Meteoritics & Planetary Science 41, Nr 10, 1453–1467 (2006)
Abstract available online at http://meteoritics.org

Nature of the Martian uplands: Effect on Martian meteorite age distribution and secondary cratering

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(Received 19 September 2005; revision accepted 04 June 2006)

Abstract–Martian meteorites (MMs) have been launched from an estimated 5–9 sites on Mars within the last 20 Myr. Some 80–89% of these launch sites sampled igneous rock formations from only the last 29% of Martian time. We hypothesize that this imbalance arises not merely from poor statistics, but because the launch processes are dominated by two main phenomena: first, much of the older Martian surface is inefficient in launching rocks during impacts, and second, the volumetrically enormous reservoir of original cumulate crust enhances launch probability for 4.5 Gyr old rocks. There are four lines of evidence for the first point, not all of equal strength. First, impact theory implies that MM launch is favored by surface exposures of near-surface coherent rock ($\leq 10^2$ m deep), whereas Noachian surfaces generally should have $\geq 10^2$ m of loose or weakly cemented regolith with high ice content, reducing efficiency of rock launch. Second, similarly, both Mars Exploration Rovers found sedimentary strata, 1–2 orders of magnitude weaker than Martian igneous rocks, favoring low launch efficiency among some fluvial-derived Hesperian and Noachian rocks. Even if launched, such rocks may be unrecognized as meteorites on Earth. Third, statistics of MM formation age versus cosmic-ray exposure (CRE) age weakly suggest that older surfaces may need larger, deeper craters to launch rocks. Fourth, in direct confirmation, one of us (N. G. B.) has found that older surfaces need larger craters to produce secondary impact crater fields (cf. Barlow and Block 2004). In a survey of 200 craters, the smallest Noachian, Hesperian, and Amazonian craters with prominent fields of secondaries have diameters of ~45 km, ~19 km, and ~10 km, respectively. Because 40% of Mars is Noachian, and 74% is either Noachian or Hesperian, the subsurface geologic characteristics of the older areas probably affect statistics of recognized MMs and production rates of secondary crater populations, and the MM and secondary crater statistics may give us clues to those properties.

INTRODUCTION

A literature review by Nyquist et al. (2001) shows that Martian meteorites (henceforth MMs) come from about 4–8 sites on Mars, based on comparison of solidification ages, cosmic-ray exposure (CRE) ages, and petrochemical properties. Later discovery and dating of basaltic shergottite Dhofar 019, with the oldest known exposure age of ~20 Myr, suggest still another impact site (Head 2002), and we adopt 5–9 as the most probable number of impact sites sampled by MMs. Multiple independent finds from some of the sites, however, suggest that not many more major launch sites remain to be sampled by MMs. All but one of the sites have formation ages $\lesssim$1.3 Gyr, meaning that some 80–89% of the launches come from sites formed in the last 29% of Martian time. As has been widely discussed (cf. Nyquist et al. 2004), this suggests a paradox: why are older samples not more common? The paradox is reduced if only five launch sites are represented (four out of nine from last 29% of Martian time) but is greater if more sites are represented. (e.g., eight out of nine from the last 29% of Martian time).

The meteorites have all been launched within the last 20 Myr, based on cosmic-ray exposure (CRE) ages (Nyquist et al. 2004; Head 2002). Therefore, any discussion of the paradox must assume that the launches are occurring from terrain distributions existing in the last 20 Myr—essentially the stratigraphic units we see today.

The above discussion does not represent the entire statistical nature of the paradox, because the remaining sampled site (the ALH 84001 site) is hardly a random sample from the time interval 1.3–4.5 Gyr ago, as might be expected if impacts are randomly ejecting rocks on a planet with the surficial layers of uniform geological/mechanical properties. Rather, ALH 84001 is a cumulate rock that solidified exactly at the planetary formation age of 4.5 Gyr ago; in other words, it is piece of the primordial Martian crust (as will be discussed in the "Special Significance of ALH 84001" section).

Our problem is thus to examine whether there are reasons why the MM inventory favors young igneous rocks and primordial crust fragments, and nothing in between. By implication, we examine why launch not only of MMs, but also of fallback ejecta and secondary impact craters, may be favored in the youngest igneous rock units and exposures of the primordial crust, but is not favored in most of the highly cratered Noachian and Hesperian upland stratigraphic units covering some 40–74% of Mars.

HEAVILY CRATERED UPLAND CRUST: THEORETICAL CONSIDERATIONS

First, we consider the theoretical effects of heavy cratering and Martian environment on launch efficiency in older upland materials.

Regolith Production and its Effect on Material Properties

The oldest Martian crust approaches saturation equilibrium values of crater density at large crater diameters (D ~ 45–128 km). These densities are comparable to those of the lunar far-side uplands (McCauley et al. 1972; Hartmann 1973a; Tanaka 1986; Barlow 1988; Tanaka et al. 1988). Craters roughly in the intermediate range 250 m < D < 45 km, however, apparently have not formed fast enough to keep up with Martian erosional and depositional losses. They are usually seen at less than saturation numbers, even on the oldest surfaces. The full, saturation-level complement of impacts no doubt occurred, however, as is seen by saturation equilibrium densities on Phobos (Hartmann and Neukum 2001, Fig. 3) and by near-saturation densities among ancient, moderate-sized craters, seen, for example, in exhumed plains of Terra Meridiani (Hartmann et al. 2001, Fig. 9).

From purely geometric considerations (independent of impact cratering models or inferences about surface age), Hartmann (1980, 2003) and Hartmann et al. (2001) pointed out that such high accumulated crater densities ensure production of fragmental material and brecciated rock sufficient to reach depths of hundreds of meters, or even a few kilometers in crater-saturated regions. The high primordial cratering rates (whether gradually declining or in a cataclysm 3.9 Gyr ago) ensure this happened within intervals as short as a few hundred Myr on any unit formed before ~4 Gyr (such units would be Noachian; cf. "Questions of Regolith Depth versus Absolute Age," later in this article). The reasoning is that at saturation crater densities (~32× average lunar mare crater densities), some 100–200% of the surface is covered by impact craters of original depth $d \gtrsim$ 1–2 km (i.e., a typical spot has been hit about once or twice on average by a crater at least this deep), implying deep gardening to such a depth. (We speak of a mean characteristic depth. "Regolith depth" is rather poorly defined, because regolith grades into coarser material at depth, and depth may vary locally with location depending on where the larger impacts occurred.)

At crater densities below saturation, the regolith depth drops nonproportionally to the drop in density, due to the shape of the diameter distribution of craters (number versus diameter). For example, at half the saturation density, the regolith depth is far less than half of what it was at saturation. This is because 100% of the area is covered by craters with original depth $\gtrsim$200 m, implying gardening to only about that depth. These concepts were used to account successfully for regolith depths of the order 10–20 m in the lunar maria, where the density at large D is only ~3% saturation, roughly corresponding to mid-Hesperian surfaces on Mars. At that density, ≥100% of the surface is covered by craters of diameter D > 22–44 m, and original depth d ~ 10–20 m (e.g., Hartmann et al. 2001, Table 1). These concepts were used in early lunar analysis to coin the term "megaregolith" (Short and Forman 1972; Hartmann 1973b).

Note that this first-order reasoning about regolith generation depends not on theoretical modeling of regolith evolution or knowledge of absolute ages, but rather on simple geometry. Because it involves direct observations of craters of all origins (mostly with diameters >1 km), it is not likely to be affected by recent discussions of Martian ratios of secondary/primary craters (e.g., McEwen et al. 2005; Block and Barlow 2005). The important point is that total depth of gardening must be some function of observable crater density, which is directly observable independent of inferred age.

Based on the above considerations, Hartmann and Neukum (2001, p. 191) and Hartmann et al. (2001, p. 49–52) concluded that the most heavily cratered Martian uplands cannot have pristine, coherent massive igneous rock strata at the surface (pristine layers would have low crater densities). Rather, the oldest units with high densities of observable craters must consist mostly of deep (>100 m) layers of once-fragmented and impact-gardened material. Regolith can be transported and removed after it forms, of course, but a near-saturation density of surviving craters on a surface requires some depth of initially fragmented material, formed from overlapping ejecta blankets, beneath the surface.

