Survival times of meter-sized boulders on the surface of the Moon

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ABSTRACT

Analysis of the abundance of ejecta boulders \( \geq 2 \text{ m in diameter on the rims of twelve lunar craters (150–950 m in diameter of known formation ages (2–300 Ma)} \) led to estimates of the survival times of meter-sized boulders against collisional destruction on the Moon. The median survival time, when 50% of the original rock population \( \geq 2 \text{ m was destroyed}, \) is about 40–80 Ma, while the 99% survival time (99% of rocks destroyed) is about 150–300 Ma. These estimates are a factor of 5 shorter than the survival times that one would extrapolate from the calculations of Horz et al. (1975a) for surface rocks \( < 20 \text{ cm in diameter}. \) However, recent experimental insights into the effective strength of different sized targets (Housen and Holsapple, 1999) suggest that meter-sized boulders have effective strengths a factor of 2–3 less than 10 cm sized rocks, thus reducing the survival times of meter-sized boulder by similar factors. Additionally, Horz et al. (1988) demonstrated that the cumulative effects of multiple impacts are more severe than assumed in the 1975 paper, thus decreasing the survival times of all surface rocks, regardless of size, by an estimated 20–30%. Also, typical crater ejecta are fractured at macroscopic and microscopic scales, and thus most likely weaker than the “pristine” crystalline rocks used in laboratory “calibration” experiments. These considerations bring the model calculations into much better agreement with our actual boulder observations. As a consequence we suggest that the new estimates are more realistic than those of Horz et al. (1975a). Accounting for the differences in impact velocities and impact rates for the Moon and Mars, our survival times of lunar rocks \( \geq 2 \text{ m in diameter may also apply, within a factor of 2, to the surface boulders of Phobos and Deimos.} \)

1. Introduction

Rock boulders are frequently observed on the surfaces of planetary bodies and their residence times at the surface can reveal the nature and rates of small scale erosion and weathering processes. In this paper we consider the survival times of meter-sized boulders on the surface of the Moon. As shown by Gault and Wedekind (1969), Shoemaker (1971), Gault et al. (1972), Horz et al. (1975a), and McDonnell et al. (1977), the destruction of lunar surface boulders is largely accomplished by collisional disruption due to a single or a small number of relatively energetic impact events that deliver the critical rupture energy \( (E_R) \); a surface rock is deemed destroyed when the largest fragment remaining after some energetic collision is \( < 0.5 \) the original rock mass (Gault and Wedekind, 1969). Relatively small \( (< 0.001 E_R) \) yet numerous impacts are unable to generate penetrative fractures and merely cause some surface abrasion akin to sand blasting. The dominant process on the Moon is collisional disruption.

Horz et al. (1975a) specifically calculated the survival of hand specimen-sized rocks using Monte Carlo methods to simulate the impact environment (location and magnitude of impact events), and the experimental insights into the collisional destruction process available at that time, substantially relying on unpublished experiments by Gault on granites and basalts (see Horz et al., 1975a). These model-calculations produced good agreement with measured exposure ages of the Apollo rock suite. Accordingly, the median survival time at which 50% of original 10 cm diameter rocks were destroyed is on the order of 107 years, while the 99% survival time (where 99% of the original rock population is destroyed) is on the order of 3.5 \( \times 10^7 \) years. A large number of subsequent collisional fragmentation experiments on various geologic materials, including meteorites, and conducted by a number of experimental groups, are summarized by Cintala and Horz (2008). These subsequent investigations confirmed the results of Gault on crystalline rocks and substantiated the experimental basis of the Horz et al. (1975a) model calculations.

