PARTICLE TRACK RECORDS IN THE LUNA-24 DRILL CORE SOIL SAMPLES

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Grain-size separates of six soil samples taken from various depths in the Luna-24 drill core soil column have been analysed using the particle track technique. The observed track records in these samples indicate highly mature nature of the soil samples in the upper meter of this soil column, while the soil samples in the lower portion are predominantly immature to sub-mature in nature. The existence of a meter thick track-rich soil layer, in which most of the individual grains have received solar flare irradiation cannot be explained by the conventional impact-layering process leading to the growth of regolith at a given site. It is proposed that accumulation of this track-rich zone has taken place through the process of downslope movement of regolith material along the crater walls, following an impact cratering event at the drill core site itself. Compatibility of such a depositional scenario with the observed records of other near-surface and sub-surface cosmogenic effects in this drill core soil samples is discussed.

INTRODUCTION

THE Luna-24 automatic space probe has retrieved a soil column from the lunar surface in August, 1976. The sampling site was situated on the southeast side of *Mare Crisium.* Although the length of the retrieved soil column was 160 cm (Florensky *et al.*, 1978), the effective sampling depth was ~ 140 cm since the drilling was done at an angle of ~ 30°, and the study of ^{26}Al activity in samples from this core indicate a possible loss of ~ 10 cm soil layer near the top of the core (Florensky *et al.*, 1978; Bhandari & Potdar, 1979). A study of solar flare and galactic cosmic ray heavy nuclei tracks have been carried out in six samples taken at different depths in this soil column. Because of the extremely depth sensitive production rate of particle tracks, with an attenuation depth scale of ~ 10 cm, the track method is extremely useful in delineating the near-surface exposure histories of lunar soil samples. In this paper, the author describes the results of the particle track studies carried out and discusses these results along with those obtained by others in an attempt to understand the exposure and the evolutionary history of the Luna-24 drill core soil column.

SAMPLE DETAILS AND EXPERIMENTAL PROCEDURES

The details of the six samples analysed in the present work are given in Table I. Out of the four major and twenty seven minor petrographic units seen in this drill core (Florensky *et al.*, 1978), the author has received representative samples from three

TABLE I

Particle track data for Luna-24 soil samples*

Sample Number	Depth below lunar surface (cm)	Size fraction** (micron)	No. of grains analysed	ρ_{min} (x10^6cm^{-2})	ρ_q (x10^6cm^{-2})	N_H/N
24087, 11	35	40–90	46	22.0	100.0	.91
		>100	24	1.5	100.0	.95
24123, 14	66	40–90	53	24.0	100.0	.98
		>100	23	1.6	030.0	.69
24148, 12	87	40–90	53	2.8	100.0	.88
		>100	37	1.0	030.0	.60
24163, 12	100	40–90	42	2.6	022.0	.62
		>100	33	.28	005.0	.36
24179, 12	114	40–90	52	45.0	100.0	.98
		>100	33	6.0	060.0	.76
24190, 11	124	40–90	35	1.4	008.0	.37
		>100	36	.1	000.5	.41

*The track data for > 100 micron size fraction are from Goswami (1978).
**The > 100 micron size fraction mostly contain grains in the size range 100–300 microns.

major units. No samples from the coarse grained unit (unit–I), representing the topmost ~ 15 cm of this drill core soil column have been received.

Two grain-size 'separates', 40–90 micron and > 100 micron, have been analysed in each sample. The > 100 micron separates mostly contain grains in the size-range 100–300 micron. About thirty grains were hand-picked from each of these grain-size separates and processed for revelation of particle tracks following standard procedure (Bhandari *et al.*, 1972; Krishnaswami *et al.*, 1971; Lal *et al.*, 1968). Feldspar is the dominant mineral species among the grains picked up from the 40–90 micron size-separates. The percentage distribution of different mineral species in the analysed > 100 micron size separates is : feldspars (55 per cent), pyroxenes (30 per cent) and olivines (15 per cent). The track counts were made in the near-centre region of each grain using optical microscopes at magnifications of 1000–1600 X. The track densities in olivine grains were scaled up by a factor of two to take into account their higher track registration threshold compared to feldspars and pyroxenes (Bhandari *et al.*, 1972). Track densities $\geqslant 10^8$ cm^{-2} cannot be measured accurately due to limited optical resolution, and are grouped together in the present analysis. This, however, does not alter any of the conclusions drawn in this paper since no quantitative information has been derived from the grains having high track densities.

