MINIREGOLITHS II: ANATOMY OF LUNAR SURFACE SOIL

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The analysis of lunar samples has led to a knowledge of the various processes governing the maturation and surface history of lunar soil and produced considerable data on soil parameters characterizing this history. To fully understand the complex behavior of space-exposed soils there is a need for the converse study, a quantitative synthesis of these processes which will generate self-consistent sets of soil parameters representing the various scenarios for soil history. This must be done in a way clearly related to the possibly time-varying rates controlling these processes and to the residence times of observed soil units so that the most information concerning the surface and space environment can be extracted.

In pursuit of this goal we have developed over the last two years an improved, generalized Monte-Carlo model for rock and soil history called MESS.2 (Model for the Evolution of Space-exposed Surfaces, version 2). This work has built upon the experience gained from earlier models (1,2) and has considerably broader scope of application. Initial results of MESS.2 are being presented for the first time.

For soil applications the purpose of MESS.2 is to transform meteoroid impact event characteristics and size distribution, soil mechanical properties, and the depth profiles and other characteristics of production processes (for solar flare and galactic cosmic ray tracks, solar wind concentrations, remnant magnetism, microcraters, glassy material, etc.) into effective production time distributions and final depth profiles for soil parameters, as functions of particle size and total in situ residence times within surface layers of given thickness. From these distributions the characteristics and frequencies of simulated complex soils are readily constructed for a given scenario. MESS.2 uses our technique of breaking the problem down into a series of simulations each encompassing a limited range of depths and corresponding event sizes. On each simulated size scale an ensemble of independent soil particles (about 200) is monitored in three dimensions while impact events are individually processed using an origin-dependent ejecta map. We simulate layers of about 1mm, 1cm, and 10cm thickness which correspond to typical sampling intervals.

A look at ~100-micron-diameter soil particles will illustrate the model and its results. First, particles of diameter 100 microns are monitored for a time T_{MM} in a surface layer of thickness D_s=1.5mm subject to impacts generating soil craters of 1mm to <1cm diameter. Smaller impacts are assumed to pit or destroy the particle. Larger events are assumed to effectively bury or excavate the layer over a sampling area and thereby determine the residence time T_{MM}. Therefore the expected distribution of T_{MM} will be determined by simulations on larger size scales. On all scales the details of soil topography, surface structure stability, and soil density and graininess are taken into account.

After a time T_{MM} a fraction $f_e(T_{MM})_{100}$ of the monitored particles will have been exposed at the surface for a total time t according to the distribution (normalized to 1) denoted $f_g(T_{MM})_{100}$. The ensemble average exposure time is then given by:

$$(1) \quad I_{EX}(T_{MM})_{100} = f_e(T_{MM})_{100} \int_0^{T_{MM}} t \; f_g(t,T_{MM})_{100} \; dt$$

The results of MESS.2 calculations are fit well by the forms:

(2) $f_e(T_{MM})_{100} = (D_r/D_s)[1-\exp(-T_{MM}/T_r)]$ and

(3) $f_g(t,T_{MM})_{100} = [\exp(-t/K_T T_{MM})]/[1-\exp(-K_1/K_T)]$ for $0<t<K_1 T_{MM}$ and
$f_g(t,T_{MM})_{100} = 0$ for $t>K_1 T_{MM}$.

The factor K_1 represents a cutoff due to finite grain and event sizes; $K_1=0.4$ in equation 3. The factor K_T governs particle exposure time; $K_T=0.16$ for 100-micron particles in a 1.5mm surface layer. A depth D_r represents the median depth to which the layer can be mixed when the maximum depth mixed is similar to the layer thickness (as guaranteed by the event range chosen for a given scale) and hence the ratio D_r/D_s represents a mixing or exposure efficiency for that surface layer; $D_r/D_s=0.35$ in equation 2. A time T_r governs how quickly this median depth is reached; $T_r=2.6$m.y. in equation 2 for a typical impact rate. Note that the equilibrium apparently reached by f_e (due to the restricted event range) will not be physically typical--larger impacts will restrict T_{MM} so that most surface layers will not reach this equilibrium before burial or destruction.