The present paper purses a totally different approach to estimate the survival times of lunar surface boulders. It takes
advantage of the superb spatial resolution of the LROC NAC images (Robinson et al., 2010) which reveal the presence of numerous surface boulders on the rims and ejecta deposits of relatively fresh, small (< 1 km diameter) impact craters. The smallest boulders that can be recognized with confidence in these images are on the order of 2 m. Suitable LROC images are available for the Apollo landing sites, including 6 craters for which the absolute formation ages are known from the measured exposure histories of returned Apollo samples. Additionally, Basilevsky (1976) detailed the general morphologic evolution and degradation of similar-sized craters and proposed some relative timescale for craters < 1 km in diameter. LROC images include many such craters and an additional 6 such craters were selected in this study to complement the dated Apollo craters. The boulder population of these 12 craters ranged from some maximum at the youngest crater to essentially zero at the most degraded structure. The progressive decrease of the boulder-population can thus be traced with time, and estimates for the survival times of meter-sized boulders can be derived.

2. Survival times of lunar rock fragments of centimeter–decimeter size

The erosion and collisional destruction of lunar surface rocks by hypervelocity impact at a wide variety of scales became evident with the return of Apollo surface images and samples in the early 1970s (Shoemaker, 1971) (Fig. 1). The returned rocks especially displayed evidence of surface abrasion by micrometeorites, but also of penetrative fracturing, and eventual disruption by more energetic events (Gault et al., 1972; Neukum, 1973; Horz et al., 1974, 1975a; Horz, 1977; McDonnell et al., 1977).

Two mechanisms of erosion became evident: (1) abrasion of rocks by relatively small micrometeorite impactors and (2) catastrophic destruction of rocks by relatively energetic events. It was found that the dominant process of lunar rock destruction is their catastrophic disruption by the impact of one or a few energetic particles capable of producing penetrative fractures at the dimensional scale of the entire target rock; the much less energetic small scale impact environment merely causes abrasion akin to “sandblasting” and plays a minor role with hand specimen sized rocks (Horz et al., 1975a; McDonnell et al., 1977; Horz, 1977). This conclusion was based on impact experiments with glass, basalt and granite spheres and cubes, as well as with bonded sand targets, between 5 and 10 cm in size, and at impact velocities ~1 to 7 km/s (Gault and Wedekind, 1969; Gault et al., 1972 and as detailed by Horz et al., 1975a). Horz et al. (1975a) describe the critical rupture energy (\(E_R\)) per gram target material (ergs/g) as

\[E_R = 8.4 \times 10^6 \times \delta^{0.77} \times m^{0.925}\]

where \(\delta\) is the target density (3 g/cm\(^3\)) and \(m\) is the target mass (in grams) for targets of spherical geometry.

Calculations of survival times require the use of a projectile and ultimately energy flux at the lunar surface. Horz et al. (1975a) used the microrocrater production rates estimated by Hartung and Storzer (1974) and Horz et al. (1975b), and assumed these rates to be constant over recent geologic history. The results of their calculations are summarized in Table 1, including extrapolations to meter-sized boulders which were done by graphical extension of Figure 11 of Horz et al. (1975a).

Table 1 contains estimates of the time required to destroy 50% (median survival time) of the rocks of a given size and the time required to destroy 99% of the rocks (1% survival level). The survival times calculated by Horz et al. (1975a) are consistent with measured exposure ages of returned Apollo rocks, the reason why their Figures 11–14 are limited to spherical rocks < 20 cm in diameter. Linear extrapolation of these figures suggests that rocks with diameters ~2 to 4 m, which are seen with confidence in the LROC NAC images, have median survival times of ~250 to 500 Ma and their 99% destruction level is reached at some ~700 to 1500 Ma.

3. Survival times of lunar rock fragments of meter size

One can test the above survival times for meter-sized lunar rocks by observing the evolution of boulder populations on the rims of relatively small lunar craters of different, absolute formation ages. Penetration through the unconsolidated regolith into bedrock and ejection of the meter-size boulders is typical for lunar craters ~100 m in diameter and larger, the reason why we consider only craters with diameters ≥150 m. We also analyzed the local geologic setting of each candidate crater to verify that morphologically fresh craters, akin to the candidate or smaller, had rocky ejecta. We are thus confident that we selected twelve craters for this investigation that penetrated through the regolith and originally had rocky ejecta on their rims.

