44

LUNAR SOIL MATURATION, PART III : SHORT-TERM AND LONG-TERM AGING OF RADIATION DAMAGE FEATURES IN THE REGOLITH. G. Bastin, G.M. Comstock, J.C. Dran, J.P. Duraud[+], M. Maurette, C. Thibaut. Laboratoire René-Bernas, 91406 Orsay and ; [+] Service de Chimie-Physique, CEN de Saclay, 91 Gif-sur-Yvette.

I - INTRODUCTION. The exposure of lunar dust grains in the solar wind and in fluxes of more energetic solar nuclei produce ultra-thin amorphous coatings and nuclear particle tracks respectively. A comparison of the "old" fossil tracks and coatings to the "fresh" ones obtained for calibration purposes during artificial irradiation of similar grains can give interesting information concerning both ancient solar radiation (see Chapter 3) and lunar dynamic processes (see Paper I). However this comparison, unless properly corrected, is meaningless if "aging" processes have modified the characteristics of the "old" radiation damage features during the maturation of the lunar regolith. In this paper we essentially show that the tracks, but not the amorphous coatings, have been severely "aged" and we discuss how to properly use both types of radiation damage features to study ancient solar nuclear particle fluxes.

II- AGING OF RADIATION DAMAGE FEATURES IN THE REGOLITH.
      II.1. Laboratory evidence for short-term aging :(A). Tracks. In lunar dust grains the following characteristics show first that the "fresh" tracks (FT) produced with an artificial beam of 537 MeV iron nuclei at the University of Manchester are different from the "old" fossil tracks (OT), essentially due to VH nuclei of solar origin, and then strongly suggest that VH tracks freshly registered in lunar dust grains should undergo a very rapid short-term aging during their first near-surface exposure on the Moon : 1. the FT unless artificially stabilized (see Chapter II.3) disappear very quickly by "ionization" annealing in the electron beam of the 1.5 MeV electron microscope. On the contrary the OT are very stable under the beam ; 2. by applying our newly developed "GINT" method (see Chapter III.3) we found that the length distribution of the FT and OT are very different. For example in feldspar grains from rock 15475 the FT lengths are peaked at about $L_o \sim 36\mu$ with a relatively high proportion of tracks ($\sim 10\%$) showing lengths greater than 55μ, after the "normal" etching time, t_o. However, the FT lengths drastically vary with the etching time and a few tracks($\sim 0.1\%$)become etched to $\sim 70\mu$ after increasing this time up to $10t_o$. In contrast the length distribution of the OT in the same grains (which are certainly non mature as they were shielded inside the rock) is narrowly peaked at about $L_o \sim 15\mu$ and does not show any marked change with the etching time. The OT shortening is even more pronounced in feldspars from mature soils where Population II tracks have lengths $\sim 2\mu$ (see Chapter II.2) ; 3. in a given grain the OT etch at least 2 times faster than the FT ; 4. during thermal annealings conducted for feldspars the FT show a striking low temperature fading which is not observed for the OT and which is extremely marked for both the high energy (537 MeV) and low energy (23 MeV) ends of the FT. In particular by using conditions that simulate a 72-hours exposure of the FT in the"lunar day time", the length distribution of the 537 MeV FT is already drastically modified with the shortest tracks being almost completely suppressed (fig. 1) and the longest ones showing a shortening of about 75%. When the annealing is pursued at higher temperature (400°C) the large spread in the

AGING OF RADIATION DAMAGE FEATURES

Bastin, G. et al

FT length distribution is considerably reduced as a result of the preferential fading of the high energy part of the tracks and becomes roughly similar to that observed for the OT in lunar igneous rocks. Finally both types of tracks disappear at much higher temperatures ($\sim$700°C) with the OT being slightly more resistant than the FT ; (B). <u>Amorphous coatings</u> : the thickness and the appearance of the amorphous coatings are not affected by short-term aging. Indeed, the old as well as the fresh coatings are observed unmodified in the HVEM over long period of time, at high beam current. Furthermore the fresh coatings do not show any low temperature annealing and they only disappear, as do the old coatings, at high temperatures ($\sim$750°C for 2 hours).

  II.2. Lunar evidence for an additional long-term aging of the tracks. The OT shortening is more marked for mature than for non mature soil sample and this indicates that subsequent to their short-term aging the OT suffer a long-term aging possibly due to their repeated near-surface exposure on the Moon. In fact there are at least 2 populations of tracks in 200 mesh grains : Population I is characterized by a relatively low density of tracks (10^7-10^8. cm^{-2}) generally $\sim$10μ in length with a wide range of gradients (Γ = 1 to 10) which are anisotropic ; Population II is characterized by much higher densities ($\gtrsim$$10^9$.$cm^{-2}$) of short tracks (L$\sim$2$\mu$) with significant but more shallow (Γ = 1 to 3) and generally rather isotropic gradients. We interpret Population I as being younger tracks formed when their soil layer was last near the surface and Population II as being older more mature tracks which result from being processed through several ejecta layers and near-surface gardening processes. In the most mature soil samples we also discovered a 3rd population of very short tracks (L$\sim$0.5μ) with even higher densities ($\gtrsim$5 x 10^9 cm^{-2}) but we cannot be certain that they represent very mature OT, as they show no gradient.