RESULTS AND DISCUSSION

The results obtained in the present work have been summarized in Table I, where the observed track record in each sample is indicated in terms of the conventional track parameters ρ_{min} (minimum track density), ρ_q (quartile track density) and N_H/N (fraction of track rich grains). The results for the > 100 micron size fraction have been published earlier (Goswami, 1978). The track parameters ρ_{min} and ρ_q are measures of the integrated near surface exposure duration of a given soil sample (Arrhenius *et al.*, 1971; Fleischer & Hart, 1973), and the parameter N_H/N represent the fraction of grains in a given soil sample that have received solar flare irradiation due to their exposure within the first millimeter in the lunar regolith. The observed track data for the two grain-size separates are similar except for samples 24123, 24148 and 24163. The track data given in Table I indicate that the soil sample 24087 is the most heavily irradiated among the six soils analysed by us. The soil samples 24123, 24148 and 24179 are also characterized by relatively high values of the track parameters. The values of the track parameters for the soil samples 24163 and 24190, on the other hand, are relatively low, and reflects the immature nature of these soils. Based on the above observations, it is postulated here that the Luna-24 drill core soil column can be divided into two distinct zones as far as particle track irradiation record is concerned : an *upper* zone, representing the top meter of the soil column, where most of the soils are highly mature, and a *lower* zone, representing the lower ~ 40 cm of this drill core, where the soil samples are characterized by their varying maturities. Such a broad division of this soil column is also supported by the presently available additional track data for soils from this drill core due to Crozaz (1978), Blanford and Wood (1978), Kashkarov *et al.* (1978). This can be clearly seen from Fig. 1, wherein are plotted values for N_H/N, and ρ_q for the different Luna-24 soil samples analysed by us and other groups. Apart from the N_H/N data of Kashkarov *et al.* (1978) which are systematically lower, and may be due to the large grain-size (200–370 micron) used in their analyses and observational limitations as well, the other track data clearly indicate the highly mature nature of all the soils in the *upper zone* of this soil column, and the presence of predominantly immature and sub-mature soils in the *lower zone* of this drill core. The absence of solar flare irradiated grains in soil from the micro-gabbro layer 24170 (Crozaz, 1978) also indicate definite presence of immature soils in the lower zone of the Luna-24 drill core soil column.

An additional observation of interest is the distinct grouping in track densities of individual soil grains in the > 100 micron size fraction of soils 24163 and 24190 (see Fig. 2). In general, the observed track density frequency distribution in a given soil sample is characterized by its lunar surface exposure duration. An immature lunar soil, having a short surface exposure duration, is characterized by abundant soil grains with low track densities. With increasing exposure age, as in the case of mature soil samples, the peak in the track density frequency distribution shift towards higher track densities. However, a mix of mature and immature soil components can lead to distinct groupings in track density frequency distribution as can be seen in the case of soils 24163 and 24190. The track data for these samples thus indicate the presence of mixed lunar soils, in the lower zone of the Luna-24 drill core column, consisting of both a mature and an immature soil component. None of the other soils analysed here and elsewhere show such a trend. McKay *et al.*, (1978) have proposed a two component model for the entire Luna-24 core, based on the observed bi-modal grain size distribution in all the samples analysed by them. While the

