may be shallow due to low-velocity impacts, gardening to only ~60% the depth of high-velocity primaries; and (2) rather than estimate the number of impact craters smaller than the actual counts via the HNPF, just extrapolate from actual observed craters. The crater counts of [10] extend down to ~60 m on the VL1 and Pathfinder terrains, but most of the gardening is accomplished by smaller craters. Use of these new assumptions leads to an estimate of <0.5 m of regolith, and the thickness may be spatially variable due to the clustering of secondary impacts. The presence of thin regolith of variable thickness is consistent with the observations at three landing sites and with the small-scale features seen in MOC images at 1.5-3 m/pixel of Late Hesperian and Early Amazonian terrains.

Consistency of Age Constraints from Small and Large Craters. It is difficult to reconcile the HNPF with the small-crater age constraints of at least 3 craters larger than 10 km diameter: (1) Zunil (7.7 N, 166 E; 10.1 km diameter), (2) McMurdo (84 S, 0 E; 23 km), and a (3) crater just west of the Olympus Mons aureole (23 N, 207 E; 29 km; ref. 14). All three craters appear to be very young on the basis of the sparse densities of small craters superimposed either on the large crater or surfaces older than the large crater. Explaining the few primary craters on parts of the south polar layered deposits requires that the McMurdo impact happened within the past 100 Ka according to [15]. The absence of craters resolvable at 6 m/pixel (craters ~24 m or larger) over a 72 km^2 area of an ejecta lobe of the third crater [14] indicates that it is younger than 50 Ka according to the HNPF.

All three craters are superimposed on Upper Amazonian terrains, which cover just 7% of Mars [16], so there must be craters of comparable size and age on the other 93% of the surface. Fresh craters are easier to recognize on young terrains and are much better sampled at high resolution than craters of comparable size and age on older terrains. According the HNPF we should expect 3 craters ≥10 km to impact on 7% of Mars in ~40 Ma, or 2 craters ≥20 km in ~70 Ma. However, the HNPF for small craters indicates ages of less than 100 Ka for the two larger craters, a 700-fold disparity. Either Mars has experienced 2 highly improbable impacts in the last 100 Ka, or the HNPF predicts too many small primary craters.

Why are there fewer small primary craters than expected? The evidence for fewer small primary craters than expected is surprising because previous workers have concluded that Mars and the Moon are cratered by the same population of small bodies [17]. Here are 4 working hypotheses: **(1)** The lunar production function for craters smaller than 250 m (where the lunar maria have reached equilibrium saturation) has not been correctly estimated. **(2)** Eolian processes on Mars somehow erase primary craters faster than secondaries. **(3)** The flattening of the size-frequency distribution reflects the actual population of small asteroidal fragments near Mars, as suggested for the main asteroid belt [18, 19]. **(4)** The long-term atmospheric density of Mars has significantly reduced the production and affected the morphologies of small primary craters. Mars is thought to experience quasi-periodic climate change, and the atmospheric pressure should be near 0 at low obliquity, but in order to reduce the number of craters 20-60 m in diameter by more a factor of 10 would require that Mars has almost never had an atmospheric pressure as low as that of today.

Implications for Age Constraints on Young Surfaces. There are very few if any craters larger than 2 km [cf. 16] on the youngest Martian terrains, providing a very weak constraint on the ages. However, the diameters at which secondaries dominate become smaller for younger terrains, so potentially we can date young terrains using craters smaller than 1 km. Unfortunately, the production function for primaries is highly uncertain for craters smaller than ~300 m.

What is the maximum age we can assign to terrains free of any craters larger than 300 m? The number of primary craters ≥300 m per km^2 per Ma is ~3.5 x 10^{-5} via the HNPF, so the maximum age is a function of the area of crater-free terrain. For terrains covering ~100 km^2 the upper age limit is ~300 Ma, or ~600 Ma given other uncertainties [3]. This means we cannot rule out the hypothesis that some morphologies, such as flow features in middle latitudes, form via extremely slow processes [20]. Mustard et al. [21] stated that the absence of craters larger than 100 m on the high-latitude mantle of volatile-rich material indicates a maximum age of 0.15 Ma. Recalculating based on the absence of craters larger than 300 m increases the maximum age to 10 Ma. Since many gullies cut this debris mantle, their upper age limit is also ~10 Ma.

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