  II.3.Nature of the short-term aging process. In non-mature lunar dust grains the marked OT shortening is due to the lunar thermal cycle and proceeds via the rapid annealing of the high energy part of the tracks. Furthermore, the implantation of heavy doses of solar wind nuclei in lunar dust grains plays certainly a major role in the rapid stabilization of the OT against ionization and perhaps thermal annealings as we observed the latent FT only in grains that were exposed to heavy doses of simulated solar wind subsequently to the iron beam irradiation.

III. RADIATION DAMAGE PARAMETERS (RDP) AND ANCIENT SOLAR NUCLEAR PARTICLE FLUXES.
  III.1. RDP that are not affected by aging. The thickness, Δ, of the amorphous coatings and the proportion of coated grains, P(Δ), in a given soil sample seem to be the only RDP that are not modified by aging effects : 1.P(Δ) is a useful "solar wind" index that correlates well with other indices of soil maturity ; 2. the distribution of the coating thickness, $\delta(\Delta)$, as a function of the depth in lunar core tube reflects the variation with time of the thermal properties of the ancient solar wind. So far no secular trend with depth has been found both in the Apollo 15 and 16 core tubes but various clear stratifications in $\delta(\Delta)$ have been observed.

  III.2.RDP that are possibly affected by aging. It is very difficult to decide whether or not the low energy tracks which produce the "suprathermal" and solar flare track gradients (ST and SF gradients) are most affected by aging

AGING OF RADIATION DAMAGE FEATURES

Bastin, G. et al

than the tracks that are totally registered deeper within a grain. With these reservations, the main results of our track gradients studies are : 1. the SF gradients associated to the "older" population II are in general much less steep and more isotropic than those observed for the "young" population I. Our theoretical simulations (see Part I, Chapter III.2) suggest that this maturation of the gradients is consistent with repeated exposures in different orientations and depths ; 2. non-mature soils do not contain ST gradient ; 3. the proportion of grains with ST gradients in mature soil samples do not seem correlated either with $P(\Delta)$ or with the smaller proportion of grains showing large coatings ($\Delta \gtrsim$ 800 Å). This observation suggests that the ST gradients are not due to particles emitted in correlation with solar wind nuclei ; 4. very few layers in the Apollo 15 core tube contain grains with ST gradients whereas all layers contain grains with SF gradients and this would be expected if most grains retain a thin shielding layer of "sticky" micron-sized grains during their exposure on the top surface of the regolith.

   III.3. RDP that are severely affected by aging. It is quite clear that aging processes have drastically modified the track parameters (total etchable length, L_O ; etching rate, V_O ; stability against thermal and ionization annealing) that are currently used in several applications of the track method to lunar samples. To understand the nature of the track aging processes as well as to learn how to "demodulate" fossil track parameters from aging effects it is necessary to study the track length distribution and track etching rate, both for the OT and several types of FT, as functions of various environmental parameters. Lal was the first in 1969 to propose a very cleaver method to measure L_O values in meteoritic crystals in which both individual long OT and cleavages were used to inject the etching solution into the OT (TINT and TINCLES method respectively). When we applied these techniques to the tiny 200 mesh lunar dust grains containing severely aged tracks and very few cleavages many difficulties were encountered. For example the etching behavior was highly irreproductible from one track-or-cleavage to the other. Therefore we decided to develop a new method that we call the "giant track-in track" method (GINT method) to minimize such difficulties. In this method which is illustrated in figure 2 an individual grain is irradiated with a high dose of 400 MeV argon ions ($\gtrsim 10^{13}.cm^{-2}$), that are perpendicular to the sample and collimated with a rectangular slit with a very small aperture ($\sim 2\mu$). We thus get a "giant" argon track resulting from the overlapping of many individual tracks and extending to depth of about 60 microns, which has well defined geometrical and etching characteristics, and which can be used to measure in a reproducible way track length distribution from the edges to the center of a grain or rock.
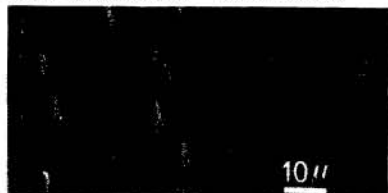
Figure 1
not annealed   annealed

Figure 2 : "GINT" method