DYNAMICS OF GROOVE FORMATION ON PHOBOS BY EJECTA FROM STICKNEY CRATER: PREDICTIONS AND TESTS.

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Summary: Numerous theories have been proposed for the formation of grooves on Phobos, and no single explanation is likely to account completely for the wide variety of morphologies and orientations observed [1-9]. One set of grooves is geographically associated with the impact crater Stickney. As a possible explanation for the characteristics of this type of groove set, we test the hypothesis that these grooves were formed by ejecta clasts which left Stickney at velocities such that they were able to slide, roll, and/or bounce to distances comparable to observed groove lengths (of the order of one-quarter of the circumference of Phobos), partly crushing the regolith and partly pushing it aside as they moved. We show that this mechanism is physically possible and is consistent with the sizes, shapes, lengths, linearity and distribution of some of the grooves for plausible values of the material properties of both the regolith and the ejecta clasts. Because the escape velocity from Phobos varies by more than a factor of two over the surface of the satellite, it is possible for ejecta clasts to leave the surface again after generating grooves. On the basis of this model we make testable predictions about the surface characteristics and distribution of such grooves and their deposits.

Discussion and Analysis: A variety of models have been proposed for the formation of the grooves and crater chains detected on Phobos including 1) original primary layering, 2) drag forces generated during capture of the satellite, 3) tidal distortion 4) impact fracturing, 5) impact fracturing accompanied by degassing, 6) impact fracturing accompanied by regolith drainage, 7) impact fracturing later followed by regolith drainage, 8) ejecta emplacement and secondary cratering associated with the Stickney event, and 9) multiple origins.

Two factors caused us to reassess theories: 1) continuing analysis of high resolution images of linear tracks on the Moon formed by rolling and bouncing boulders has shown that these features show many similarities to grooves on Phobos; 2) continued study of the formation of impact craters on very small bodies such as asteroids and the satellites of Mars underlines the unusual and often counterintuitive nature of the cratering process and the resulting ejecta emplacement patterns. Ejection velocities associated with the vast majority of the material forming crater deposits on the Moon are sufficient to cause this material to exceed escape velocity on asteroids and Phobos and Deimos, and thus to leave the impacted body. The only ejecta remaining on the impacted body in these cases is likely to be the material that is least shocked and latest excavated at very low velocities (e.g., below escape velocity); ejecta from Stickney-sized craters on Phobos will look and behave very differently from ejecta on larger bodies, with emphasis on the low-velocity emplacement of ejecta blocks, perhaps similar to the tracks from rolling and bouncing blocks observed on the Moon.

We explore the consequences of assuming that the Phobos grooves were formed by ejecta clasts with diameters of the order of 100 m which left Stickney at velocities such that they were able to roll or bounce to distances of the order of one quarter the circumference of Phobos, partly crushing the regolith and partly pushing it aside as they moved. Using basic soil mechanics relationships and estimates of regolith material properties, we calculate the range of sizes of the boulders that would be responsible for the observed grooves. We then consider the motions of clasts ejected from the 10 km diameter crater Stickney which just fail to reach escape velocity in the Phobos environment. We show that groove formation by these clasts is physically possible and that the sizes, shapes, lengths, linearities and distributions of some grooves are consistent with plausible values of the material properties of both the regolith and the ejecta clasts. We also show that there are several possibilities for the fate of these clasts. Some of the clasts will be abraded and diminished in size during their traverse before coming to rest. Because the escape velocity from Phobos varies by more than a factor of two over the surface of the satellite, it is also possible for some of the clasts to leave the surface again after generating grooves. The paths of all primary crater ejecta clasts produced on Phobos must be considered in terms of the total gravity field of both Phobos and Mars. We thus draw a distinction between *super-orbital*, *orbital* and *sub-orbital* ejecta (Fig. 1).

Ejecta leaving the surface of Phobos at speeds greater than its escape velocity (3 to 8 m/s, depending on the position on the surface and the direction of launch) but less than the escape speed from the Mars system (a few km/s) are termed *orbital*. These clasts are potentially available to re-impact the Phobos surface at speeds similar to those at which they were launched and at elevations to the horizontal of order 45 degrees, thus producing craters with a wide range of sizes, some of which would not be distinguishable from primary impact craters. Ejecta leaving at even higher velocities (*super-orbital* ejecta) may be regarded as part of the general solar system meteoroid flux and neglected in terms of future impacts with Phobos. *Sub-orbital* clasts are those having an ejection velocity less than the escape velocity from Phobos alone. Such clasts are projected from near the edge of the crater cavity. They are excavated by stress waves having small stress amplitudes and stress gradients, and so will tend to be relatively coarse, relatively more coherent, and to be ejected at low speeds and at low elevation angles. There are expected to be very strong correlations between the sizes and the horizontal and vertical velocity components of such ejecta clasts.

For example, calculations show that clasts with sizes of the order of a few tens of meters may re-impact the surface at ranges of a few to 20 km. If such clasts disturb ten times their own mass of the surface on impact they may excavate secondary features up to 100 m in size. The peak stress induced in such an impacting clast will be of order 0.1 bar, and it will not survive the re-impact intact unless its strength is greater than this value. Most consolidated silicate rocks have strengths in the range of tens to a hundred bars and are thus likely to survive reimpact. The strength of an ejecta clast composed of material that has been through a rubble-pile-forming event and possibly partially re-lithified by later impacts is much harder to predict, but such clasts are likely to be relatively weak. If an ejecta clast does survive, it may continue on an escape path if the re-impact is at a grazing angle and the local escape velocity at the point of first contact is less than that at the initial launch point. Alternatively, it may lose enough energy to cause it to follow a non-escape path subsequently, thus bouncing one or more times. The

number of bounces, the spacing between the contacts, and the ultimate fate of the ejecta clast again depend critically on the elastic properties of the ejecta clast and the surface (which, depending on the size of the clast, may effectively be an assemblage of relatively small regolith particles, a mixture of clast sizes approaching that of the impacting clast, or another single clast supported by a regolith matrix). Of even more interest are sub-orbital ejecta clasts leaving the crater cavity at speeds of 3 to 8 m/s (i.e., just below, or essentially at, the local escape velocity) and at elevation angles close to zero. These clasts will travel out of the crater, over the crater rim crest and onto the crater rim in the terminal stages of the cratering event and may slide, roll, or bounce along the surface, producing a groove-like disturbance of the pre-existing surface with a width smaller than, or similar to, their own diameter.

