PARTICLE TRACK RECORD OF THE LUNA MISSIONS*

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Abstract. Measurements are reported of particle-track densities in 100–200 μ crystalline grains taken from one level of the soil column returned from the lunar highlands between Mare Fecunditatis and Mare Crisium by Luna 20 and from two levels in that from Mare Fecunditatis by Luna 16. Ninety-three percent of the grains from Luna 16 have very high densities, $> 10^8$ cm^{-2} and the lower-track density grains are all in the deeper soil level. In contrast, most Luna 20 grains show densities $< 10^8$ cm^{-2}. Track density gradients and exposure times have been measured for six Luna 16 grains with a wide spread in absolute track densities. The more extensive track counts in crystals strengthens our earlier conclusion that the Luna 16 soil has received long irradiations very close to the surface. Two possible histories are that the highly irradiated soil blanket at the Luna 16 site is either well mixed and thin, or else has accumulated by transport from surrounding higher regions. The single sample of doubtful depth from Luna 20 shows a much lesser near-surface irradiation, giving results similar to those on the Apollo 12 core and the 54–80 depth sample from the Apollo 15 deep core.

1. Introduction

We report here the densities of fossil cosmic ray tracks that have been measured in soil grains taken from cores returned by the Luna 16 and Luna 20 missions (Vinogradov, 1971, 1972). These represent samples from two of the seven lunar sites which have so far been analyzed for their cosmic ray irradiation record and hence are important for understanding the properties of lunar surface mechanics and history.

Preliminary data for crystalline grains from Luna 16 that were presented in an earlier Letter (Comstock *et al.*, 1972) indicated that essentially all of the grains had been irradiated within $\sim$1 mm of the lunar surface, most of them for at least 10^6 yr. In the present Letter we report Luna 20 results and updated measurements of the crystalline grains from Luna 16, new data from glass fragments, and measurements of track density gradients within individual grains.

2. Observations and Discussion

A. CRYSTALLINE GRAINS

We analyzed grains with diameters of 100–200 μm (and occasionally larger) selected from depth intervals 6–8 cm (L-16-17A, designated 'level 1') and 29–31 cm (L-16-17G, designated 'level 4') of the returned soil column from Luna 16. The distribution of track densities measured in 2 feldspar, 31 pyroxene, and 8 olivine grains from Luna 16 is shown in Figure 1. From Luna 20 we analyzed the single sample, possibly mixed during retrieval, that was available from a depth at 19–27 cm. Figure 2 shows the results

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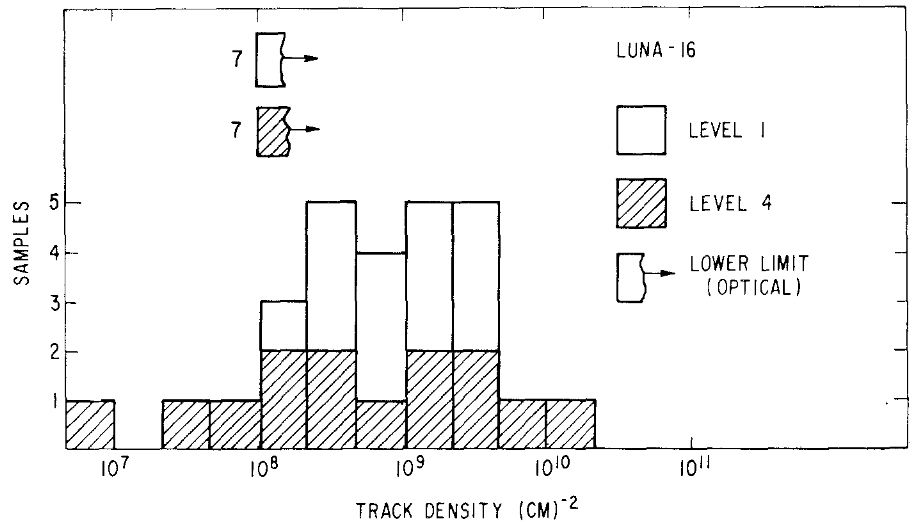

Fig. 1. Distribution of track densities from Luna 16: level 1 (6 to 8 cm) and level 4 (29 to 31 cm). Fourteen samples could be assigned only a lower limit of 10^8 cm^{-2}. Samples with track density gradients are represented by their lowest density. Pyroxenes adjusted for etching efficiency of 0.7.

