Planetary and Space Science 117 (2015) 312–328

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Survival times of meter-sized rock boulders on the surface of airless bodies

A.T. Basilevsky [a,b], J.W. Head [b], F. Horz [c], K. Ramsley [b]

[a] Vernadsky Institute, RAS, Moscow 119991, Russia
[b] Brown University, Providence, RI 02912, USA
[c] LZ Technology Inc., Houston, TX 77058, USA

ARTICLE INFO

Article history:
Received 8 June 2015
Received in revised form
12 July 2015
Accepted 13 July 2015
Available online 29 July 2015

Keywords:
Rock fragments
Meteorite bombardment
Thermal stress
Exposure age

ABSTRACT

Rock boulders are typical features of the surfaces of many airless bodies, so the possibility of estimating their potential survival times may provide insights into the rates of surface-modification processes. As an opening point of this study we employ estimates of the survival times of meter-sized boulders on the surface of the Moon based on analysis of the spatial density of boulders on the rims of small lunar craters of known absolute age (Basilevsky et al., 2013), and apply them, with necessary corrections, to boulders on other bodies. In this approach the major factor of rock destruction is considered to be impacts of meteorites. However another factor of the rock destruction, thermal fatigue due to day–night cycling, does exist and it was claimed by Delbo et al. (2014) as being more important than meteorite impacts. They concluded this on the basis of known presence of fine material on the surface of small asteroids, claiming that due to extremely low gravity on those bodies, the products of meteorite bombardment should leave these bodies, and thus their presence indicates that the process of thermal fatigue should be much more effective there. Delbo et al. (2014) made laboratory experiments on heating–cooling centimeter-sized samples of chondrites and, applying some assumptions and theoretical modeling concluded that, for example, at 1 AU distance from the Sun, the lifetime of 10 cm rock fragments on asteroids with period of rotation from 2.2 to 6 h should be only $\sim 10^3$ to 10^4 years (that is $\sim 3.5 \times 10^6$ to 1.5×10^7 thermal cycles) and the larger the rock, the faster it should be destroyed.

In response to those conclusions we assessed the results of earlier laboratory experiments, which show that only a part of comminuted material produced by high-velocity impacts into solid rocks is ejected from the crater while another part is not ejected but stays exposed on the target surface and is present in its subsurface. This means that the presence of granulometrically fine material on the surface of small asteroids does not prove the predominance of thermal stresses over rupture by meteorite impacts as a factor in the comminution of the surface material. We then analyzed images of lunar rocks of decimeters- to meters-size whose lunar surface exposure ages were radiometrically dated. This analysis shows that the presence of the fragment on the lunar surface for a time period 26–400 Ma (that is, $\sim 3 \times 10^8$ to 5×10^9 day–night thermal cycles) did not lead to the formation of any features conclusively supporting rock destruction by thermal cycles. In turn, this means that on the lunar surface as well as on the surface of other bodies at 1 AU and further from the Sun, the destruction of rocks by thermal fatigue is secondary compared to rock rupture by the meteorite impacts. The possible implications of the difference in environments on fast spinning asteroids and on the Moon require additional analysis

Then utilizing the entire catalog of inner solar system minor planet orbits out to Jupiter as a proxy for the distribution of potential impactors throughout the inner solar system, we calculated the meteorite flux and impact velocities for a number of airless bodies to use them for estimates of survival times of rock boulders on their surfaces (normalized to those for lunar boulders). We found that if the average survival time for meter-size rock boulders on the surface of the Moon is 1, then considering rupture by the meteorite impacts as the major process of rock destruction, for Phobos it is ~ 0.8, for Deimos ~ 0.7, for asteroid Itokawa ~ 1, for Eros ~ 0.3, for Vesta and Ceres ~ 0.03 and for the average of the first 150 Trojans discovered is ~ 12.5. Implications of these findings are that on the surfaces of Vesta and Ceres, compared to the Moon, the regolith layer should generally have a larger thickness and higher maturity, while small craters with rocky ejecta are rare. On the typical Trojans, where impact flux is closer to that

E-mail address: atbas@geokhi.ru (A.T. Basilevsky).

http://dx.doi.org/10.1016/j.pss.2015.07.003

on the Moon, but the impact velocities are by factor 4 lower, the situation should be the opposite: thinner layer of regolith, lower maturity and a larger percentage of small craters with rocky ejecta. These predictions and observations can be tested with future robotic and human exploration of the Moon and small bodies.

1. Introduction

Rock fragments and boulders are typical features of the surfaces of many airless bodies and estimating their potential survival times may provide significant insights into the rates of surface-modification processes and thus the geologic histories of these bodies in general. Initial estimates of the survival times of hand specimen-sized rocks exposed to the lunar surface environment were made based on laboratory impact experiments into the collisional fragmentation of rocks combined with estimates of the lunar surface meteorite flux and stochastic modeling of the impact environment (e.g., Horz et al., 1975a, b; Cintala and Horz, 2008). The aim of the present study is to estimate the survival times of meter-sized rock boulders seen in the numerous orbital images of the surfaces of airless bodies (e.g., Thomas et al., 2001; Robinson et al., 2010; Mazrouei et al., 2014). As an opening point, we employ estimates of the survival times of meter-sized boulders on the surface of the Moon, as recently described by Basilevsky et al. (2013), and apply them, with necessary corrections, to boulders on other airless bodies. This new approach by Basilevsky et al. (2013) was based on the analysis of the spatial density of boulders on the rims of small lunar craters of known absolute formation age. Additionally, Basilevski et al. (2013) assumed that the major factor in boulder destruction is catastrophic disruption by the meteorite impacts. The potential role of diurnal temperature cycling was mentioned there but not considered in detail.