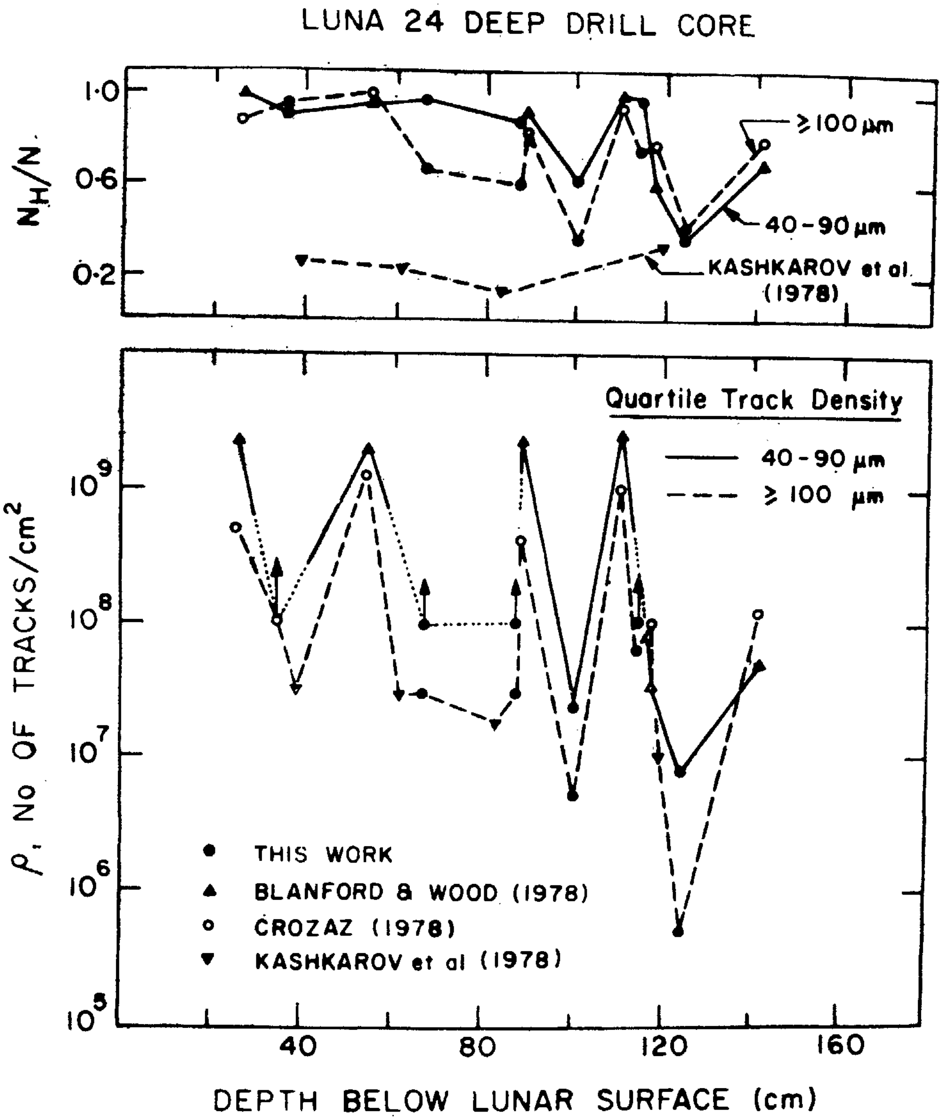

FIG. 1. Observed variations in the track parameters N_H/N, and ρ_q in various samples from the Luna- 24 deep drill core. The > 100 micron data are based on the present work and the work of Crozaz (1978) and Kashkarov *et al.* (1978) who have analysed grains in the size range > 50 micron and 200–370 micron respectively.

track data indicate such a possibility in the case of a few soil samples, the observed bi-modal grain size distributions in most of the soil samples is in no way correlated with their particle track irradiation histories.