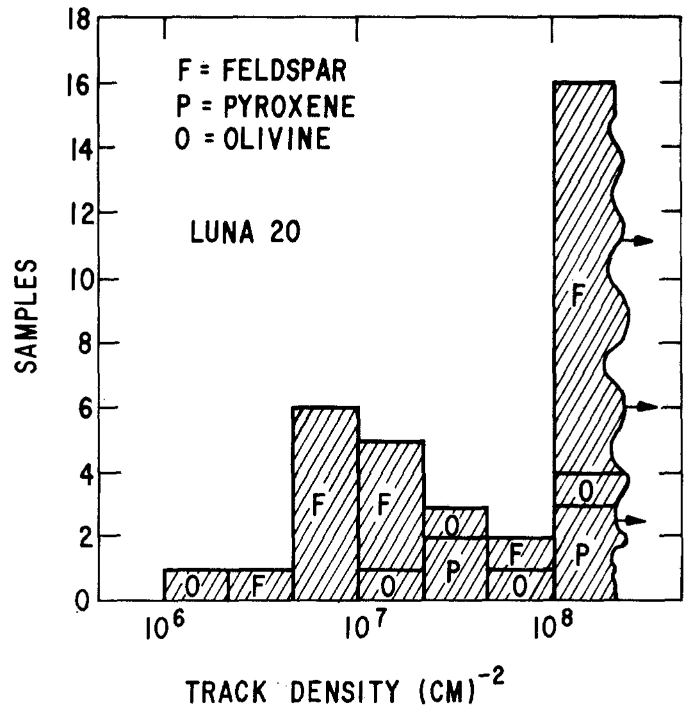

Fig. 2. Distribution of track densities from Luna 20, 19 to 27 cm depth. Data treated as in Figure 1.

for 23 feldspar, 6 pyroxene, and 5 olivine crystals. Definite track counts for track densities greater than 10^8 cm^{-2} were obtained by observing platinum-shadowed track replicas with a transmission electron microscope (MacDougall *et al.*, 1971; Fleischer *et al.*, 1970). The 14 samples in Figure 1 and 16 in Figure 2 shown as lower limits are known to have track densities $>10^8$ cm^{-2} but were not accurately counted.

B. LUNA 16 RESULTS

Of those samples with definitely measured densities those from level 1 have a median track density of nearly 10^9 cm^{-2} and 100% have densities $>10^8$ cm^{-2}. Those from level 4 have a median track density of about 5×10^8 cm^{-2}, and only $\sim$80% have densities $>10^8$ cm^{-2}, with one sample $<10^7$ cm^{-2}. The extremely high track densities are comparable to the results of other workers for the Luna 16 soil (Kashkarov, 1971; Phakey and Price, 1972; Walker and Zimmerman, 1972; Poupeau *et al.*, 1972) but are in general much higher than for Apollo 11, 12, and 14 soils (Comstock *et al.*, 1972), and references therein; (Poupeau *et al.*, 1972; Crozaz *et al.*, 1972; Phakey *et al.*, 1972; Hart *et al.*, 1972). Very high track densities have been found to predominate in certain portions of the Apollo 15 deep soil core (Crozaz *et al.*, 1972; Phakey *et al.*, 1972). However, for a set of 13 samples from 54–8 cm depth we find considerably lower values, which could be merely evidence of the natural and to a large extent statistical differences of soil layers at different depths, but equally well could be due to systematic differences in experimental procedures. For example, on micron-sized particles Borg *et al.* (1971) and Barber *et al.* (1971) find track densities $\sim 10^{10}$–10^{11}; on 50–100 μ particles from the same Apollo 12 core Arrhenius *et al.* (1971) and Crozaz *et al.* (1971) find median densities $\sim 8 \times 10^7$; on 100–200 μ particles we find a median density of 2.5×10^7 (Comstock *et al.*, 1971). In short the differences are systematic and size correlated, the larger grains having in general fewer tracks. In understanding these differences we must distinguish two cases – grains with perceptible track density gradients and those without. In grains with gradients that indicate they were exposed at the very surface the size effect would result naturally from similar times of exposure to solar flare particles that have a steep energy spectrum. For grains without perceptible gradients the differing track densities would indicate shorter average surface exposure for the larger grains, and therefore less time during which they were subject to direct impact by incoming small projectiles. Because of the problems brought up by these systematic differences, we will intercompare our results only with previous work on crystals of the same average size.