By assuming the regolith depth versus crater density curves given in Hartmann et al. (2001) and the definitions of the Amazonian, Hesperian, and Noachian era boundaries of Tanaka (1986), we can crudely estimate a characteristic range of regolith depths for each era, independent of assumptions about absolute age. The original model (Hartmann et al. 2001, Fig. 1b) dealt with mean depth of pulverized regolith material, but the regolith must grade into coarser material at depth and heavily fractured, weakened bedrock material below that; therefore, we also estimate the characteristic depth to the (ill-defined) base of this weakened, fractured zone, assumed to be 3× regolith model depth for regolith (which refers to relatively fine material). Based on Tanaka's assigned crater densities, in typical Amazonian units these depths would range from 0 m in the latest units to roughly 8–18 m, and the fractured zone would reach from 0 m to 24–54 m. In Hesperian terrain, the figures would be on the order of 12–50 m for regolith and 36–150 m for the fractured zone. In Noachian terrain we would anticipate 50 to many hundreds of meters of regolith and 150 m to kilometers for the fractured zone. (Our four-layer description, with loose, fine regolith grading into coarse regolith over fractured bedrock, underlain by more coherent bedrock, is more realistic than the two-layer description of Head et al. [2002], with regolith over coherent bedrock, but of course harder to incorporate into numerical impact models. The gradation of layering, however, is important in assessing MM launch effects.)

An obvious question at this point is: what are the absolute ages of units that have generated a given depth of regolith (however defined), such as 30 m or 100 m? How do they relate to the possible "soft cutoff" age of 1.3 Gyr in the MM statistics? (We say "soft cutoff" because the statistical sample of MM launch sites is too small to assert any sharp cutoff at this age. See further discussions below.) The answer is currently clouded by uncertainty in absolute dates in mid-Martian history. Because of robust evidence of much higher mean cratering rates before 3.9 Gyr ago (whether by a cataclysm at 3.9 Gyr or by more gradual sweep-up of asteroidal/cometary debris), it appears fairly firm that all surfaces older than ~3.9 or 4.1 Gyr were saturated and had enough cratering to generate hundreds of meters of gardened debris, but regolith depths on surfaces 1.3 Gyr or 2 Gyr old are uncertain. We will return to absolute age issues and their implications in the "Questions of Regolith Depth versus Absolute Age" section.

Martian megaregolith would be different from lunar megaregolith. The latter appears to be commonly (but not uniformly) welded into strong, coherent impact breccias in a dry environment (Warren 2001). Martian megaregolith would have been more likely to be affected and mobilized by eolian and fluvial transport, and cemented (if at all) under very different conditions, although existence of cemented breccias is indicated by MM Yamato-793605. In speaking of characteristic mean depths, therefore, we recognize that Martian megaregolith, in contrast to lunar examples, would have been thinned in some areas by removal and thickened in other areas by deposition. Wherever it existed (and as fast as it was created), it would have served as an ideal sink for the large amounts of early Martian water, which was apparently abundant at about the same time as the early intense cratering. Evidence for such early water now includes abundant ancient fluvial morphologic features, as well as evaporites in all or most MMs (McCauley et al. 1972; Baker 1982; Malin and Edgett 2001; Bridges et al. 2001; Squyres et al. 2004). Direct evidence of substantial modern subsurface ice at depths of ~400 m at low latitudes to <100 m at 65° latitudes comes from observations of depths reached by craters with layered ejecta patterns, and from direct mapping of H abundances by Mars Odyssey (cf. Squyres et al. 1992; Barlow et al. 2001; Boynton et al. 2002).

The discussion so far leads to an idealized picture of the Noachian and Hesperian Martian upland subsurfaces as consisting of tens or hundreds of meters of fragmental material weakly bonded by evaporites and ices. Nature, however, is always more complicated than simple models, and the subsurface materials of Noachian and Hesperian uplands, though weak, may involve complex layering. Tanaka et al. (1988), Crown et al. (1992), Mest and Crown (2001), and many others have documented from stratigraphic and morphologic considerations that ancient fluvial, periglacial, volcanic eolian materials are probably interbedded among the putative weakly cemented impact ejecta layers in the old uplands. Carbonate-cemented layers in southwestern U.S. deserts, for example, can be quite strong but are commonly found in thin layers interbedded with crumbly alluvium. Weakly cemented, sulfur-rich duricrust was discovered on the surface at both Viking landing sites. In general, Martian subsurface materials in old cratered uplands may be crudely analogous to terrestrial desert alluvial fill, weakly bonded by ice and/or evaporites—quite different from the generally basaltic materials in the upper 100 m of Amazonian Martian lava-covered plains, such as Tharsis Planitia, Amazonis Planitia, Elysium Planitia, and the slopes of the large volcanoes, where lava flow textures are often visible at 5–10 m scale (Keszthelyi et al. 2000; Hartmann et al. 2001).

Ejecta Launch Efficiency as a Function of Near-Surface Material Properties

According to classic impact theory (Melosh 1984, 1989), strong, coherent surface rock favors ejection of high-speed solid blocks, and loose or weakly consolidated regolith does not. According to this theoretical treatment, the launch of rocks off Mars occurs due to a process of spallation, where the fastest rocks are launched primarily from near-surface spall layers of coherent rock. Melosh (1989) found that the spallation layer is quite thin, with spallation depth h of the order of 1/2 the impacting projectile radius = $d_p/2$, but dependent on distance from impact. This spallation or launch depth is thus a small fraction of the crater diameter (see the "Synthesis: Quantitative Analysis of Observations" section for quantitative discussion). Impacts into fragmental or weakly consolidated material dissipate impact energy, reducing efficiency of high-velocity launch of large, solid rocks.

Head et al. (2002) correctly suggested that the "classic" modeling of rock ejection needs to be expanded to include surface regolith layers. They modeled impacts into bare bedrock, regolith-covered bedrock (regolith up to 150 m in thickness), and semi-infinite regolith. Combining impact frequency evidence with detailed impact modeling, they found that craters as small as 3.1 km in bare basalt could launch enough rocks in the size range needed to account for the lherzolitic shergottites, and (though faced with some cell-size limitations on their models) concluded that MMs could come from primary craters as small as 3.1–7 km. Beck et al. (2005) used shock histories to conclude, similarly, that Zagami and certain related shergottites were launched typically from craters about 1.5–5 km in diameter.

Recent work by Artemieva and Ivanov (2004) softens the idealized distinctions made in the Melosh theory between coherent rock layers and "launch-inhibited" loose material. Isotopic measurements suggest that the pre-Earth atmospheric sizes of most MMs are characteristically of the order 0.2–1 m (Eugster et al. 2002), and Artemieva and Ivanov conclude that high-speed launch of such meter-scale rocks off Mars may not be restricted to coherent bedrock layers. They suggest from modeling considerations that meter-scale surface rocks, embedded in regolith-like surface soils, can be launched off Mars. However, this process has much less efficiency than launch from coherent rock layers, because meter-scale rocks apparently amount to a small percent of the volume of near-surface layers. The largest rocks launched from loose regolith or weakly (ice-?) bonded regolith would be no bigger than the largest fragments scattered in the layer. Fragments smaller than ~10–50 cm probably would not escape the Martian atmosphere efficiently because of drag effects (Popova et al. 2003; Artemieva and Ivanov 2004). The work of Artemieva and Ivanov, therefore, while softening the modeling distinction between regolith and coherent rock, still supports our overall view that an impact into loose surface material will launch fewer rocks than an impact into coherent rock surfaces. Head et al. (2002) estimate that 10^6–10^7 meter-scale rocks must be ejected from Mars by a given impact to produce MMs, so if impacts occur in deep regolith, enormous total volumes (i.e., large craters) would be needed to produce sufficient rocks. In view of the general ideas sketched above about regolith, Head et al. commented briefly that larger craters, with diameters D ~ 20 km, would be needed to launch adequate rocks to produce MMs from "ancient terrains of Mars"—a result we will confirm in the "Heavily Cratered Upland Crust: Observational Considerations" section. For a given surface layer of regolith overlying solid bedrock, efficiencies increase as the impactor and crater size are increased to the point that h is greater than regolith depth, so that the regolith layer becomes a skin effect. The problem then is that larger craters are much less frequent. In the context of MMs, we need crater sizes likely to have formed on Mars in the last 20 Myr—the characteristic interval during which MMs were launched, as found from CRE ages. We will return to quantitative work on crater sizes and regolith depth in the "Synthesis: Qunatitative Analysis of Observations" section, after relevant observational discussions.