In our approach we assume that all boulders observed on the crater rims are produced or exposed in the initial cratering event and then evolve on the surface. Possible excavation of boulders by newly formed, smaller craters is not significant, as such craters are rare in our test areas, as detailed in the discussion. Also, none of the test areas contained large, fresh craters in the vicinity that could have buried meter-sized boulders under its ejecta.

The LROC NAC images used in our study have a spatial resolution ~ 0.5 m per pixel and we can see reliably all rock fragments ≥ 2 m in diameter. The website http://apollo.mene-tek.com/LRO_NAC_Apollo_Images.html was very helpful in searching for the appropriate images. Within the rim of each of these twelve craters, a 100 × 100 m\(^2\) area was selected and it was within this (high-resolution) square where we studied and counted the abundance of surface boulders. The locations of the 100 × 100 m\(^2\) areas within the crater rims considered were carefully selected to ensure that we had a typical area representative of the terrain. Fig. 2 illustrates two examples of this approach.

Using high-resolution LROC NAC images, a total of twelve craters were studied and the results are summarized in Figs. 3–5 and Table 2. The diameters of these twelve craters vary from 180 to 950 m. In principle, the difference in the crater diameters could somehow affect our results. But because among the twelve considered craters the smaller and the larger ones are both morphologically fresh and subdued to very subdued, this influence seems not to result in a systematic error, but rather leads to some “noise”.

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<th>(10^1)</th>
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<td>6.2</td>
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<tr>
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<td>224.8</td>
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* assuming that the rock is of spherical shape.
The absolute formation ages of six craters were determined by cosmic ray exposure studies of samples collected by the Apollo astronauts on the rims or ejecta deposits of these craters (Arvidson et al., 1975; Borchard et al., 1986; Eugster, 1999; Funkhauser, 1971; Kirsten et al., 1973a, 1973b; Stettler et al., 1973; Turner et al., 1971; Waenke et al., 1971). These are: South Ray, North Ray, Cone, Camelot, Surveyor and Elbow. Following is a brief summary of their characteristics:

1) The morphologically very prominent South Ray Crater is \( \sim 680 \text{ m} \) in diameter and dominates the southern Apollo 16 landing site (Muehlberger et al., 1972). The astronauts did not visit this crater but they could identify and sample its ejecta at some distance from the crater. Its age of \( \sim 2 \text{ Ma} \) is based on the cosmic ray exposure time of numerous samples (Arvidson et al., 1975; Eugster, 1999). The LROC images show that the rim and inner slopes are covered with numerous rock fragments with diameters from \( 2 \text{ to } 15–20 \text{ m} \) (Fig. 3a) and areas devoid of boulders are rare. Several small impact craters, a few meters in diameter, are superposed on the ejecta blanket.

2) The morphologically very prominent Cone Crater, \( \sim 340 \text{ m} \) in diameter, is located at the Apollo 14 site (Swann et al., 1971). The astronauts climbed up close to the rim crest and sampled its ejecta. Based on these samples it was possible to estimate its age as \( \sim 26 \text{ Ma} \) (Turner et al., 1971). In the LROC images and in situ Apollo surface photography it is seen that the crater rim and inner slopes are covered with numerous rock fragments with diameters from \( 1\text{ to }5–10 \text{ m} \), forming clusters among areas almost free of boulders (Fig. 3f). A number of craters, 3 to 10 m in diameter, are superposed on the ejecta.

3) North Ray Crater, \( \sim 950 \text{ m} \) in diameter, dominates the Northern portion of the Apollo 16 site (Muehlberger et al., 1972). The astronauts reached its eastern rim; they sampled its ejecta on the rim and at some distance to the east. Based on these samples it was possible to estimate its age as \( \sim 50 \text{ Ma} \) (Arvidson et al., 1975; Borchard et al., 1986; Fernandes et al., 2013). In the LROC images and in situ Apollo surface photography it is seen that the crater rim and inner slopes are covered with numerous rock fragments with diameters from \( \sim 1\text{ to }5–10 \text{ m} \), forming clusters among areas almost free of boulders (Fig. 3f). A number of craters, 3 to 10 m in diameter, are superposed on the ejecta.