Track densities of 10^8–10^{10} cm^{-2} in 100 μm-grains require irradiation at soil depths <1 mm for a total of $\gtrsim(10^5$–$10^7)$ yr (Comstock, 1971). Material within the top millimeter of soil is disturbed by micrometeoroid impacts on a time scale of $<10^5$ yr (Shoemaker *et al.*, 1970). This means that each soil grain has had many chances to reside very near the surface, through repeated impact-excavation and reburial. In other words, the top soil is well mixed in the sense that the grains have resided for significant periods of time at levels other than where they were ultimately located.

This description does not rule out stratification and other significant periods of time in undisturbed soil.

Our data suggest that level 4 is somewhat less irradiated than level 1. This also was observed by Kashkarov (1971) as we cited earlier (Comstock *et al.*, 1972). We know that shallower layers will be mixed by meteoroid impacts more often than will deeper layers, and this mechanism has been shown (Comstock, 1971) to lead to a greater total dosage for the shallower levels by about the ratio observed, (level 1/level 4)$\lesssim 2$. This observation, therefore, is consistent with the specific mixing mechanism referenced.

As we have noted earlier (Comstock *et al.*, 1972), for a closed population of soil only about 30 cm could have been irradiated with the observed extreme dosage during the lifetime of the Moon. Appreciably deeper material could have been disturbed early in the history of the maria surface but not since then, suggesting a relatively shallow regolith for this part of Mare Fecunditatis. Indeed, the Luna 16 soil column does become coarser near its lower end at $\sim$40 cm (Vinogradov, 1971).

On the other hand, a regolith may contain a high track density down to much greater depths, as others have reported for the Apollo 15 deep core (Crozaz *et al.*, 1972; Phakey *et al.*, 1972) provided there is a net in-flow of grains which previously were highly irradiated, perhaps during surface transport. We cannot rule out this possibility for the Luna 16 site but we emphasize that our results imply that a thin irradiated layer exists at the sampled site or else at surrounding higher ground where transport of soil would originate.

C. TRACK DENSITY GRADIENTS IN LUNA 16 SAMPLES

Steep track density gradients for long tracks ($>1\ \mu$m) were observable in six crystalline grains, three from level 1 and three from level 4. Others may have had track gradients which were not clearly visible due to saturation effects at the very high track densities involved.

The measured track profiles were found to obey an inverse power lay with depth, $P(D)=CD^{-\gamma}$ with exponent γ ranging roughly from 0.7 to 1.0 for $D\lesssim 600\ \mu$m. This behavior is similar to that observed in grains from other soils (Hart *et al.*, 1972) and appears to be independent of material type. The magnitude (coefficient C) varies widely from grain to grain for the Luna 16 soil. For example, at a depth of 20 μm within the various grains the track densities extend from 4×10^8 cm^{-2} to 1×10^{10} cm^{-2}.

Possible interpretations of track density gradients in soil grains are discussed elsewhere (Hart *et al.*, 1972; Comstock, 1971); here we emphasize only those points pertinent to the present discussion.