Workers such as Warren (2001) have discussed lunar meteorite launch processes and pointed out that lunar meteorites include numbers of coherently cemented regolith breccias as well as relatively weak clods. It has been suggested to us that the strongly cemented lunar regolith-derived meteorites prove that deep regolith materials have high, not low, launch efficiency. However, as argued in the previous section, Martian regolith and megaregolith are almost certainly very different from the lunar equivalent. Consider a deep lunar regolith or megaregolith stratum welded into a coherent layer cemented by glasses and materials that may require temperatures approaching 1000 K to melt. Such a layer can be expected to react to impact very differently from a regolith cemented in part by ice that turns into steam in the wet or ice-rich Martian environment at temperatures around 300 K. Furthermore, because initial intense cratering would have produced a permeable regolith sink for later Martian waters, porous regolith breccias in many or most areas are likely to have been wetted and to contain significant amounts of water or ice that could make their impact response quite different from impacts into lunar regoliths and breccias. Issues of regolith launch efficiency are affected also by uncertainty in the processes that weld regolith into coherent breccias: how much occurs during impact on the surface and how much occurs later, perhaps at depth. This is a fruitful subject for further work in both the context of Mars and the Moon.

Questions of Regolith Depth versus Absolute Age

We are now driven to a more specific quantitative question: have Martian surface units older than 1.3 Gyr, or perhaps ~2 Gyr, been gardened to a fine enough scale and otherwise altered to a great enough depth to inhibit launch of the meter-scale rocks needed to make MMs, and larger rocks needed to make secondary craters? Answering this question involves 1) the absolute calibration of crater density with age, and 2) detailed models of the effect of thin surface layers (10 m? 30 m? 100 m?) on the launch of boulder-scale regolith ejecta at $V > V_{escape}$.

Both issues tax current quantitative knowledge. Furthermore, the problem is statistical, because we have sampled the launch capabilities of Mars at only 5–9 sites. We are proposing not a sharp cutoff in launch properties at 1.3 Gyr, but rather a soft cutoff, in which launch efficiency for ≥ meter-scale rocks decreases as we go back from 1.3 Gyr to 3 Gyr. (A few new MMs of age 1.8 Gyr or 2.4 Gyr would not disprove our conclusions, but enough MMs to fill the gap from 1.3 to 4.5 Gyr uniformly would disprove them.)

Hartmann and Neukum (2001) concluded that the absolute age of units with crater density corresponding to the Noachian/Hesperian boundary is about 3.5–3.7 Gyr. This is fairly well constrained because the cratering rate was substantially higher before this; older surfaces would have too many craters to be at the boundary, and younger surfaces too few. Geometric regolith modeling (Hartmann et al. 2001, Fig. 1) makes it fairly clear that Noachian surfaces (displaying more than ~3.7 Gyr of cratering) will have fragmental or fractured surface layers deeper than the 150–350 m depth modeled by Head et al. (2002), and this would strongly inhibit launch of spalled bedrock in their impact model for craters of $D \lesssim$ 3–7 km in diameter. In the Artemieva/Ivanov (2004) model, a few rocks would be launched from the regolith but would be restricted to maximum fragment size in the granular layer (small percentage of volume in blocks larger than 1 m).

Can younger layers, closer to the observed MM "soft cutoff" age of 1.3 Gyr, have enough gardening to inhibit rock launch? Absolute ages from crater counts, in the middle third of Martian history, necessarily have much higher uncertainties, due primarily to the roughly factor 2 uncertainties in the Martian crater production rate. Hartmann and Neukum (2001) concluded that while the absolute age of units with crater density corresponding to the Hesperian/Amazonian boundary most probably lies around 3.3–2.9 Gyr ago, it might be as recent as 2.0 Gyr ago. Hesperian units may have gardening effects perhaps 12–50 m deep (based on Hartmann et al. 2001, Fig. 1), and fractured material well below that. Thus, even in the Hesperian, the model of Head et al. (2002) suggests craters 3–7 km are too small for efficient launch of MMs, as they themselves concluded for "ancient terrains," and this statement may conceivably apply to surfaces as young as 2.0 Gyr. The 1.3 Gyr maximum age of the main group of MMs (excluding ALH 84001; see the "Special Significance of ALH 84001" section), probably lies in the Amazonian era, and it is harder to make a case that typical surfaces of, say, 1.3 to 2 Gyr ages, have enough regolith to retard launch of MMs.

Effects of ground ice introduce a major additional complication, not considered by Head et al. (2002). As mentioned above, deep regolith produces a perfect sink for water, resulting in massive ground ice deposits. As MMs began to be recognized in the 1980s, there were suggestions that ground ice, converted by impact to expanding gas, could help launch rocks off Mars. However, ice impregnated into granular, porous, or fractured target material would likely cause "steam-blast" explosions that would break up such material and retard launch of large solid blocks. Martian craters with layered ejecta give evidence that impacts into ice-rich regions produce not dry rock masses and dust, but a volatile-rich ejecta curtain forming a tight ejecta pattern around the crater (Stewart et al. 2001; Barlow and Perez 2003). Existing theoretical models of launch of MMs off Mars do not adequately consider such effects.

EVOLUTION OF ANCIENT UPLAND MATERIALS: EFFECTS OF WEAK SEDIMENTARY ROCKS

Recent discoveries add a second effect that reduces launch efficiency, in addition to regolith effects. Martian megaregolith materials, contrary to those of the moon, were probably mobile in the early Martian fluvial and eolian environment, with some probably deposited in lacustrine environments. Recent discoveries confirmed this when direct detection of weakly cemented sedimentary rock units on Mars was made by the Opportunity rover in a probable exhumed lakebed at Meridiani Planum (Squyres et al. 2004) and later by the Spirit rover in cratered hills in Gusev crater. At both sites, the thinly layered sedimentary rocks, containing tens % sulfates, were found to have only ~1–10% the grinding strengths (joules expended/volume pulverized) as coherent basaltic rocks on Earth and Mars (Arvidson et al. 2004, Table 1). Given the abundance of fluvial surface features and the discovery of such sedimentary rocks at two out of three rover landing sites, we suggest such materials may be a non-negligible component of rocks in older regions of Mars. We anticipate such weak, weathered sediments would have lower launch efficiency than basalts, possibly shattering under hypervelocity impact into smaller characteristic fragment sizes than strong bedrock, especially if some of the porous sediments contain ice.

Aside from the reduced efficiency of sediment launch, we have the possibility of reduced efficiency of identification on Earth. Questions arise whether these would have been collected and identified on Earth during at least some early meteorite surveys (Hartmann and Neukum 2001, p. 191). For example, Schneider et al. (2000) showed that even the fusion crusts of some such materials may have different coloration than usually associated with meteorites, inhibiting retrieval.

To summarize so far, we suggest on theoretical grounds that Noachian surfaces do not efficiently launch MMs into space, because, being probably older than ~3.5 Gyr, they are rich in loose regolith, weakly cemented regolith, and weak sediments, all of which are likely ice rich. Even Hesperian surfaces (likely as young as ~3 Gyr and possibly as young as 2 Gyr) have retarded efficiency. However, it is unlikely that there is a sharp cutoff in MM launch efficiency at 1.3 Gyr.

HEAVILY CRATERED UPLAND CRUST: OBSERVATIONAL CONSIDERATIONS

Direct observations strongly support the general findings of the previous two sections. One relevant observation was made by Malin as early as 1999 from Mars Global Surveyor's (MGS) imaging observations: areas that are smooth and sparsely cratered at kilometer scale tend to look rough at decameter scale, whereas areas that look rough and cratered at kilometer scale tend to look smooth at decameter scale (cf. Malin and Edgett 2001, pp. 23, 479 for discussion). "Malin's rule" is consistent with our model, in which the youngest Martian lava plains preserve coherent rock lava flow textures without much regolith, but ancient cratered uplands have surfaces consisting of loose, deep materials, which tend not to hold small-scale relief or rough textures at 10 m MGS imaging scales. Here we focus on two more specific observations.