4) The morphologically degraded Camelot Crater, \( \sim 650 \text{ m} \) in diameter, is located at the Apollo 17 landing site (Muehlberger et al., 1973). Astronauts traversed its rim and sampled remnants of its ejecta. Based on these samples it was possible to estimate its age as \( \sim 85 \text{ to } \leq 140 \text{ Ma} \) (Kirsten et al., 1973b) and we assume \( \sim 100 \text{ Ma} \). The images taken from orbit and in situ show the crater rim and inner slopes to possess clusters of rock fragments with diameters from \( \sim 2 \text{ to } 5 \text{ m} \), yet much of the test area is free of boulders (Fig. 3h). Superposed craters, 3 to 10 m in diameter, commence to become numerous here.

5) Surveyor Crater, \( \sim 200 \text{ m} \) in diameter, is even more degraded than Camelot (Shoemaker et al., 1970); the Apollo 12 lunar module landed on its N-rim. The astronauts sampled remnants of boulders on the slope of central peak complex of lunar crater Schiller (image LROC NAC M109502471LC).
of its ejecta and these samples yielded age estimates of 180 to 240 Ma. (Funkhauser, 1971; Waenke et al., 1971); we assume 200 Ma to be representative. The images taken from orbit and in situ by Apollo show rare clusters of rock fragments with diameters from \( \sim 2 \) to 3 m on the rim and inner slope, but most of the area is free of boulders (Fig. 3j). Superposed craters of 3 to 15–20 m in diameter are numerous here.

6) The morphologically degraded Elbow Crater, \( \sim 400 \) m in diameter, is located at the Apollo 15 site (Swann et al., 1972). Astronauts reached its rim and sampled remnants of its ejecta. Its age is estimated at \( \sim 280 \) to 330 Ma (Stettler et al., 1973; Kirsten et al., 1973a), and we assume 300 Ma. The images taken from orbit and in situ show only rare rock fragments, with diameters of a few decimeters, but most of the area is boulder-free (Fig. 3l). Superposed craters of 3 to 15–20 m in diameter are abundant. A boulder \( \sim 2 \) m in diameter is seen in the study area inside a crater of about 10 m in diameter; this boulder may be not a remnant of the primary rock population of Elbow crater, but one that was excavated later by this small crater.

The absolute ages of the other six craters are based on their morphologic appearance and size, as suggested by Basilevsky (1976). This method compares the degradational state of a crater with that of dated Apollo craters, including the above 6 structures, but also including smaller craters that were eliminated from the present study, because there was no assurance that they had a substantial boulder population initially. More recently, Basilevsky and Head (2012) demonstrated that this morphologic approach to relative and absolute crater ages agrees well with dating by crater counting methods (Morota et al., 2009). However, its accuracy is difficult to estimate and lies probably within \( \pm 50\% \) of the determined age value.

The group of six additional craters included:

1) A morphologically fresh crater, 200 m diameter, \( \sim 13 \) km south of the Luna 24 landing site, penetrating the basaltic plains of Mare Crisium (Fig. 3b). It is probably a secondary crater by ejecta from the farside crater Giordano Bruno. The morphologic age of these secondaries was estimated to be between 5 and 10 Ma (Basilevsky and Head, 2012). Abundant rocks of 2 to 10 m in diameter are seen in the study area.

2) A morphologically fresh 400 m crater \( \sim 18 \) km north of the Apollo 12 site, superposed on the basaltic plains of this region of Oceanus Procellarum (Fig. 3c). Judging from shadow measurements on image M120005333LC, the western inner slope is very steep, about 35°. This implies that this crater belongs to the morphologically prominent class A of Basilevsky (1976) and suggests that its age is close to that of Cone Crater at the Apollo 14 landing site, i.e.