Summary of Predictions and Tests from the Analysis: To provide a basis for comparison with new data from spacecraft missions we summarize the predictions and tests from our model. 1) General distribution of ejecta: The low gravity and escape velocity of Phobos mean that the vast majority of ejecta clasts will leave the satellite; remaining fragments will have undergone the least amount of impact-related stress and will be preferentially the largest clasts involved in the cratering process. 2) Block excavation and the crater interior: These last blocks leaving the crater interior will not only be relatively large but will also depart at low velocities and low elevation angles. Many of them are likely to be dislodged from the crater floor in the final stages of the event and spread outward from the crater interior up the walls and out over the rim. Depending on their point of origin, these boulders could easily form tracks in the crater interior, continuing up the crater wall and out over the rim. 3) Morphology and structure of the grooves: Groove widths: The widths of grooves should be comparable to the size range of blocks shown to be capable of producing grooves on Phobos by this mechanism. The radii of the ejecta clasts required to produce grooves 100 m wide would lie in the range ~80 to 140 m, with larger grooves requiring proportionally larger clasts. Groove width-to-depth ratios: Consideration of the vertical forces acting on clasts shows that groove-like depressions with depth-to-width ratios in the range 0.05 to 0.17 are expected if the regolith cohesive strength is similar to or, more likely, a factor of 10 smaller than, that of the lunar regolith. Groove lengths: Ejecta clasts with radii in excess of ~100 m launched at speeds in the range 3 to 6 m/s are able to travel to distances of 10 to 30 km even if the regolith strength is near the upper end of the range implied by the groove shapes (see Fig. 4) and is thus comparable with the strength of the lunar regolith. Groove morphology: Rolling and bouncing boulders could produce linear grooves (if the boulder is relatively rounded and rolling), chains of isolated craters (if the boulder is bouncing and leaving the ground between bounces), chains of connected craters (if the boulder is bouncing and not leaving the ground between bounces), or linear grooves with associated pits (if the boulder is rolling and bouncing and not leaving the surface). Change in groove morphology with distance: Monotonic decrease in velocity of rolling boulders, and any change in the size and morphology of the boulder, will result in variations in groove morphology with range. In addition, when allowance is made for the influence of the non-spherical shape of Phobos on the motion of ejecta clasts, it is found that the speed of a clast may increase again after an initial decrease. These factors should

result in changes of morphology along groove paths, as gravity, velocity and local topography vary. In addition, since the escape velocity from Phobos varies by more than a factor of two over the surface, this allows the possibility of ejecta clasts leaving the surface even after they have already generated grooves 10 to 20 km long. In this latter case, a change in morphology from coalesced pits, to isolated pits (where the boulder bounced several times as it increased velocity), to no groove at all (downrange of its launch point), might be predicted. Groove linearity: Grooves produced by the mechanism described here would be linear and would not be expected to deviate significantly from their path over the vast majority of their traverse. Even where preexisting topography was encountered (an older impact crater for example), a simple analysis shows that the combination of the forward velocity and the observed slopes is such that boulder tracks would deviate laterally from their forward path by no more than a few meters. 4) Map pattern distribution of grooves: Any preexisting structural or stratigraphic fabric will tend to dictate the exit directions of large boulders from the crater cavity, in contrast to the more radially symmetrical, shock-dominated distribution of ejecta leaving the cavity at earlier stages. Therefore, boulders ejected from Stickney in the terminal stages of the cratering event at very low velocities could easily produce distinctive, non-symmetrical ejecta patterns reflecting substrate heterogeneities.

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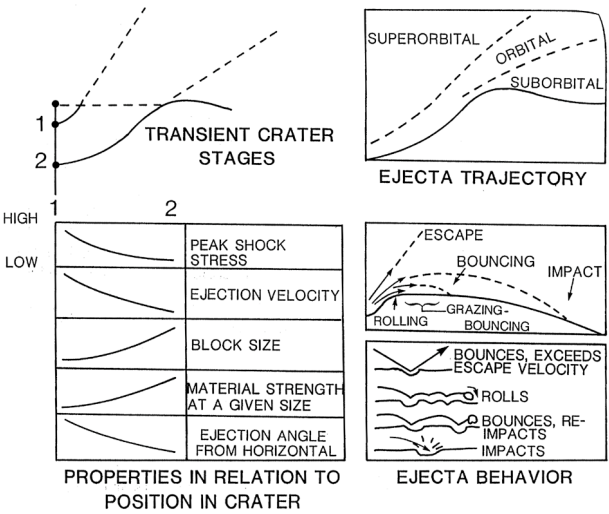

Figure 1. Super-orbital, orbital, and suborbital ejecta from a large crater on Phobos (ejecta trajectory) and the geometry of the interaction of a horizontally moving spherical ejecta clast with the regolith surface (ejecta behavior). Also shown schematically are transient crater stages and various ejecta properties in relation to position in the transient cavity and crater.