Relation of MM Formation Ages and CRE Ages

A weak but intriguing argument for our model comes from the plot of rock formation ages versus cosmic-ray exposure ages. As reproduced and discussed by Nyquist et al. (2001), such a plot has been used to identify numbers of launch sites, and it shows some tendency for older rocks to have been launched longer ago. For example, in the Nyquist et al. (2001) plot, both of the oldest sites (naklite/chassignite site with 1.3 Gyr rocks and ALH 84001 site with 4.5 Gyr rock) were launched more than 10 Myr ago, whereas all rocks younger than 480 Myr were launched less than 5 Myr ago. The correlation was later somewhat reduced (a bad sign!) by reports that Dhofar 019, an olivine-phyric shergottite, has a young crystallization age of 575 Myr (Borg et al. 2002), but has the oldest known exposure age, variously reported as 19.8 and 20.7 Myr (Shukolyukov et al. 2000; Park et al. 2003). If the weak correlation is meaningful, it suggests that young rocks are launched more frequently and old rocks are launched less frequently, which is equivalent to saying that young rocks tend to be launched from smaller impact craters, and old rocks need larger (less frequent) craters. Because of the stochastic nature of large versus small impacts as a function of time and target region, any such correlation should not be strong. The weak correlation fits our model in which old regions have deeper regolith-influenced, "launch-inhibited" layers. Indeed, the smaller craters would tend to eject smaller volumes of material than large craters, in which case the heliocentric-orbiting supply of rocks from the typical young launch site reaches zero faster, perhaps contributing to why we see no young rocks from sites launched more than 5 Myr ago. This argument is obviously highly subject to stochastic factors. MMs that we receive on Earth are also filtered by the dynamics of loss from heliocentric orbits. In other words, 50 Myr ago a large Martian crater might have launched a huge volume of MMs, and our current flux of them might be small; but 8 Myr ago a small Martian crater could contribute the larger flux of present-day MMs. The observation in this section does not prove our model, but the statistics are intriguing and seem to go in the right direction, and do not seem accounted for otherwise.

Lack of Secondaries from Craters on Old Surfaces

A much stronger argument, the strongest argument in this paper, comes from an observation of secondary impact crater fields. One of us (Barlow, in Barlow and Block 2004) surveyed the abundance of secondary impact crater fields in the Martian uplands and found a deficiency relative to secondary impact crater fields in the sparsely cratered Martian lava plains. This observation directly confirms our expectation that the Martian uplands do not launch coherent rocks as efficiently as in the younger plains. We have extended that survey to include approximately 200 fresh impact craters (i.e., those surrounded by a well-preserved ejecta blanket). These were craters of diameter ≥5 km within latitudes ±60° on Noachian-aged plateau units (Npl1, Npl2, Nple, Nplr, Nplh, and Npld), Hesperian-aged ridged plains units (Hr, Hs, Hsu, and Hsl), and Amazonian-aged volcanic plains (Aa3, At4, and At5) (stratigraphic units from Scott and Tanaka 1986 and Greeley and Guest 1987). These craters were selected from those already identified as displaying "radial" ejecta morphology or "diverse" ejecta morphology (i.e., composed of both layered and radial ejecta morphology in Barlow's revised [2003] *Catalog of Large Martian Impact Craters*). The study utilized primarily THEMIS daytime infrared images of 100 m/pixel resolution and, where available, THEMIS visible images of 18 m/pixel resolution. Because of the difficulty in identifying the specific primary crater from which widely dispersed, or "distant," secondaries originate, we looked for secondary fields close to the primary crater or just beyond a layered ("fluidized") ejecta pattern. The results of this survey reveal that large fresh primary craters (D > 45 km) on all terrains are usually surrounded by secondary craters and crater chains, but smaller fresh primary craters may or may not have obvious secondaries, depending on the terrain. We emphasize that the survey concentrated on fresh primary impacts; it was the background surfaces that varied in age. Thus, the secondary fields were equally as fresh, and our finding is not due to some systematic effect with age of the secondaries, such as loss of old secondaries due to erosion or non-recognition of eroded secondaries under given lighting angles.

Figures 1–3 give examples of this effect. Figures 1 and 2 compare a layered-ejecta young crater on a young plain to a similar-sized young crater on an old unit. The detailed view in Fig. 1a shows a multitude of small, somewhat radially elongated secondaries beyond the rampart ejecta of a crater on an Amazonian plain, but no secondaries atop the rampart ejecta—an important observation in interpreting the other figures. It means that craters found atop layered ejecta are probably not local secondaries, but part of a subsequent accumulation of background primaries and secondaries. In Fig. 1b, we see these types of small craters scattered through the frame (including inside the primary), but no concentration of characteristic elongated, small secondaries beyond the lobate ejecta of a crater on a Noachian plain. Figure 2 shows a comparison with more of the craters' surroundings. In Fig. 2a we see a moderate density of craters on the Amazonian plain beyond the rampart ejecta; Fig. 2b shows fewer craters beyond the rampart ejecta even though the background Noachian stratigraphic unit is older—indicating

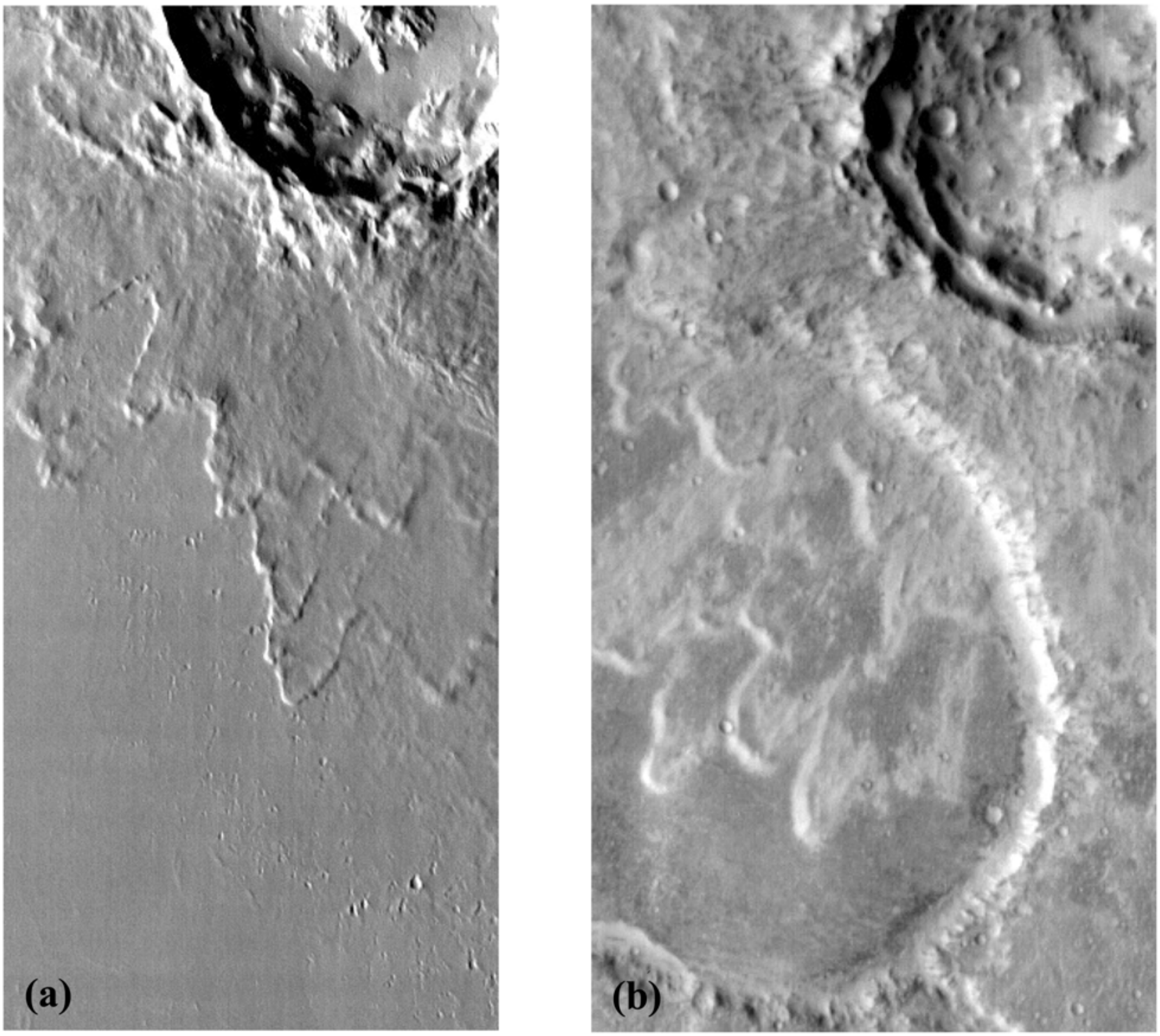

Fig. 1. A comparison of secondary cratering from similar-sized craters on Amazonian volcanic plains and a Noachian cratered plateau unit. a) Secondary craters are seen beyond the layered ejecta blanket, but not on the blanket, surrounding a crater 28 km in diameter on Amazonian unit Aa3 (23.2°N, 207.8°E; THEMIS image I01990002). b) Secondary craters are not seen beyond the layered ejecta from this crater, 25 km in diameter, on Noachian unit Npld (5.1°S, 53.0°E; THEMIS image I01446006).