![Fig. 2.](image-url)
between 20 and 30 Ma (Basilevsky, 1976). Abundant rocks of 2 to 10 m in diameter are seen in the study area.

3) The third member is a 180 m crater near the Lunokhod 1 site in Mare Imbrium (Fig. 3e). It is 350 m west of the small crater Albert (http://planetarynames.wr.usgs.gov/). Its depth, as measured on the topographic map of this area (Karachevtseva et al., 2012, 2013), is ~22 m. This diameter/depth ratio identifies this crater as morphologic class B, yet close to the AB boundary of Basilevsky (1976). We estimate its age to be 30 to 40 Ma. Blocks 2 to 5 m in diameter with a few larger ones are seen in the study area, but significant parts are almost free of them. Several craters smaller than 10 m in diameter are seen in the study area.

Fig. 3. The 100 × 100 m² analysis areas on the rims of twelve lunar craters for which absolute formation ages were known or estimated: (a) South Ray Crater at the Apollo 16 site, (b) 200 m crater in the vicinity of Luna 24 site, (c) 400 m crater in the vicinity of Apollo 12 site, (d) Cone Crater at the Apollo 14 site, (e) 180 m crater in the area of Lunokhod 1, (f) North Ray Crater at Apollo 16, (g) 450 m crater Borya in the area of Lunokhod 1, (h) Camelot Crater at Apollo 17, (i) Spook Crater close to the Apollo 16 lander, (j) Surveyor Crater 1 at Apollo 12, (k) 300 m crater at the Apollo 14 site, (l) Elbow crater at the Apollo 15 site. Upper right hand of each framelet identifies the target terrain: H – highland, M – mare; the lower left shows the estimated crater age. White arrows show rock fragments. Parts of images M144524996RC, M119449091RE, M120005333LC, M114064206LC, M175502049RC, M129187331LC, M175502049RC, M134985003LC, M126825870LC, M117650516RC, M131765772LC, and M117467833RC, respectively.

Fig. 4. Cumulative number of rocks > 2 m in each of the 100 × 100 m² analysis areas of the 12 lunar craters labeled (a–l) in Fig. 3. Gray symbols designate highland sites and black symbols represent mare sites. Note the systematic decrease of boulder populations with increasing crater age (a–l).
4) The fourth crater is the 450 m crater Borya (http://planetary names.wr.usgs.gov/); it is also located in the Lunokhod 1 area of Mare Imbrium (Fig. 3g). Its depth is ~52 m. (Karachevtseva et al., 2012, 2013). This identifies this structure as morphologic class AB, close to the boundary with B of Basilevsky (1976). We estimate its formation age to be 50 to 60 Ma. Blocks 2 to 5 m in diameter with a few larger ones are seen dispersed in the study area. Craters smaller than 10 m in diameter are seen in the study area.

5) The morphologically degraded crater Spook, some 700 m in diameter, is located ~500 m west of the Apollo 16 lunar module (Fig. 3i). Judging from shadow measurements of image M102064759RC taken at the Sun elevation ~5°, the depth/diameter ratio of this crater is about 1/7. This places it at the boundary between morphologic classes AB and B. We suggest a formation age of 150–200 Ma. Several craters 10–20 m in diameter are seen in the study area. A boulder ~2 m in diameter is seen in the study area on the rim of the 20 m crater. It may be not a remnant of the primary rock fragment field of Spook crater, but excavated by this relatively small crater.

6) This morphologically degraded crater, 300 m in diameter, occurs ~150 m NNE of the Apollo 14 lunar module (Fig. 3k).

Analyzing the shadow geometries of images M132943081RC and M131765772LC, the depth/diameter ratio of this crater is 1/10. This places it at the boundary between morphologic classes B and BC of Basilevsky and Head (2012) and suggests that its age is close to ~300 Ma (Basilevsky, 1976). A few boulders of 2–4 m in diameter are seen in the study area. Numerous craters smaller than 10 m in diameter occur in the study area.

