Regolith Stirring and Exposure: 3-Dimensional Study,
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Intro. Lunar soil samples apparently have experienced exposure to cosmic rays (galactic and/or solar) through some remarkably orderly process. That is to say, soil samples showing exposure contain very few -- if any -- unexposed grains. The uniformity with which each grain in the sample has received at least some exposure is an important datum. It can be used to assess various proposed histories of the lunar material. This paper presents the results of a three-dimensional computer simulation of regolith exposure. Excavation and mixing of the soil according to the cratering frequency law of Shoemaker et al. (1) is employed. The results confirm the indications of the earlier one-dimensional study (2) -- exposure in situ, with churning by meteorites, is insufficient to explain the notable extent to which unexposed grains are absent.

Cosmic-ray penetration depths. The galactic cosmic-ray flux is attenuated, at a depth of about 64 cm, by a factor of $10^{-4}$ with respect to the flux received in the top 10 cm or so of the soil (3). Solar cosmic rays are of lower energy and have an effective penetration depth of less than 1 cm. (Lunar soil samples commonly have been obtained, by core tubes, from depths of about 2 meters or more. Two meters is more than 3 times the maximum depth at which significant exposure can occur.)

Review of observed cosmic-ray track density distributions
Typically, 95% of the grains in soil samples readily reveal a substantial track density (4). The minimum track density of grains in this 95% is about $(1/1000)$ or more of the mean grain track density seen in the sample (3). Observation of tracks in the remaining 5% of the grains is more difficult. However, use of special techniques (particularly ones involving electron microscopy) has revealed comparable levels of exposure in most of the remaining 5%. The percentage of a typical sample's grains for which exposure remains to be established is only 1 or 2%. That is, the fraction of unexposed grains (in samples showing exposure) may be zero; the most stringent upper limit which *(This figure, of course, excludes the glass component of samples. Retention of etchable tracks in glass is known to be poor.)* **(Grains which required special techniques in order for tracks to be observable were found to exhibit slip dislocations which broke the tracks into short segments, making observation difficult(4). Distortion and/or annealing of some of the grains by impacts is in any case to be expected.)*** *(The proviso "in samples showing exposure" refers to the possibility of a sample showing no tracks. The latter could result from annealing of the sample, by heat or shock, in impact events.)*
The three-dimensional calculation was used to perform a Monte-Carlo simulation of regolith exposure accompanied by cratering. It was assumed that the meteorite flux, whatever its absolute value may have been, had the form\( F(c) \propto c^{-2.93} \). \( F \) is the flux of meteorites causing craters of diameter greater than or equal to \( c \). (Small-scale excavations occur more frequently than large-scale excavations.) The conclusions of the study are not very sensitive to the crater production law assumed. The aspect ratio \( b \) of the craters (ratio of diameter to depth) was taken to be a single constant for craters of all sizes. A value for \( b \) was not chosen; it does not enter when one merely specifies that tilling by meteorites has reached to a certain median depth. Craters of square aperture and vertical sides were chosen for simplicity. The excavated material was taken to be deposited in a blanket of uniform thickness and square border surrounding the crater. (See Figure 1.) The ratio \( \eta \) of ejecta blanket thickness to crater depth was taken to be independent of crater depth. The value of \( \eta \) in the basic calculation was chosen to be 1/8, for reasons of computational tractability. The results can be scaled for other values of \( \eta \).

Each event excavates material which thereupon becomes arrayed in a thin blanket. At each time-step, one unit of aging is accorded to all material within a certain depth beneath the surface. (One time-step is the time-constant for an impact to create a single excavation of minimum depth.) Compounding of statistics was employed to deal with the effects of successively smaller-scale classes of cratering events. The material was dealt with in the form of distribution functions, rather than following a limited number of grains. We define \( N(0) \) to be the fraction of a sample's material which has never resided within an exposure-length \( \lambda \) beneath the surface. The dependence of \( N(0) \) upon \( \eta \) can be shown to be: \( N(0) \propto \eta^\gamma \), where \( \gamma \) is a positive number less than 1.0. Care was taken that all approximations have the effect of underestimating \( N(0) \) rather than overestimating it.

As tilling proceeds, \( N(0) \) would be diminished rapidly were it not for the fact that the greatest depth to which cratering has occurred will increase, on average, linearly with the number of time-steps. Admixture of previously unprocessed material from beneath is unavoidable in the actual case and was artificially excluded in the theoretical simulation to less an extent than in the calculations of others (e.g.,(3).) The deeper excavations continually spoil what might otherwise have been a distribution with no unexposed grains. \( N(0) \) decreases with time initially. Thereafter, there is an approach to what is essentially a steady state.
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Results of the three-dimensional calculation. The calculation yielded the distributions $N(L_{tilled}, L, E_z)$ in amount of time $E_z$ spent within an exposure-depth $λ$ beneath the surface. $L$ is the depth at which the soil sample is found. $L_{tilled}$ is the median depth to which tilling of the regolith proceeded. It is, of course, the distribution in relative degree of exposure which is of import and, most simply, one may consider the fraction $N(L_{tilled}, L, 0)$ which has never experienced residence within the depth $λ$ beneath the surface.

Typical results are shown in Figure 2. We reiterate that the zero- and low-exposure end of the histograms represents an underestimation.

Conclusions. It can be seen from the theoretical results that in-situ meteoritic tilling fails to explain the remarkable extent to which unexposed grains are absent from the majority of lunar soil samples. From the upper limit to the observed value of $N(0)$ and from the form of the dependence upon $η$, we have that the ejecta-blanket thickness factor $η$ may be significantly smaller than $1/200$ without invalidating the conclusions of this study. The results indicate that pre-exposure in space (and/or during transit by some orderly process from the uplands) is required for the bulk of the lunar soil.


Fig. 1. Model. Cratering events throw out blankets of ejecta.

Fig. 2. Time spent within a cosmic-ray exposure depth is recorded. A large number of unexposed grains is seen to result.