that many of the small craters on the plain in Fig. 2a are secondaries, and that the crater on the Noachian unit produced substantially fewer, if any, secondaries. (We discount the likelihood of erosive loss of the secondaries after the crater formed, because the structural detail of the crater itself appears well preserved.) Figure 3 makes a similar comparison of craters on a Hesperian unit; the slightly smaller crater in Fig. 3b has dramatically fewer secondaries.

Significantly, the survey revealed a progressive increase in crater diameter D needed to launch secondaries as the age of background terrain increases. On Amazonian volcanic plains, we found craters as small as $D \sim 10$ km surrounded by secondaries. On Hesperian ridged plains units, the smallest crater which had a discernible secondary crater field had $D \sim 19$ km, while on Noachian terrain units it was $D \sim 45$ km. The limits are not precise. As shown in Fig. 3, even on a single geologic unit, small differences in D and d appear to affect the presence of secondaries. Cases were found where one crater might lack secondaries and a slightly smaller one not far away might have secondaries—variations which we attribute to localized differences in subsurface structure and volatile content.

The Noachian regions covered in this survey constitute ~31% of the entire surface area of Mars, while the surveyed Hesperian regions make up ~5% and the surveyed Amazonian regions, ~3%. The fact that we surveyed enough Noachian units to make up almost one-third of the entire planet's surface and found essentially no craters <45 km in diameter

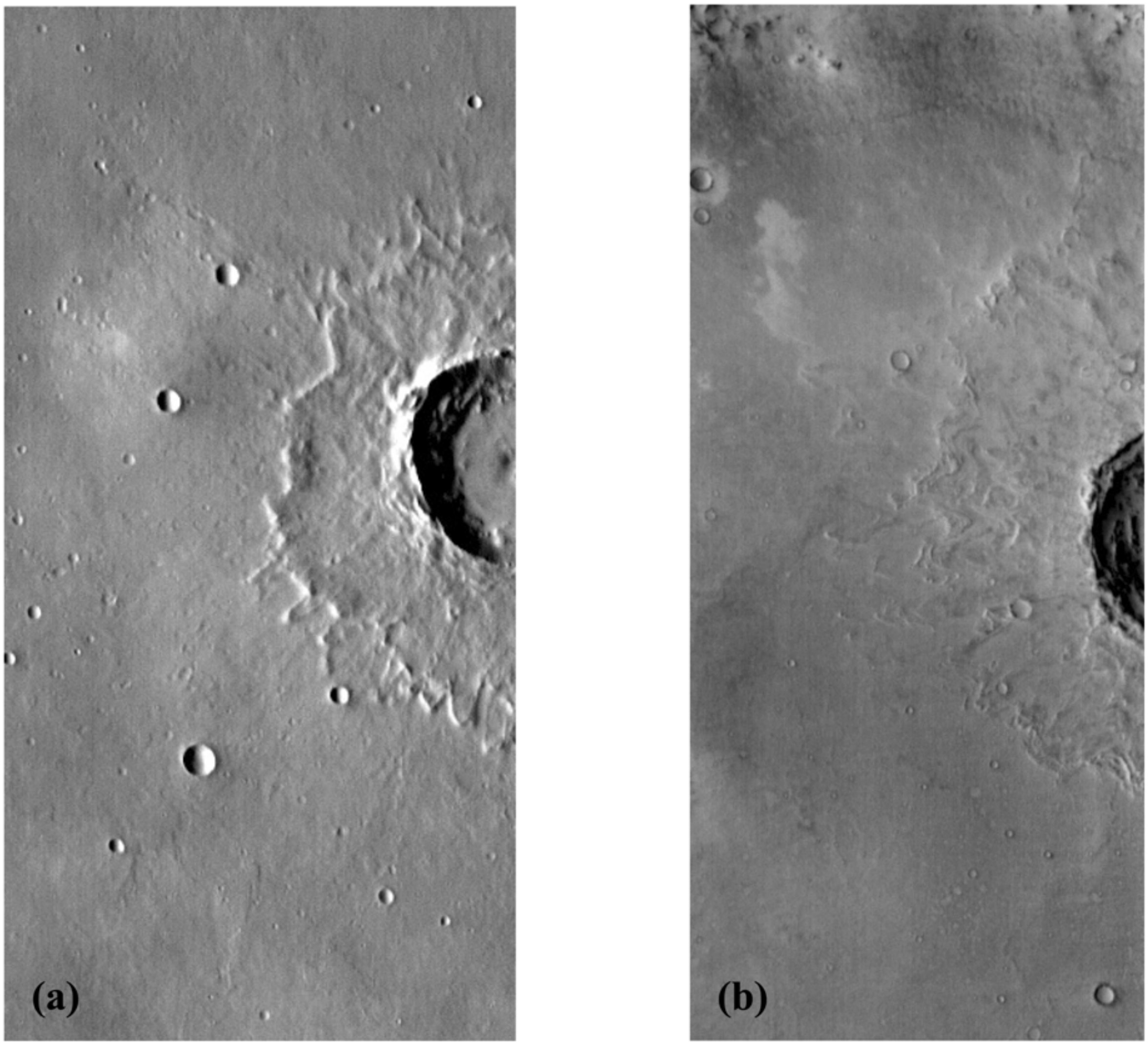

Fig. 2. A comparison of secondary cratering from similar-sized craters on Amazonian volcanic plains and Noachian plateau unit. a) Abundant secondary craters appear left of the layered ejecta blanket surrounding a crater 14 km in diameter on Amazonian stratigraphic unit At4 (22.5°N, 267.9°E; THEMIS image I02662005). b) Secondary craters are not associated with this crater, 16.6 km in diameter, on the Noachian stratigraphic unit Npld. Note that although the background is classified as older, fewer craters are seen than in (a), showing that the craters in (a) are dominated by secondaries (10.4°S, 3.1°E; THEMIS image I01249001).

with secondary crater fields proves that some property of these older regions retards launch of coherent large blocks—in agreement with the "Heavily Cratered Upland Crust: Theoretical Considerations" section and with the lack of MMs from such regions.

We did not find obvious differences in sizes of craters with secondaries within the major geologic systems: for example, the smallest crater with a secondary crater chain found on the upper Late Noachian Npl2 unit was 48 km, while the smallest on the Middle Noachian Npl1 unit was 47 km. Future studies with larger samples might seek such effects. Also, high-resolution Martian Orbiter Camera (MOC) images do reveal boulders ejected locally around craters of $D < 10$ km in what have been interpreted as fresh lava or bedrock areas; thus for the youngest areas there is an issue of the scale at which rocks are ejected but are too slow and small to make well-formed secondary impact craters. The overall pattern is striking, however; 10–20 km primary craters may have close secondary crater fields in Amazonian volcanic plains but not in Hesperian and Noachian terrain.

These results confirm a theoretical prediction by Head et al. (2002, p. 1754): in their study of spall effects with various thickness of regolith over solid rock, they estimated D of ~20 km for the minimum size crater needed to eject substantial amounts of potential MM material from "ancient terrains" of Mars. The result is also consistent with the work of McEwen et al. (2005) on 10 km crater Zunil, which has launched many secondaries from a young lava plain. (Note that larger ejected blocks—and probably larger craters—are needed to create secondary craters than to create MMs.)

