QUANTITATIVE EVALUATION OF BALLISTIC SEDIMENTATION;

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On Earth tectonic forces are continually supplying surfaces of relatively fresh relief. On the more quiescent Moon, however, gradational processes of a different nature may have billions of years in which to modify an ancient landform, producing a surface morphology quite different from our terrestrial experience. Lunar mountain ranges many billions of years old may still possess several km of relief, yet are remarkably smoothed and rounded. This lunar morphology differs considerably from similar-sized terrestrial mountains undergoing any rate of terrestrial-style degradation, and the geomorphic contrast between the two cases merits evaluation. Three mechanisms have been proposed by which downslope mass movement occurs on the Moon: thermal creep [1]; seismic shaking [2, 3]; and ballistic sedimentation [4]. The current study evaluates quantitatively the ballistic sedimentation hypothesis of Young [4].

Young endeavored to explain the break in slope found just above many mare-highland contacts as an accumulation of debris produced by net downslope movement of impact ejecta. His hypothesis represents an explanation supplemental to the "high-lava mark" hypothesis proposed by many workers [e.g., 5, 6, 7, 8]. The current study's quantitative evaluation of the ballistic sedimentation hypothesis [4] takes a four-fold approach: (1) development of physical theory for net mass movement downslope by impact; (2) testing the derived expressions with simple impact cratering experiments; (3) searching for field evidence that the derived and tested physical process actually operates on the Moon; and (4) discussion of implications for Hadley area geology.

The geometry of the impact-on-slope situation is portrayed in figure 1. An impact normal to the slope is assumed. α is the slope angle and ϕ is the initial trajectory angle between the ejecta and the slope (here taken to be 45°). Trajectory 1 represents ejecta moving in the upslope direction; upslope ejecta travel distance measured on the slope is UET. Trajectory 2 represents ejecta moving downslope, with its travel distance being DET. Trajectory 3 represents material ejected slightly upslope (and toward the reader) but necessarily landing at the same elevation as the impact point. Trajectory 4 represents material ejected initially along the contour of the impact point (directly toward the reader), but that later lands slightly downslope. A general expression has been derived, and for the case of Mount Hadley ($\alpha = 30°$) the expected downslope ejecta travel DET = $1.855\ V_i^2/g_m$ and the expected upslope ejecta travel UET = $1.058\ V_i^2/g_m$. Thus the expected DET:UET ratio for these conditions is 1.75 : 1. The sector of material ejected between trajectories 3 and 4, multiplied by 2 to include the other side of the impact point, is the net material moved downhill by the impact. For the case of Mount Hadley the sectors are each 35° wide, giving a net mass moved downslope of 19.4% of the total ejecta mass of any impact.

Laboratory testing of the derived ratio of downslope:upslope ejecta travel distances was carried out by using a simple slingshot to propel a number of BBs into a specially prepared sand target inclined at 30°. Impact angles were normal to the sloping surface. After several trials four impact craters were obtained that were suitable for analysis. For each crater the downslope and upslope ejecta travel distances were measured and the DET:UET ratio computed. The average DET:UET ratio was found to be 1.8 : 1, in close agreement with the predicted ratio of 1.75 : 1.

When the test craters are photographed with the camera mounted just off the laboratory floor to mimic the perspective of an astronaut on the lunar surface, the craters are foreshortened and their ejecta blankets appear as wide, comet-like cones -- the brightest concentration of ejecta being confined to just upslope of the crater rim. Finding such features on the lunar surface requires a number of special conditions: (1) the candidate craters must be young and fresh; (2) the candidate craters must be large enough to be seen from a distance; (3) the candidate craters must be located on a relatively steep slope; and (4) the lighting must be nearly normal to the slope for the ejecta distribution to be well displayed. Hasselblad frame AS15-84-11240 fits most of these requirements well. Taken by the Apollo 15 astronauts, it portrays Hill 305, a 1500 m high range northwest of the landing site. Examination of this photograph reveals several craters on the hillside that bear the expected characteristics.

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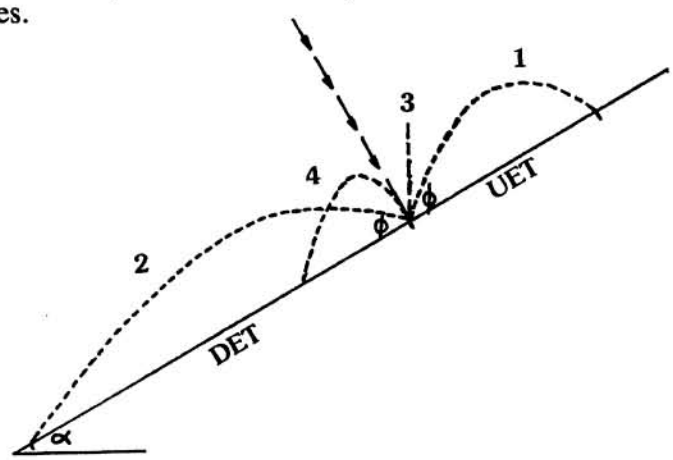
Mount Hadley, the highest, steepest mountain close by the Apollo 15 landing site, was never illuminated with the ideal conditions of Hill 305 during the astronauts' stay. However, many photographs were taken of Mt. Hadley while under extremely low-angle lighting conditions (relative to its flank) in the excitement that the lineations plainly visible represented bedrock stratigraphy. However, simple surface models of extremely fine powder under low-, narrow-angle illumination suggested that the lineations on Mt. Hadley did not represent bedrock stratigraphy but were a lighting artifact of hummocky terrain viewed under low lighting conditions [9]. These conclusions regarding bedrock stratigraphy seem quite reasonable, but the Mt. Hadley photographs must be revaluated for the purposes of the current study. Theory developed in this study, simple crater experiments, some field evidence from Hill 305, and the steep slopes (30°) of Mt. Hadley imply that substantial amounts of mass movement through ballistic sedimentation down the flanks of Mt. Hadley have occured during the past three billion years. One might expect a fine-scale, hummocky, almost terrace-like texture on the mountain's slopes. The horizontal lineations on Mt. Hadley, therefore, could be the signature of this downslope mass movement.

Quantitative evaluation of the ballistic sedimentation hypothesis has resulted in physical theory that suggests ballistic sedimentation is a significant mass-wasting process on the Moon. Simple impact crater experiments support the physical theory developed in this study. Field evidence from the Apollo 15 site, including the appearance of impact craters on Hill 305 and possibly the horizontal lineations on Mt. Hadley, further suggests that ballistic sedimentation is an important mass-wasting process on the Moon. The results of this study are not definitive enough to determine what fraction of Mt. Hadley's basal scarp is mass-wasted debris from above, but current results suggest the debris fraction could be significant. This study has dealt with ballistic sedimentation on a per-crater basis; further work is required to determine the cumulative effect of this process on lunar slopes.

Figure 1.



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