LUNAR SOIL MATURATION, PART I : MICROSCOPIC AND MACROSCOPIC DYNAMIC PROCESSES IN THE REGOLITH. J. Borg, G.M. Comstock, Y. Langevin, M. Maurette, C. Thibaut. Laboratoire René-Bernas, 91406, France.

I - GENERAL INTRODUCTION TO PARTS I, II, III. One of the major problems in lunar science concerns the "maturation" of the lunar regolith with time which results from complex interactions between the lunar surface and its space environment. We present a progress report which is divided into three very distinct parts and concerns the combined effects of such "Moon-Space" interactions on lunar dust grains. In this paper (Part I) which is designed for LSI topic 2 we analyse purely "mechanical" effects due to dynamic processes acting either at a very shallow depth (<100μ) or at great depth ($\sim$1m) in the regolith and we try to evaluate various time constants attached to such microscopic and macroscopic processes. In part II and III, specifically designed for LSI topic 6, we treat other classes of effects due to the maturation of the regolith such as the synthesis of new "products" in the lunar soil (Part II) and the "aging" of radiation damage features in lunar dust grains (Part III).

II - MICROSCOPIC DYNAMIC PROCESSES ON THE TOP SURFACE OF THE REGOLITH.

II.1. Lunar wind microgardening. We already suggested that the expanding gas clouds that constitute the lunar wind can communicate a momentum to the lunar dust grains exposed on the top surface of the regolith. Such an interaction can trigger the individual turn-over of the grains at a rate, ν_{1w}(number of turn-overs per year), computed as a function of the grain size with the following assumptions : the grains are spherical ; a turn-over only occurs when the displacement of the grain is greater than its radius, r ; the frictional forces acting on the grains are negligible ; a "most probable" grain elevation, h, above the lunar surface is introduced which is estimated from the roughness of the lunar soil on a microscopic scale. Our main results are : a) the micron-sized grains have much higher turn-over rates ($\nu_{1w} \sim 1$/year for r=1μ and h $\sim$2r) than the coarser ones ($\nu_{1w} \sim 10^{-6}$/year, for r=100μ and h$\sim$5μ) and this conclusion is evidenced by our radiation damage studies that show homogeneous amorphous coatings on the micron-sized grains but very inhomogeneous "2-micron" track gradients in the 200 mesh grains ; b) about one time every 1000 years the finest soil grains (r $\sim$ 1000 Å) can be ejected at speeds of $\gtrsim$20 meters/sec during lunar wind "impact" and this contributes to their collisional sticking on the surface of larger grains (see Chapter II.3).

II.2. Solar wind sputtering. We have just completed an extensive set of artificial solar wind type implantations with low energy ions (0.2<E<3keV/amu) ranging from hydrogen up to lead nuclei (1). A great variety of targets were used, including micron-sized grains either found in the lunar regolith or proposed as plausible models for cosmic dust particles. From high voltage electron microscope (HVEM) observations we first evaluated for each target and each type of ion the critical flux values, ϕ_c, which correspond both to the formation of an amorphous coating of radiation damaged materiel on the grains and to a severe rounding of their habit due to ion sputtering (in table I, column 2, we report the ϕ_c values estimated for α-particles which are the most efficient "coating + rounding" ions in space). Then we directly determined the ion sputtering erosion rate, S, of feldspar grains by using a double irradiation technique where a

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Table I

Target	$\phi_c(\alpha)$ (α/cm^2)	Γ_{sw} (years)
Glass	$<5.10^{15}$	$<5.10^{3}$
Pyrox	5.10^{15}	5.10^{3}
Felds	10^{16}	10^{4}
Olivi	3.10^{16}	3.10^{4}
SiC	10^{17}	10^{5}
Ilm	2.10^{17}	2.10^{5}
Magn	5.10^{17}	5.10^{5}
Graph	$>5.10^{17}$	$>5.10^{5}$

thick amorphous coating produced by 3 keV/amu ions is subsequently gradually eroded away with a beam of 0.2 keV/amu ions. Finally the erosion rates and the lifetime of micron-sized grains in the contemporary solar wind (Table I, column 3) was deduced first by using the ϕ_c scalings for going from feldspars to the other minerals and then by dividing the S values so far obtained for a parallel beam of ions by a "lunar geometrical factor" of about 10. Our results clearly suggest that solar wind sputtering alone can already contribute to the "mineralogical-chemical" fractionation effects observed in the finest size fractions of mature soil samples (see paper II).