In the present analysis we first briefly review the lunar results. Then we discuss the potential role of thermal cycling, and we will show, that it is probably less important than the collisional disruption by meteorite impacts. Finally, we consider the meteorite bombardment on a number of airless bodies in terms of projectile flux and velocities and, based on this, we will estimate the survival times of meter-sized boulders on various bodies.

2. Survival times of rock fragments on the surface of the Moon

As defined by Gault and Wedekind, (1969), a rock is deemed destroyed when its largest collisional fragment is <0.5 the original target mass (M_0); this condition obviously mandates some critical kinetic energy (E_{crit}.) of the impactor. This threshold energy can be delivered either by a single impact or—in cumulative fashion-by a number of modestly less energetic events (Horz et al., 1986). Single events $>E_{crit}$. will result in "overkill", i.e. progressively more fine-grained fragment populations (Fujiwara, 1989; Cintala and Horz, 2008) compared to the $E_{kin}=E_{crit}$ case. Single impact events at $<E_{crit}$. will merely produce a crater in the target object, possibly some penetrative fractures, but will not result in the physical disintegration of the target. The specific energy to produce a crater may be expressed as ergs/g of displaced crater mass, and it is typically an order of magnitude smaller than E_{crit}, the latter expressed as ergs/g of M_0; (Fujiwara et al. 1989; Cintala and Horz, 2008). The generation of relatively few, penetrative fractures – consuming modest amounts of energy – is critical for the collisional destruction of rocks and contrasts with the additional energy needed to comminute and physically eject the relatively finegrained ejecta in a cratering event. This order of magnitude difference in the specific energy needed for the cratering and collisional destruction process also implies, that the catastrophic fragmentation of rocks utterly dominates the survival-times of planetary surface rocks and that erosion akin to sandblasting by very small micrometeorites is a subordinate process. Applying the above principles based on laboratory impact experiments, Horz (1985) calculated the survival times of hand specimen-sized rocks exposed to the lunar surface environment, using the lunar meteorite flux of Horz et al. (1975a,b), combined with a statistical Monte Carlo approach to simulate the stochastic nature of the impact process.

They showed that 50% of originally 10 cm diameter rocks should be destroyed in approximately 10^7 years, while the destruction of 99% of the original rock population is on the order of 3.5×10^7 years; in generalizing this result the "mean life time" of lunar surface rocks is approximatyely 3.5 time shorter than the time needed to destroy 99% of all similar-sized rocks. Horz et al. (1975a) also calculated the survival times of different sized rocks (2–20 cm in diameter corresponding to 0.01–10 kg in mass), and they found that the mean lifetime increases by approximately a factor of 3 per order of magnitude in mass. The simulated sizes and masses of lunar rocks corresponded to typical hand-specimen sized rocks returned by Apollo, some of them of known surface residence times based on either solar flare tracks or those from more energetic galactic particles (e.g. Crozaz et al., 1974) or noble gas spallation products (e.g. Pepin et al., 1974). The calculated mean survival times are in excellent agreement with the track-based exposure ages, yet most noble gas ages are somewhat older than permitted by Horz et al. (1975a), suggesting that these rocks resided in the subsurface for considerable period of time. Extrapolating the Horz et al. (1975a) collisional lifetimes to 2 m sized boulders results in a mean survival time of approximately 4×10^8 years, and essentially complete destruction at the 99% probability level le after 1.5×10^9 years.

A completely different approach to estimate the survival times of meter-sized lunar boulders was suggested by Basilevsky et al. (2013). Fresh lunar craters larger than several tens of meters in diameter typically penetrate the regolith and excavate bedrock; the rims of such pristine craters are covered with numerous rock fragments and meter-sized boulders, but the rims are degraded and thus much older craters contain noticeably smaller numbers of boulders or none at all. There is thus a distinct relationship between spatial density of boulders and absolute time as inferred from the degradational state of craters. Basilevsky et al. (2013) quantified this relationship by photogeologic analysis of the spatial density of boulders >2 m in size of 6 craters within the Apollo landing sites for which the absolute formation ages were known from the analysis of the exposure ages of rocks collected at specific craters (e.g. Arvidson et al., 1975; Eugster, 1999). Fig. 1 illustrates the areas (100×100 m^2) analyzed from these Apollo craters that ranged from 2 to 300 Ma in formation age. Added to these Apollo craters were six other craters whose absolute age was estimated based on their degradational state (Basilevsky, 1976; Basilevsky and Head, 2012) and that were complementary to the Apollo impacts.

The results of this analysis are illustrated in Fig. 2 and show a clear relationship between boulder density and crater formation age, the latter synonymous with as exposure age of the specific rim-areas analyzed. For exposures on the lunar surface of a few million years, only a small fraction of meter-sized boulders are destroyed but after several tens of million years $\sim$50% are destroyed, and for times of 200–300 Ma, $\sim$90 to 99% of the original boulder population is obliterated. These results are in good