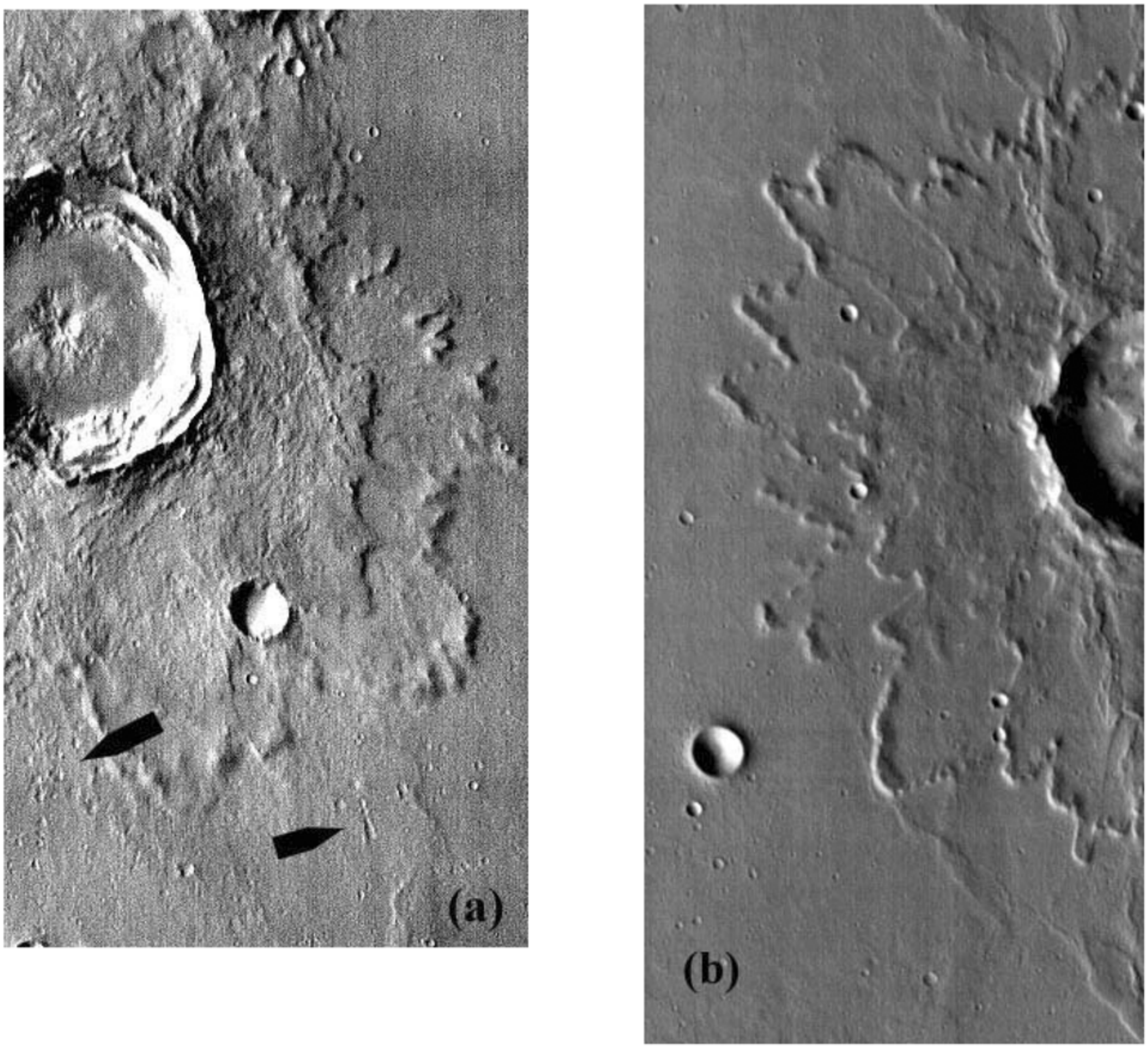

Fig. 3. Fresh craters on Hesperian ridged plains. a) This crater, 18.7 km in diameter, displays secondary craters beyond the layered ejecta boundary (arrows highlight a few of the secondary crater chains). The crater is located on the Hesperian ridged plains of Lunae Planum at 10.51°N, 290.60°E (THEMIS image I02761003). (b) This crater, 15.9 km in diameter, is located to the southeast of the one shown in part (a), at 8.34°S, 297.14°E. Although this crater is located on the same terrain and appears morphologically fresher than that in (a), no secondary crater chains are visible beyond the distal rampart of the layered ejecta blanket. The major difference between these two craters is their size (THEMIS image I09489019).

Production of widely scattered "distant secondary craters" from old Martian uplands is thus demonstrably less efficient than from young volcanic plains. This effect is somewhat tempered, however, by the fact that the largest blocks of high-speed ejecta come from the very large craters (Vickery 1986, 1987), which can penetrate megaregolith and produce high-speed blocks by spallation. Thus, the largest examples of distant secondaries, or large clusters of secondary material, may be produced by the largest primary craters dotted all over Mars—craters with D perhaps greater than 80 km (Popova et al., Forthcoming), for which regolith layers are merely a skin effect. In any case, a Zunil-size crater would be much less likely to create many secondaries on Noachian, Hesperian, and perhaps even Early Amazonian terrain than on Late Amazonian terrain.

SYNTHESIS: QUANTITATIVE ANALYSIS OF OBSERVATIONS

The results of the previous sections allow a more quantitative analysis. "Classic" impact theory indicates spallation depth $h \sim 1/2$ projectile diameter d_p. Assuming d_p averages 1/20 of the primary crater diameter D, we have $h \sim D/40$. However, newer impact modeling by Artemieva

Table 1. Estimates of characteristics depths of gardened layer.

1	2	3	4
Era	Model "regolith" depth (m) ["Theoretical Considerations" section]	Estimated depth of "launch-inhibited fractured, weakened zone" (m) ["Theoretical Considerations" section]	Minimum depth to top of spall zone to produce secondaries (m) [this paper + Artemieva/Ivanov 2004 formulation, "Synthesis" section]
Amazonian	0 to ~8–18 m	0 to ~24–54 m	50 m
Hesperian	~12 to 50 m	~36 to 150 m	95 m
Noachian	~50 m to hundreds m	~150 m to kms	225 m

Note: Estimates in columns 2, 3, and 4 are independent of assumptions about absolute age. Columns 2 and 3 depend only on crater density and depth characteristics defined by Tanaka (1986). Second figure gives max. estimate of depth in regions from earliest part of listed era. Column 4 depends on Barlow's observations of minimum crater sizes to produce secondaries, and Artemieva/Ivanov's scaling of spallation layer thickness (see text).

and Ivanov (2004, pp. 89, 91) emphasizes a thinner bedrock spallation layer h of only ~1/10 d_p. In that case we have $h \sim D_{min}/200$. The minimum sizes of craters with secondary craters thus can give us an estimate of the minimum depth of "launch-inhibited" material (regolith, fragmental, and weak materials) that must be penetrated in order to reach a spall zone of coherent rock and efficiently produce sizeable high-velocity ejecta blocks. In other words, "launch-inhibited" regolith depth $\leq D_{min}/40$ or $D_{min}/200$. The theoretical result by Head et al. (2002) that MM-launching craters have minimum size around 3.1–7 km is thus equivalent in their formulation to a regolith or launch-inhibited zone of depth of order (3.1 km/40) = 77 m to (7 km/40) = 175 m, but in the Artemieva/Ivanov formulation the depth would be ≤15–35 m. Presumably these numbers apply mainly to Amazonian-era lava plains.

This can be compared to our observational result in the "Heavily Cratered Upland Crust: Observational Considerations" section, where we found in the Amazonian era a characteristic D_{min} = 10 km, indicating a characteristic launch-inhibited zone depth $h \leq$ 50–250 m to reach coherent rock and produce secondaries—reasonable agreement with the above range. Note that the more recent Artemieva/Ivanov result is the first, smaller figure, 50 m. For the Hesperian the figures are D_{min} = 19 km, h = 95–475 m; for the Noachian, D_{min} = 45 km, $h \leq$ 225–1100 m.