As can be seen in Figs. 3–5, and Table 2, the rims of the first three craters having ages of ~2, 5–10 and 20–30 Ma, respectively, have very rocky, pristine surfaces. Rims of the next three craters with the ages ~26, 30–40 and ~50 Ma have moderately rocky surfaces and it appears that 50% or more of their primary rock population has been destroyed. Rims of the next two craters, having ages 50–60 and ~100 Ma, show the presence of the rock clusters, but most of the rim area is devoid of rock fragments. Referring to Figs. 4 and 5, typical spatial densities for > 2 m boulders in fresh craters such as South Ray are 300–400 per test area of 100 × 100 m (0.01 km²). The spatial densities for boulders > 10 m in Fig. 4 compare favorably with earlier boulder counts on fresh craters by e.g. Cintala and McBride (1995), yet the improved

Fig. 5. Number of boulders > 2 m observed in a 100 × 100 m² analysis area of 12 lunar craters 4 of known or estimated formation age; letters refer to craters in Fig. 3.

Table 2

<table>
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<tr>
<th>Key to</th>
<th>Site</th>
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<th>Crater age (Ma)</th>
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resolution of LROC yields substantially more meter-sized boulders in our study. The spatial density of boulders > 2 m drops to typically < 100 samples/test area for craters between 40 and 100 Ma. This seems approximately the time frame within which some 50% of the original boulder population was destroyed. One may also conclude that up to 70–90% of the rock population was destroyed at craters some 120–150 Ma old. The rims of the 3 oldest craters (> 200 Ma) have < 10 boulders/test area, if not n < 5, suggesting that > 95% of all boulders were destroyed. The oldest structure investigated is the 400 m Elbow Crater and it had had only one marginally visible boulder > 2 m on its rim and ejecta blanket. It is important to note that on the rims of relatively young (< 100 Ma) craters (cases a through h in Figs. 3 and 4) boulders of 10–20 m across are present although rare, but on the rims of relatively old (> 150 Ma) craters (cases i through l in Figs. 3 and 4) only boulders 2–4 m across are seen.

Rounding the crater formation ages and preserved rock populations as shown in Fig. 5, we estimate the survival times of boulders 2–4 m in diameter to be as follows: the median survival time is about 40–80 Ma and the time needed to destroy 99% of the original boulder population is about 150–300 Ma. Fig. 5 also illustrates that the destruction of surface boulders is relatively fast initially, as long as such boulders occupy large fractions of the surface area; destruction of the last few boulders takes considerable, absolute time, consistent with impact as a stochastic process.

These are general rock destruction estimates for the twelve craters investigated, seven of which formed on mare surfaces and five in highland terrains. The mare target rocks are basalts which are mechanically strong, while the highland targets may vary from friable breccias to mechanically strong melt-bearing breccias if pure impact not melt. The noticeable decrease in the rock abundance on the rim of the 26 Ma old Cone Crater (Fig. 3d) compared to the 20–30 Ma old unnamed mare crater (Fig. 3c) is most likely due to a systematic difference in mechanical strength of mare basalts and typical highland lithologies. Similar strength effects may also apply to the rocks illustrated in Fig. 3i and k.

In summary, our photogeologic approach yields values of 40–80 Ma for the median survival time of lunar surface boulders some 2–4 m in size, and we estimate some 150–300 Ma to collisionally destroy some 99% of these boulders. These times are significantly shorter than those extrapolated from the MC of Horz et al. (1975a); 250–500 Ma for the 50% probability and 700–1500 Ma for the 99% probability of destruction for 2 m diameter boulders. Our observations therefore suggest that the residence times of meter-sized boulders are a factor of 4–5 shorter than extrapolated from Horz et al. (1975a).