A set of 100-micron-diameter particles are also simulated for a time T_{CM} in a surface layer of thickness D_s'=1cm subject to impacts generating craters of 1cm to <10cm diameter. As before, larger events will determine the distribution of T_{CM}. Now, however, we do not need to monitor the surface exposure time as this was done more accurately for the 1.5mm layer. Instead we monitor the time t' each particle spends within 1.5mm of the surface, as a function of T_{CM}, and replace T_{MM} with t' in equations 1-3 to determine the distribution of surface exposure time for the ensemble of particles. According to MESS.2 the fraction of 100-micron particles in a 1cm layer reaching the top 1.5mm in time T_{CM} is given by:

(4) $f_e'(T_{CM})_{100} = (D_r'/D_s')[1-\exp(-T_{CM}/T_r']$, with $D_r'/D_s'=0.30$ and $T_r'=12$m.y.,

and t' is distributed according to:

(5) $f_g'(t',T_{CM})_{100} = [\exp(-t'/K_T' T_{CM})]/[1-\exp(-K_1'/K_T')]$ for $0<t'<K_1' T_{CM}$, and
$f_g'(t',T_{CM})_{100} = 0$ for $t'>K_1' T_{CM}$; $K_1'=0.9$ and $K_T'=0.61$.

The average time spent by the ensemble within 1.5mm of the surface is:

(6) $$I_{MM}'(T_{CM})_{100} = f_e'(T_{CM})_{100}\int_0^{T_{CM}} t'\ f_g'(t',T_{CM})_{100}\ dt'$$

and the average surface exposure time as a function of T_{CM} is given by:

(7) $$I_{EX}'(T_{CM})_{100} = f_e'(T_{CM})_{100}\int_0^{T_{CM}} I_{EX}(t')_{100}\ f_g'(t',T_{CM})_{100}\ dt'.$$

We have carried this process one step further, to 10cm (decimeter) surface layers, deriving corresponding distributions and ensemble averages $I_{EX}''(T_{DM})_{100}$, $I_{MM}''(T_{DM})_{100}$, and $I_{CM}''(T_{DM})_{100}$. For 1mm-diameter particles we have simulated 1cm and 10cm layers deriving $I_{EX}'(T_{CM})_{mm}$, $I_{EX}''(T_{DM})_{mm}$, and $I_{CM}''(T_{DM})_{mm}$. Particles of $\gtrsim$1mm diameter suffer greater probability of destruction while on the surface so an additional,exponential loss factor would multiply their exposure time distributions f_g', f_g'', etc. before integration to obtain the I functions. Particles much smaller than 100

microns are also being studied but they involve the additional complexity of possibly sticking to larger grains part of the time, which effects their exposure history.

Processes requiring direct surface exposure (e.g. solar wind implantation and microcrater production) will be governed by:

$$(8) \quad C_i(T_L) = F_i \int I_{EX}^{(L)}(T_L)_g \, (a_o/\rho R_g) \, dm_g/M$$

where $C_i(T_L)$ is the concentration (per unit mass) of species i generated in situ in a soil layer L after surface residence time T_L, F_i is the production rate (per unit area) at the surface. $I_{EX}^{(L)}(T_L)_g$ is the appropriate exposure time function for particles of radius R_g, surface area exposed per unit mass given by $a_o/\rho R_g$ ($a_o \sim 1$, ρ =density), and differential mass fraction dm_g/M. In general C_i may be subject to a saturation process which can be included as an appropriate factor (e.g. $[1-\exp(-K_s t)]/K_s t$ for an erosion or leaky surface mechanism) in the distributions f_g, f_g', etc. so the I_{EX} functions would represent an <u>effective</u> exposure time.

Production processes operating throughout the top millimeter or so (e.g. remnant magnetism, approximately) will replace I_{EX} with I_{MM} in equation 8.

The behavior of the model can be shown independently of the production rates F_i by comparing the various area-time functions defined by:

$$(9) \quad G_x^{(L)}(T_L)_g = (a_o/\rho R_g) \, I_x^{(L)}(T_L)_g$$

where x stands for EX, MM, etc. and L stands for MM, CM, and DM. For example in the absence of saturation, particle communition, and sticky small grains MESS.2 gives $G_{EX}'(T_{CM})_g$ nearly independent of particle radius R_g, corresponding to volume correlation consistent with the Rosiwal Principle (3). In the limit of saturation MESS.2 gives $G_{EX}'(T_{CM})_g \propto R_g^{-n}$ where $n \approx 1/2$, not as strong as surface correlation ($1/R_g$) as a direct result of the in situ exposure inefficiency discussed above. On the other hand $G_{MM}'(T_{CM})_g$ gives a much better surface correlation with or without saturation. However particle communition, agglutination, accretion from space, species retention, etc. need also to be considered.

In addition to exposure times MESS.2 monitors the accumulation of particle tracks in the soil particles, deriving the track distribution as a function of depth and of layer residence times. The G functions can be compared with track density parameters as functions of T_L to provide a basis for interpreting observed soil parameters in a self-consistent manner. Finally, the results generated by MESS.2 describe basic soils formed in situ from pristine material. The distributions described above can be used to derive the characteristics of more complex soils formed by mixing two or more of these basic soils.

<u>References.</u>

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