As noted earlier, the values of the track parameters ρ_{min} and ρ_q are measures of integrated near surface exposure duration of a given soil sample. Thus, if we consider *zero pre-depositional track irradiation* for all the analysed soil samples, the

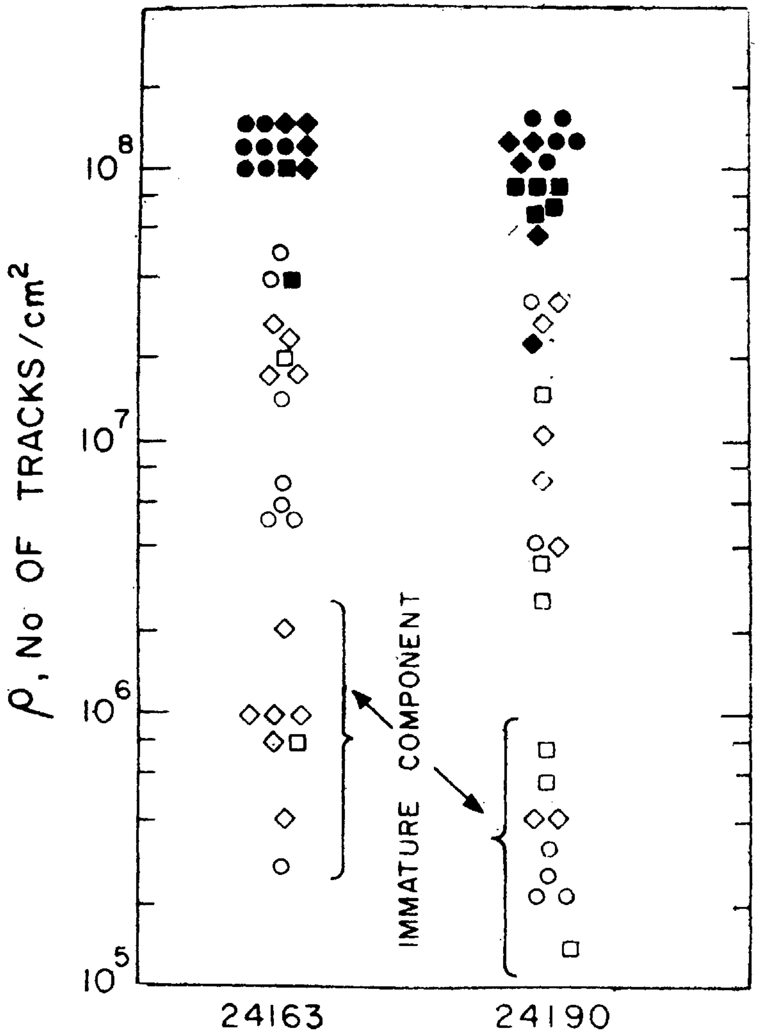

FIG. 2. Track density frequency distributions for the $>$ 100 micron size fraction in soils 24163 and 24190. Both the distributions are characterized by the presence of an immature soil component, individual grains of which are characterized by track densities $\leq 10^6$ cm^{-2}. The various symbols refer to different mineral species : ○ ≡ Feldspar, ◇ ≡ Pyroxenes, and □ ≡ Olivines. The filled symbols represent grains having solar flare irradiation.

observed track data will indicate a very slow deposition rate for the top meter of this drill core soil column, and a relatively rapid deposition rate for the soil samples in the lower zone. The high values of minimum and quartile track densities in samples from the upper zone, and the fact that most of the soil grains in samples from this zone have also received solar flare irradiation record due to their exposure within the top millimeter in the lunar regolith, indicate an average deposition rate of ~ 1 mm/m.y. for this part of the soil column. An approximate value of ~ 3 to 5 mm/m.y.

for the deposition rate of the lower zone of this soil column could be obtained, based on the observed minimum and quartile track density values in soil samples from this zone. The procedures outlined by Arrhenius *et al.* (1971) and Fleischer and Hart (1973) have been followed in making the above estimates. The identification of the analysed soil sample with a particular soil layer is based on the petrographic classification of this soil column made by Florensky *et al.* (1978), based on visual and X-radiographic observation. The petrographic data, which indicate a large number of coarse grained layers in the lower zone also support a faster deposition rate for this part of the soil column.