4. Discussion

We demonstrated that ejecta boulders, 2–4 m in size, are abundant on the rims of “young” (< 30 Ma) lunar craters < 1 km in diameter, yet similar sized craters > 200 Ma have rims and ejecta deposits essentially devoid of such boulders. Using these observations, we estimate the times at which 50% and 99% of these boulders are destroyed, to be some 40–80 Ma and some 150–300 Ma, respectively. These survival or destruction times are some factor of 5 shorter than those extrapolated from Horz et al. (1975a, 1975b). The photogeologic observations suggest that large boulders are destroyed much more rapidly than one would predict from data for the decimeter-size rocks. The above observation that the boulders of 10–20 m in diameter are observed on the rims of craters younger than 100 Ma and not seen on the rims of the older craters may suggest that the larger (10–20 m) boulders are destroyed very efficiently as well. Some of the 2 m size boulders observed occur in clusters and attest to the destruction of larger objects. It is thus possible that we overestimated the 99% destruction time for m sized boulders and that the latter may be as short as 150 Ma. The latter would bring the ratio of observed 99% and 50% destruction times (some 150/50 Ma) in much better agreement with the modeled ratio of 3.1 by Horz et al. (1975a, 1975b). At otherwise constant impact conditions, this ratio depends only on the size frequency of the impactors.

In our consideration we assumed that all boulders observed on the crater rims are produced or exposed in the initial cratering event and then evolved on the surface. We do not think that such processes as excavations of boulders by newly formed smaller craters or burial of boulders by ejecta could significantly distort our results. Such cases certainly can happen (Fig. 3i and l), but as it is seen in Figs. 3 and 5 and in Table 2 the most significant changes in the areal densities of boulders on the rims of the considered craters happened within the first ~ 50 Ma. Calculations using the lunar crater production curve by Neukum (1983) show that during this time period within the considered 100 × 100 m2 areas, only several small (10–20 m in diameter) craters are expected to be formed. Also the regolith growth rate is only approximately 1 mm/ Ma (Quaide and Oberbeck, 1975) during the Moon’s recent past and we avoided contamination of the study sites by fresh ejecta from any “large” crater, thus making burial of meter-sized boulders unlikely.

We note that the experimental basis for the MC model of Horz et al. (1975a) related to collisionally destroyed targets in the kg mass range, mostly spheres and cubes of crystalline rocks < 10 cm in size (Gault and Wedekind, 1969; Gault et al., 1972). As emphasized and tested, the model seems consistent with diverse observations about the exposure history of Apollo rocks of similar sizes as shown in Figures 12–14 in Horz et al. (1975a). Although it was suspected that much larger targets may be mechanically weaker, due to the increased number and sizes of intrinsic flaws (e.g. Grady and Kipp, 1980, Pusch et al., 2013), it was not fully appreciated until Housen and Holsapple (1989) conducted appropriately scaled impact experiments and developed some general understanding of these size-dependent strength effects. As summarized in their Figure 12, the effective target strength of a 20 cm object increases by a factor of 3–4 relative to a 200 cm object. Since Horz et al. (1975a) used a constant strength regardless of target size, inclusion of a size-dependent strength term would reduce the survival times of meter-sized boulders by similar factors. Accounting for this size-dependent target strength would bring the modeled survival times into much closer agreement with the actual observations.

Additional insights into the collisional destruction of surface rocks were also offered by Horz et al. (1986). The critical rupture energy (E0) in Eq. 1 may not only be delivered by a single event of magnitude E0, but also by a small number of events, Ea < E0; the critical rupture energy is acquired in cumulative fashion and the question arises: what is the smallest event that contributes? The MC model of Horz et al. (1975a) integrated over all energies 0.1 E0 and larger, but the later experimental work by Horz et al. (1986) suggests that impacts as small as 0.05 E0, possibly still smaller, will contribute to the collisional destruction of finite sized objects. More work is needed to determine the smallest event that contributes to the collisional destruction of surface boulders, but the implications are obvious: the smaller this event, the shorter the surface residence times compared to the existing model of Horz et al. (1975a). We estimate this effect to lead to surface residence times some 20–30% shorter than modeled in 1975.