Table 1 shows a summary of the analyses of characteristic properties for the three eras, independently derived in the "Heavily Cratered Upland Crust: Theoretical Considerations" and "Heavily Cratered Upland Crust: Observational Considerations" sections. Column 2 lists regolith depth estimated from the geometric model, based on minimum depths of craters that cumulatively cover 100% of the area, as discussed in the "Theoretical Considerations" section. Since the regolith does not end abruptly in coherent bedrock, column 3 lists the estimated total depth to the base of the zone weakened by fractures penetrating into bedrock beneath the regolith, assumed to extend 3 times the calculated regolith depth (corresponding to several crater radii below the smallest craters in saturation equilibrium). Column 4 lists the completely independent estimate of spall depth based on the Barlow observation of minimum size craters with secondaries, plus the recent Artemieva/Ivanov estimate of typical spall depth = 1/10 projectile diameter. If our ideas are correct, substantial numbers of high-speed coherent blocks, capable of making secondary crater fields, should not appear until the spall zone penetrates below the "launch-inhibited" regolith and even below the zone weakened by fracturing. Indeed, the table shows a rough but remarkable similarity between our estimates of the depth of the fractured zone from crater densities (column 3) and the theoretical spall depth of the launch-inhibited zone corresponding to observed minimum sizes of craters with secondary crater fields (combined with Artemieva/Ivanov theory). We conclude that both qualitative and quantitative arguments support the idea that older regions do not launch secondary debris as efficiently as Late Amazonian lava plains do. Independent support for these conclusions comes from work by Tornabene et al. (2005), who identified about half a dozen multi-kilometer Martian craters fresh enough to preserve clear ray systems. These were all in lava plains, not ancient uplands, and Tornabene et al. argued that only lava plains allow the spallation process that allows the launch of high-velocity jets of rocks and debris that form large-scale ray systems. While these observations warrant further study, this work appears consistent with our suggestion that Martian uplands do not launch high-velocity materials as efficiently as Martian lava plains.

CRUDE PLAUSIBILITY TEST AGAINST CRATER PRODUCTION RATE

The data cited above suggest that the primary craters which create MMs and secondary impact craters are not formed uniformly over the full 144 million km^2 of the Martian surface, but rather come preferentially from the 23.3 million km^2 (or 16%) of the present surface covered by Amazonian volcanic units (not counting other, nonvolcanic, less coherent Amazonian units), or even only the 10 million km^2 (7%) covered by the Middle and Late Amazonian volcanic units thought to be younger than about 1.3–2.0 Gyr (areas from Tanaka et al. 1988; crude dating from Hartmann and Neukum 2001). Hartmann and Neukum (2001, Fig. 14) indicate that ~6×10^{-4} craters of $D > 1$ km currently form over each km^2 per Gyr, translating to 1700 over all of Mars in the last 20 Myr. Using the power law with exponent −1.8 for the size distribution in this diameter range, we find that the number of craters larger than 7 or even 3.1 km (the minimum size range for MM launching craters from Head et al. 2002) would be 0.03 and 0.13 times the above number, respectively, or in the range of 50 to 220 candidate impact sites. Craters larger than 3 km are thought to be mostly primaries. A similar test using Hartmann's most recent iteration of Martian crater isochrons (Hartmann 2005) gives about 2.6×10^{-7} and 12×10^{-7} craters/km^2 larger than 7 and 3.1 km, respectively, on 20 Myr-old Martian surfaces, or in the range of 40 to 170 candidate craters larger than 3.1 to 7 km. These numbers appear much higher than the likely number of impact sources (especially in view of the fact that our sample of ~30 rocks includes multiple finds from single Martian sites, suggesting that the total number of major contributing Martian sites is not much higher than observed).

However, if we assume from the above paragraph that only 7–16% of Mars has coherent igneous rock units near the surface that are capable of launching appreciable number of coherent rocks, this would give numbers more like (7% × 40 =) 3 to (16% × 170 =) 30 craters on Mars that launched young igneous rocks in the last 20 Myr. These latter numbers appear plausible, based on the fact that we have sampled 5–9 such sites in the first ~30 MMs. Earlier workers, without as much discussion of regolith evolution or regolith depth in different provinces, also suggested that MMs in our collections may be launched only from a restricted percentage of the total Martian surface (Head et al. 2002, p. 1755, suggest 10–40% of Mars for shergottites, and another 10–40% for Nakhlites and Chassigny; Artemieva and Ivanov 2004, pp. 98–99, citing Head et al., mention not only regolith depth properties but also altitude of the launch site as possible factors influencing launch efficiency).

To extend this logic, let us follow the suggestion by Head et al. (2002) that craters of $D > 20$ km would be necessary to launch appreciable numbers of rocks from older upland areas under deep regolith. Using the −1.8 power law, the numbers of these would be 0.15 × the number of 7 km craters, or 0.15 × 40 or 50, = 6 or 7 sites from all over Mars. If the Noachian upland sites cover 40% of Mars, the numbers would be more like 2 or 3 impacts in the last 20 Myr. This averages less than the 3–30 sites calculated for young source regions, but suggests that we still might find some MMs launched from ancient Martian highland regolith-covered sites (if we can recognize such MMs).

One other effect comes into play to explain the observations. The whole analysis would be easier if only one size of crater launched all MMs; but in reality we have to take into account the effects of a range of crater sizes. Although small craters are more common than big ones, MMs may actually be dominated by the largest craters formed in the last 20 Myr (assuming a coherent spall zone deep enough to be tapped by the largest craters), because the number of rocks launched is proportional not to crater frequency, but more nearly to crater volume ($V \propto \sim D^3$) times crater frequency ($N \propto \sim D^{-1.82}$ for D = few km). This means that in a given period (e.g., last 20 Myr of MM launches), the number of rocks launched as a function of source crater diameter D goes as ~$D^{1.2}$. This has the interesting consequence that the number of rocks launched in that period is not controlled by the "smooth" statistics of the smallest, most numerous craters (i.e., the 3 km minimum size found by Head et al. 2002 or 1.5 km minimum of Beck et al. 2005), but rather by the highly stochastic statistics of the largest craters that can launch from the given type of terrain, not to mention whether the larger crater formed, say, 1 Myr ago (such that many fragments are still in space) or 19 Myr ago (such that most fragments have been swept up by planetary encounters). Sweep-up effects have been modeled by Gladman (1997) in some detail. He finds that 50% of potential Earth-impacts by rocks ejected from Mars would have occurred in about 15 Myr in the absence of collisional disruption; but in view of collisional disruption at aphelia in the asteroid belt, the observed half-life is closer to 7 Myr. The last, infrequent collisions with Earth could in principle extend beyond 20 Myr (though these have not turned up in CRE ages of the MM collection). The number of large source craters dominating the MMs launched in the last 20 Myr cannot be predicted precisely from first principles, but is probably less than the total number of source craters large enough to launch rocks off Mars in the same time interval.

SPECIAL SIGNIFICANCE OF ALH 84001

Any solution of the "paradox" of MM ages must take into account that the one sample older than 1.3 Gyr comes from igneous rock formed not at a random time, such as 2.1 or 3.4 Gyr, but at the unique and specific time of crustal formation, 4.5 Gyr ago. Even a model that assumes all Martian surfaces launch equally, and dismisses the "paradox" as a product of small number statistics, must face the problem that we have one rock from a narrow, unique era: an igneous cumulate sample of the original igneous crust of Mars, formed 4.50–4.56 Gyr ago (Nyquist et al. 2001). And in a model such as ours, which assumes that accumulated cratering, volatiles, and weathering effects render a surface incapable of launching rocks, one might naively expect a 4.5 Gyr rock to be the least likely to be launched! However, we must take into account the likely volume of material available for launch as MMs from a Mars where erosion and exhumation are constantly exposing old surface units (e.g., Malin and Edgett 2001). Obtaining a basaltic MM from a Martian lava flow formed 4.1 Gyr ago, for example, would be unlikely in our model because most flows are less than tens of meters thick, and would have been reduced to rubble by impacts within a hundred Myr by the early intense bombardment, if created on the surface 4.1 Myr ago (Hartmann et al. 2001). (Such a basaltic MM would be not be impossible under an ad hoc scenario, of course; a flow at 4.1 Myr ago could be quickly buried under hundreds of meters of sediments, protecting it from impact, erosion, and weathering, and then uncovered within the last few hundred Myr, exposing coherent rock capable of launching ejecta by spallation within the last 20 Myr.)