The existence of an observable true track density gradient (i.e., not due to internal crystal non-uniformities) within a 100 μm grain indicates irradiation by solar flare particles within 1 mm of the lunar surface. The slopes $\gamma\lesssim 1$ of the measured track density profiles are considerably less than the $\gamma\approx 2.5$ expected from direct irradiation by solar flare particles (Comstock, 1971; Fleischer *et al.*, 1971a; Crozaz and Walker, 1971; Price *et al.*, 1971). This is probably due to partial shielding by fine dust during irradiation or to soil abrasion after reburial. A grain whose irradiation has been shielded by dust layers of several different thicknesses can have a near power-law track density profile with $\gamma \sim 1$ (Hart *et al.*, 1972). The wide range in magnitude from one grain to another reflects the range of surface resistence or exposure times experienced by the grains.*

We can derive approximate or effective exposure times by correcting the measured depths for the shielding layers, requiring that $\gamma = 2.5$. The required shielding depths are in the range 40 μm–70 μm and the resulting six total exposure times are 0.2, 0.3, 1, 5, 7, and 7 m.y. These agree with the values of $\gtrsim(10^5\text{–}10^7)$ yr inferred earlier for all crystalline grains. It is probable that the samples in which gradients are still visible represent grains which have not suffered as extensively from abrasion, break-up, and repeated irradiation as have those with high track densities but no identifiable gradients.

D. LUNA 20 RESULTS

The Luna 20 material contrasts markedly with the Luna 16 samples – having fewer track gradients and a median track density ten times lower. Figure 3 intercompares the minimum and median track densities in various soil samples that we have examined

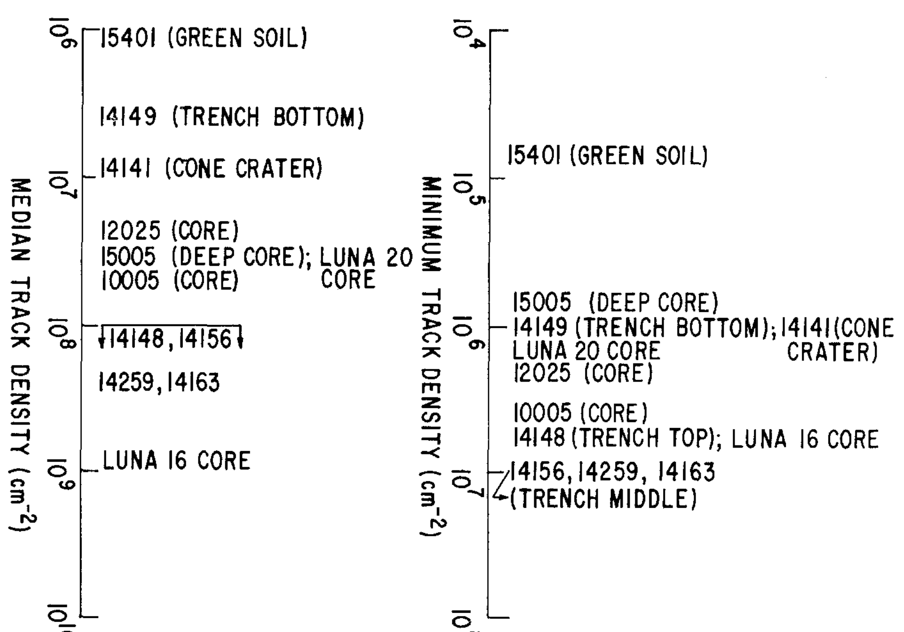

Fig. 3. Comparison of median and minimum track densities observed in various soils using common sample selection criteria. 100–200 μ grains. Data from Fleischer *et al.* (1970); Comstock *et al.* (1971) Hart *et al.* (1972), and Fleischer and Hart (1972).