Additionally, the actual micrometeorite flux used by Horz et al. (1975a) could be in error and is known to no better than a factor of 2–3 (see e.g. Gruen et al., 1985; Love and Brownlee, 1993). Also, the role of thermal cycling is unknown and possibly contributes to the destruction of lunar surface rocks, especially of relatively large size.
(e.g., Dombard et al., 2010; Capek and Vokrouhlicky, 2012; Molaro and Byrne, 2012; Mackenzie-Helnwein et al., 2009). Also, typical ejecta boulders may be internally fractured und of weaker rheology than the ideal, pristine rocks used in the experimental “calibration” studies.

Based on the above considerations, the MC model of Horz et al. (1975a) must be modified and it does not apply to meter-sized lunar surface boulders. Much shorter life times for such boulders should be expected. The above estimates, approximate as they are, provide insights into the rates of surface processes on the Moon, including the correlation with the morphologic degradation of pristine craters < 1 km in diameter. Our observations may also be used to estimate the ages of some relatively large craters whose age is old enough to have their original rocky ejecta obliterated, but at the same time too young to have suffered noticeable changes in the overall crater morphology, especially rim sharpness and steepness of its inner slopes. Morphologically fresh lunar craters of 1–20 km in diameter may be candidates for such boulder studies.

Our results may also be extrapolated to estimate the survival times of rock fragments on the surface of other atmosphereless bodies, for example, Phobos and Deimos (Thomas et al., 2000). In the vicinity of Mars and thus on its satellites, the average impact velocity is 8.62 km/s, but on the surface of the Moon it is 16.2 km/s (Ivanov, 2001). Also, the Mars/Moon crater production rate ratio, averaged over time, has a value 2.04 for impacts originating in the asteroid belt that are responsible for craters larger than a few tens of meters (Hartmann and Neukum, 2001). As a consequence, the energy flux per unit time and unit surface area onto Phobos (and Deimos) is approximately a factor of 4 less than that of the Moon, yet the impact rate is a factor of 2 higher and thus increasing the energy flux to within a factor of 2 of the lunar flux. The rate of rock disruption by meteorite impacts on the surface of Phobos and Deimos should thus be a factor 2 lower compared to the Moon and the rock survival times should be twice as long. But other potentially important factors may also contribute, such as impacts by the low-velocity crater ejecta returning to Phobos after their escape to near-Mars space (Ramsley and Head, 2013), and thermal stresses due to the rather large and frequent diurnal temperature changes (from ~130 to 300 K; Kuzmin and Zabaloueva, 2003).

5. Conclusions

1. Analysis of the abundance of rock fragments ≥ 2 m in diameter on the rims of twelve craters (150–950 m in diameter and known ages of 2–300 Ma) led to estimates of the survival times of such rocks on the surface of the Moon. It was found that the median survival time (50% of the original rock population destroyed) is about 40–80 Ma, while 99% of such rocks are destroyed in about 150–300 Ma.

2. These observed survival times are approximately a factor 5 shorter than those extrapolated from Horz et al. (1975a). This apparent disagreement is due to a number of factors. As demonstrated by Housen and Holtsapple (1999) the effective strength of meter sized boulders is less than that of decimeter-sized targets used in the experimental basis of the Horz et al. model; also, numerous less energetic events than those employed by Horz et al. (1975a) will contribute in cumulative fashion to the catastrophic disruption of surface rocks (Horz et al., 1986). Diurnal temperature cycling and associated stresses may also contribute to the destruction of lunar surface rocks (e.g., Molaro and Byrne, 2012). Additionally, the original ejecta boulders may be fractured and weakened relative to the pristine rocks employed in the experimental impact studies.

3. The photogeologically determined estimates can provide additional insights into the rates of surface processes on the Moon and can potentially be used to estimate the formation ages of relatively large (1–20 km), morphologically fresh, lunar craters.

4. The differences in the impact environment of the Moon and Mars suggest that the survival times of the rock fragments ≥ 2 m in diameter on the surface of Phobos and Deimos are within a factor of 2 of that of the Moon.

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