In contrast, the original cumulate crust was not tens of meters thick, but was tens of kilometers thick—a semi-infinite layer for our purposes. The implication is that when Martian erosion and exhumation remove the megaregolith cover in some areas of Mars, the end state is to expose the "infinite reservoir" of 4.5 Gyr old coherent rock, kilometers thick. (This megaregolith probably once averaged ≥1–3 km thick, neglecting erosion/deposition; cf. Hartmann 1973b, 2003; Hartmann et al. 2001). Thus, on a planet with active erosion and exhumation (Malin and Edgett 2001), exposure of patches of primordial crust is likely, favoring the occasional launch of crustal MMs.

Full exposure of crustal bedrock is not necessary, according to the models of Artemieva and Ivanov (2004). In regions where megaregolith has been merely thinned, but not removed by erosion, the once deep but now shallow megaregolith layers would have abundant crustal fragments from the "semi-infinite" reservoir of 4.5 Gyr old crust immediately below. Deep craters in such regions would excavate much larger volumes of 4.5 Gyr old crust that of any other rock units, due to the effectively "semi-infinite" volume of this substrate.

This effect does not work as efficiently on the Moon, because, in the absence of fluvial and subaerial erosion, the lunar primordial cumulate crust is "sequestered" under several kilometers of megaregolith and very rarely tapped by impacts in the last ~10^7–10^8 yr.

In short, Mars produces very young and very old MMs because the young rock layers are more efficient in launching MMs, and the oldest reservoir (crust) dominates in volume. Our model suggests that Mars may be the only world in the inner solar system where the original, cumulate crust exists in surface exposures or bedrock within a few hundred m of the surface.

CONCLUSIONS

1. The heavily cratered (old) Martian uplands have been gardened and fractured to substantial depths. The crater densities used to define Noachian and Hesperian terrain imply early production of regolith or megaregolith of tens to hundreds of meters, depending on age. If there is bedrock below those depths, it would be weakened by fractures extending below the loose regolith. Tanaka et al. (1988, Table 2) list 28% of Mars as being early and middle Noachian, another 12% of Mars being upper late Noachian in age, and another 34% being Hesperian, indicating that effects of megaregolith generation must be widespread, covering perhaps ~74% of Mars.
2. On Mars, unlike the Moon, this regolith and megaregolith (even if mobilized by eolian and fluvial transport) served as an ideal repository for the massive amounts of early water. Impregnation with ground ice is nearly certain at depths of >400 m (equatorial) to <100 m (high latitudes) (Squyres et al. 1992; Boynton et al. 2002). From item (1), we thus infer that the upper hundreds of meters of ancient, heavily cratered Martian uplands are likely weakly consolidated or cemented by ice and evaporite materials, and are probably interbedded with other stratigraphic layers such as weathered, impact-gardened lava flows, eolian deposits, and fluvial sedimentary deposits. Thinly bedded sediments discovered by the Opportunity and Spirit rovers in 2004 support this and have strengths typically only a few percent of Martian or terrestrial basalts (Arvidson et al. 2004), providing in situ evidence for weaker materials in these older regions. In short, old Martian near-surface layers are mostly weakly consolidated and/or ice-rich.
3. Current models indicate that the most efficient launch of high-velocity Martian rocks comes from coherent bedrock and not from fragmental or weak material (Head et al. 2002; Artemieva and Ivanov 2004). Solid materials such as fresh lavas favor launch of MMs by spallation. In loose regolith material, few large rocks per unit volume exist to be launched and escape, and dissipation of impact energy reduces efficiency of launch at $V \sim V_{escape}$. Therefore, based on (2) and (3), we infer that the oldest areas of Mars are inefficient at launching MMs. With 40% of Mars' surface dating from the Noachian period, and 74% being Hesperian or Noachian, this effect could seriously affect age distributions of MMs.
4. We report a deficiency of secondary impact craters surrounding primary impact craters in the Martian uplands, directly supporting the above conclusions. As we go from Amazonian through Hesperian to Noachian backgrounds, the minimum primary crater diameter to produce secondary fields increases from ~10 to ~19 to ~45 km, respectively
5. The 10 km crater Zunil, which broadcast secondaries over much of Mars from an impact site in young Elysium Planitia lavas, would probably not produce many secondaries from impact sites if it had formed in the 74% of Mars that is Noachian and Hesperian. This consideration may substantially reduce the expected numbers and consequences of Martian secondaries relative to earlier estimates such as that of McEwen et al. (2005).

6. The number of MM launch sites is consistent with the estimated number of Mars-meteorite-launching craters (*D* exceeding a cutoff size of about 3.1–7 km, as per Head et al. 2002) formed in the last 20 Myr on volcanic surface units formed since the beginning of the Middle or Early Amazonian (plausibly the last 1.3 Gyr), but not with such craters on the whole planet. This supports our assertion that MMs are launched primarily only from younger geologic units.
7. From theoretical modeling of impact crater processes, it is currently difficult to estimate what thickness in a surface layer of loose, weak, or ice-impregnated material is sufficient to interfere with spallation processes, or whether the amount of regolith cover on 1.3 Gyr, 2.0 Gyr, or 2.5 Gyr old coherent rock layers is truly sufficient to retard the launch of MMs. Useful future work would include a) a critical examination of the role of volatiles in modifying impact ejection models, and b) more detailed impact modeling with a fragmental layer of depth *d* overlying a deeper spall layer of thickness *h* (calculated from impactor size) of coherent rock with various specified strengths, to determine at what *d/h* ratio and rock strengths high-speed launch of high speed solid blocks is retarded.
8. The existence of a sample of the primordial igneous cumulate crust (4.5 Gyr old ALH 84001) from one out of 5–9 launch sites is probably significant and should be accounted for in any model of the statistics and mechanics of MM launch. Our explanation is that it indicates the presence of a thick, primordial Martian igneous cumulate crustal layer (too thick to have been pulverized by early cratering, i.e., > over a few km thick). We infer that Martian erosion/exhumation processes have revealed surface "exposures" of this crust in some areas (probably within tens of meters of the surface to allow spallation launch of rocks), or that bedrock masses of the crust are near enough to the surface in some areas that impacts have ejected substantial-sized blocks of it into the near-surface regolith (probably within some tens of meters of the surface, from which a piece has been launched). This semi-exposed crust probably exists over an appreciable percentage of the Martian surface (≥10%?) in order to create statistical plausibility of one sample out of 5–9 random launch sites. Among the terrestrial planets, such exposure or near-exposure of the primordial crust may be unique to Mars (since primordial crusts have been destroyed by plate tectonics on Earth and possible overturn on Venus, and is buried under megaregolith/breccia on the moon and probably on Mercury).
9. Our model may explain the crude trend in which MMs with older formation ages tend to have older cosmic-ray exposure ages, since larger craters are needed to launch rocks from most older areas (cf. the "Relation of MM Formation Ages and CRE Ages" section).

To summarize, the statistics of many igneous MMs from several <1.3 Gyr old units, and one from exactly 4.5 Gyr, are pregnant with meaning. We conclude that the fragmental, weakly bonded (and at some latitudes ice-rich) character of the top tens or hundreds of meters of upland subsurface at least partially explains the current apparent deficiency of older MMs (rocks from all but one of 5–9 launch sites come from the last 29% of Martian time). The best launch conditions occur in recent lava flows and igneous rock surface units formed in the last 1.3 Gyr, or perhaps the last 2 Gyr, and in exhumed surface exposures of the thick, coherent primordial igneous cumulate crust. Even if samples of older, weakly aggregated Martian upland sediments or weak breccias are occasionally launched and reach Earth, they may not efficiently survive atmospheric entry, or if they do, there may be selection effects against their recognition as meteorites.

Acknowledgments–Thanks to colleagues at PSI for comments and Elaine Owens for help with manuscript preparation and editing. Thanks to James N. Head and Larry Nyquist for outstandingly careful and helpful reviews and suggestions. W. K. H. was supported by NASA MDAP grant #NAG5-12217. W. K. H. also thanks the International Space Science Institute in Bern for hospitality during some of this work. N. G. B. was supported by NASA MDAP grant NAG5-12510 and the 2004 NAU Intramural Grants Program. This paper is PSI contribution number 384.

Editorial Handling—Dr. Allan Treiman

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