* Another interpretation of the reduced γ's would be the equilibrium between fine-scale erosion and track production (Comstock, 1971). This interpretation seems less likely in that it implies a wide variation in the ratio of the long-term average solar cosmic ray flux to the erosion rate.

from Apollo 11, 12, 14, and 15 (Fleischer *et al.*, 1970; Hart *et al.*, 1972; Comstock *et al.*, 1971; Fleischer and Hart, 1972), and the present Luna results. As noted earlier, because of different sample processing procedures at different laboratories (Borg *et al.*, 1971; Barber *et al.*, 1971; Arrhenius *et al.*, 1971; Crozaz *et al.*, 1971; Comstock *et al.*, 1971), only samples processed under identical procedures should be intercompared. Many of the core samples (such as our Apollo 15 core) include as many as 13 different levels; in such cases the minimum track density plotted is the median of the minima for the various levels.

Figure 3 makes it apparent that the much shorter near-surface exposure of the Luna 20 soil makes it similar to the previous Apollo 12 core sample (Comstock *et al.*, 1971) and to the portion of the Apollo 15 core that we have examined. The Apollo 15 site is appropriate for comparison with the Luna 20 site as it is the only other lunar terra region that has been sampled.

E. GLASS FRAGMENTS

Examination of ten glass samples from each of the two missions revealed tracks only in one pair of coexisting Luna 16 samples (1.6×10^5 cm^{-2} and 2.2×10^4 cm^{-2}). In four cases (again Luna 16 samples), track densities could be observed in crystals surrounded by the glass, the ratios of track densities (in crystal/in glass) being >230, >500, >800, and >8000 with 95% confidence. Since differences in etching efficiency can account for at most a ratio of 10, it is clear that considerable track fading has occurred in the glasses following their last irradiation.

Particle tracks in glass will anneal at a composition-dependent rate which decreases rapidly with increasing depth, *i.e.*, with decreasing lunar soil temperature. For example, in a typical dark lunar glass, complete track erasure may require only about 500 yr at surface temperatures but $\sim 10^7$ yr at a soil depth of 100 cm (Fleischer *et al.*, 1971b). The precise composition of the measured Luna glasses is not known. However, data for the one dark lunar glass on which track fading studies have been reported would require near surface residence to promote track loss of the degree observed. The glass must reside within a few hundred microns of the surface in order to register observable solar flare track densities and these tracks are readily erased by heating during residence at that depth. We conclude that these glass samples are consistent with the evidence of the crystalline grains, but are not useful in the present context.

3. Conclusions

We infer long total surface exposure times of 10^5–10^7 yr or more from the very high track densities in nearly all of the Luna 16 soil samples. These times imply that a typical grain has been thrown to the surface many times, so that the soil is well mixed but not diluted by previously shielded material. Some grains have suffered fewer surface exposures in the top 1 mm and retain measurable track density gradients which yield more precise exposure times of 2×10^5 to 7×10^6 yr. Considerable track fading in glass samples is also consistent with extensive near-surface residence.

If we conclude from our two samples that the same high track densities we observe are present throughout $\sim$30 cm of the soil (and Kashkarov's (1971) results on 5 layers support this interpolation), we have at least two alternatives: If no net inflow of previously irradiated material has occurred, our results would imply that this maria surface is $\sim 3 \times 10^9$ yr old, i.e., comparable with the 3.4×10^9 yr age of the one Luna 16 basalt that has been dated (Papanastassiou and Wasserburg, 1972; Huneke *et al.*, 1972), and that furthermore, material that is now at greater depths has not been exposed since early in the history of the surface. An example of a long, undisturbed, near-surface residence is the 2.4 m Apollo 15 core which has apparently been substantially undisturbed for its last 500 m.y. (Russ *et al.*, 1972).

A less dramatic but more likely alternative for the Luna 16 site is that there has been appreciable net transport of highly irradiated material into the sampled area and that the thickness of the irradiated regolith is considerably greater than the 32 cm depth that was sampled.

The Luna 20 material has had a less unusual near-surface residence, giving results that are closely similar to those from the Apollo 12 core and that portion of the Apollo 15 core that we have examined, the only other terra region from which there are samples.

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