The slow deposition rate of $\sim$ 1 mm/m.y. for the upper zone, is much lower than the average value of $\sim$ 3-7 mm/m.y. for the deposition rate of lunar drill core soil columns taken at various sites (Arrhenius *et al.*, 1971; Bhandari *et al.*, 1973; Crozaz & Dust, 1977; Fleischer & Hart, 1973; Goswami, 1977; Pepin *et al.*, 1974; Russ *et al.*, 1972). The deposition rate of $\sim$ 3 to 5 mm/m.y. for the samples in the lower zone is, however, typical of the deposition rate for the various Apollo drill core soil columns, and the growth of this soil zone can be attributed to the deposition of soil layers, one by one, in discrete impact events. The observed variation in the track parameters in samples from this zone most probably reflects the variation in the near surface exposure duration of each of the deposited soil layers. One cannot, however, rule out the possibility of pre-depositional irradiation in case of certain samples e.g., 24179.

An alternative explanation for the observed high values of the track parameters in soils from the upper zone of this drill core column is to postulate a very high level of predepositional irradiation. Such a hypothesis seems to be implausible since a continuous source of highly pre-irradiated material which can contribute to the growth of a meter thick soil layer at the drill core site seems difficult. This is primarily because of the small attenuation depth scale ($\leqslant$ 0.1 cm and $\sim$ 10 cm) in the production rate of tracks by solar flare and galactic cosmic ray heavy nuclei.

One of the important problems associated with either of the hypothesis i.e., a slow deposition or a very high pre-depositional irradiation, postulated for explaining the high track densities in the soil samples from the upper zone is the observed lack of correlation between the track data and data for other surface exposure correlated parameters e.g., solar wind ion concentration, agglutinate content, grain-size distribution etc. The noble gas data of Bhai *et al.* (1979) and Bogard and Hirsch (1978) for twelve soil samples in this drill core indicate that, except for soil 24087, all other samples in this drill core are sub-mature to immature in nature, as reflected by their low ^{36}Ar content. The analysis of nitrogen content by Murty *et al.* (1979) also indicates such a trend. The agglutinate data (McKay *et al.*, 1978) as well as ferromagnetic resonance studies of soil samples from this drill core column (Morris, 1978) also indicate immature to sub-mature nature of almost all the soil samples in this drill core. It is not possible to explain such an anticorrelation unless one postulates a very special exposure history for the upper zone soil samples which are extremely mature from particle track point of view but do not have complimentary concentrations of solar wind ions, agglutinate content etc. A plausible way of achieving this is to let material be exposed for short time interval over a large surface area, followed by its accumulation at a given site. The present author therefore, suggests that the accumulation of the upper meter of the Luna–24 drill core soil column took place through the process of downslope movement of regolith material along crater walls, ollowing a cratering event at the drill core site itself which removed about a meter of preexisting regolith. The high track densities in most of the grains in samples from the upper zone must have resulted during the crater filling up process when they have received solar flare irradiation with varying shielding conditions. The low concentrations of solar-wind ions in these samples require that zero-shielding exposure of individual grains, during the downslope movement, occurred with very low probability. This is also supported by the results of combined microcrater and track studies of soil grains from various samples of this drill core (Goswami & Shah, 1979), which indicate that $>$ 50 per cent of the grains having solar flare track records were never exposed in the lunar surface with shielding $\leqslant$ 0.1 micron. Since agglutinates are product of micro-meteorite impact (McKay *et al.*, 1971), the low agglutinate contents of these samples (McKay *et al.*, 1978) is a direct result of lack of adequate near surface exposure of soil layers due to the fast accretion rate during the crater filling up process.

The evolution of the Luna–24 drill core soil column thus seems to be rather complex and possibly consists of three distinct stages : (*i*) growth of regolith at the site following the usual impact layering process, (*ii*) a cratering event which removed the top meter of the pre-existing regolith, (*iii*) filling up of the crater by downslope movement of regolith material. Although it is difficult to delineate the exact time scales for each of these depositional sequences a combined analysis of both noble gas and track data indicate that the cratering event most probably occurred $\sim$ 400 m.y. back, the filling up process took $\sim$ 50–100 m.y., and the soil column has remained undisturbed for last $\sim$ 300 m.y. (Goswami *et al.*, 1979).

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