II.3. Microaggregation of lunar dust grains. There are two extreme examples of dust aggregation products in the lunar regolith that are the lunar breccias and the micron-sized dust aggregates observed in mature soil samples. These microaggregates seem to belong to two distinct types : in type I the secondary particles attached to the central grains have a much smaller radius (∿ 1000 Å) than the central grain ; in type II the constituant particles in the aggregates have about the same radius (∿ 1μ). Such aggregates could result either from the desaggregation of weakly consolided breccias or from the collisional radiation damage sticking (CRDS) of individual grains already covered with an amorphous coating. Our pellet sintering experiments now conducted both with lunar soil samples and with artificially irradiated grains as well as our HVEM observations of lunar dust grains firmly stuck to the mineral paint of the Surveyor III spacecraft favor a CRDS origin for at least the type I aggregates. From our measured density of micron-sized lunar dust grains on the Surveyor paint ($\sim 0.05/\mu^2$) we deduce a collisional sticking probability of about 0.2 for such grains, if we suppose that they were set in ballistic motion at speeds of about 50-100 m/sec by the Apollo 12 rocket exhaust. If the same sticking coefficient is applied to describe a $\gtrsim$ 20m/sec collision between two lunar dust grains set in motion either via ejecta blankets or by rare but violent lunar wind "impact" it can be shown that the lunar wind is likely to be the major contributor for triggering the CRDS of the grains. Then the number of secondary particles, N_s, attached to the central grain of a type I aggregate and which increases up to values of about 10 with the various indices of soil maturity, could be used to deduce a maximum integrated residence time of the grains in the lunar wind ($\lesssim 10^4$ years for $N_s \lesssim 10$), which is compatible with the lifetime of the grains against solar wind sputtering. A similar argument shows that the lunar wind cannot account for the formation of type II aggregate.

III - MACROSCOPIC DYNAMIC PROCESSES IN THE LUNAR REGOLITH AS DECIPHERED FROM RADIATION DAMAGE STRATIGRAPHY IN LUNAR CORE TUBE.

III.1. Some of the raw data and their statistical analysis. For each 200 mesh grain we measure the track density at the grain center (ρ_c), near the edge (3μ - 5μ) but still in the solar flare particle region (ρ_b) and when possible still closer to the edge $\lesssim 1\mu(\rho_\mu)$. The ratios $\Gamma = \rho_b/\rho_c$ and $\Gamma_\mu = \rho_\mu/\rho_b$ then characterize the solar flare and "suprathermal"particle gradients which may be present in the grains. For each grain, Γ and Γ_μ can be determined from opposite egdes to yield information on multiple exposures. Finally ρ_c, Γ and Γ_μ can be determined for different regimes of track lengths, to yield chronological information based on track aging (see paper III). Our computer program then searches for correlations among these various measurements of ρ_c, Γ and Γ_μ and analyses their distribution as a function of both maturity indices and depth in core tubes. We thus get general conclusions that are independant of model assumptions : 1. nearly all 200 mesh soil grains have at one time resided within 1 mm of the surface, most have resided there in several different orientations and about half have had less than 1 grain radius ($\sim 50\mu$) of covering material and hence have been exposed to very low energy ions. Since ejecta layers are typically $\sim$1cm thick our results further show that near-surface gardening processes play an important role in the maturation of the grains ; 2. we have identified and characterized at least 2 populations of abundant primary particle tracks (see paper III) that we interpret as being either "younger" tracks formed when the grains were last near surface (Population 1) or "older", more mature tracks (Population II) that have been severely aged in the regolith. The median density of Population I tracks (which is not given by the lowest track densities in a layer) varies widely from layer to layer reflecting the difference in their last surface residence time.

III.2. Theoretical simulation of irradiation history. To quantitatively interpret soil maturity and accurately determine surface residence time and core chronology from track population I and II we are perfecting a series of computer simulation programs which increase step by step the complexity (and maturity) of the irradiation history for artificially generated "soil grains" : 1. the first step determines the track formation rate and track length distributions as a function of depth and investigates the effect on the track gradients of a variable or uneven shielding thickness. Such simple irradiation histories, which have so far been the only ones used by others, explain some of the young Population I track distributions in individual grains but not their statistical distribution in a given soil layer ; 2. the second step is to simulate the latest irradiation history due to a near-surface (1μ-1cm) gardening process. The comparison of the artificially generated track distribution with the population I track distribution will yield the best values for the latest surface residence time for each layer and therefore a good core chronology can be constructed. It is important that this model be constructed carefully since our experimental results show that the total track density in most of the grains has resulted essentially from near-surface exposure of the grains ; 3. the 3rd step is intended to predict the characteristics of mature Population II tracks, by combining the effects of several simulated near-surface gardening episodes for random residence times and including the relatively small additional dosage received during burial below $\sim$1cm. The comparison between the artificially generated "old" tracks and Population II tracks should then tell us how many ejecta blanket episodes are needed and perhaps give some information on impact rates in the past.

REFERENCE : (1) Ion implantation effects in cosmic dust grains. J.P. Bibring, Y. Langevin, M. Maurette, R. Meunier, accepted for publication in EPSL, 1973.