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Cosmic ray irradiation pattern at the Apollo 17 site: Implications to lunar regolith dynamics

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Abstract—Cosmic ray fossil track studies have been made in a suite of Apollo 17 samples representing different selenological units at the Taurus-Littrow region. The cosmic ray irradiation patterns in these samples as well as in those from earlier lunar missions have been analyzed to understand the prominent processes controlling the evolution of the lunar regolith. Highlights of the results are:

(i) Local topographic features play an important role in the regolith evolution at certain sites; the Luna 16 and North Massif (Apollo 17) samples provide evidence for regolith growth by rollover, downslope, of soil grains.

(ii) Concordant surface exposure ages of soil and rock samples from several ejecta blankets, based on the fossil track and Ar^{38}, Kr^{81} methods, establishes general validity of the fossil track method for deducing surface exposure ages and regolith deposition rates.

(iii) A good correlation is observed for the surface parameters indicative of surface dwell of regolith components: the concentration of agglutinates, solar wind implanted rare gases and carbon and visual albedo and the fraction of *track-rich* grains. This analysis places on a firmer footing, the possibility of establishing an accurate chronological sequence for the lunar soils. An agglutinate production rate is derived on the basis of these data. The fraction, f_A of agglutinates produced per million years at the surface during the exposure of a soil sample, is given by

$$f_A = (1/d) \times 2.4 \times 10^{-2}$$

where d is the thickness of the soil layer (in centimeters): this relation is valid for exposure periods $\lesssim 70$ m.y.

(iv) A detailed analysis of the fossil track parameters in the scoop and core samples suggests an appreciable temporal variation in the micrometeorite influx rate during the last few hundred million years.

INTRODUCTION

WITH THE AVAILABILITY of Apollo 12 core and scoop samples, the fossil track (FT) technique was established as an important tool for delineating the dominant modes governing the irradiation pattern and the evolution of the lunar regolith (Arrhenius *et al.*, 1971). The FT method whose applicability here owes primarily to the very highly depth sensitive production rate of fossil tracks has been extensively employed for the characterization of the lunar surface processes as well (Arrhenius *et al.*, 1971; Bhandari *et al.*, 1972a, 1972c, 1973a, 1973b; Comstock *et al.*, 1971; Crozaz *et al.*, 1972; Fleischer and Hart, 1973a; Phakey *et al.*, 1972). Some important conclusions emerging from our present and earlier FT studies are summarized below:

(a) The *dominant* mode of regolith growth at the Apollo 12 and 15 sites is a discrete deposition of layers with an average "sedimentation" rate of the order of (1–3) millimeters per m.y.

(b) A deposited layer generally remains on the lunar surface for periods ranging from less than a million year to few tens of million years before it is blanketed by another layer.

(c) During its exposure on the lunar surface, the upper horizons (<1 cm) undergo impact gardening due to the continuous micrometeoritic bombardment and other (e.g. electrostatic) processes.

None of the above conclusions is in conflict with evidence based on other observations related to lunar surface or near surface processes in an aggregate soil sample such as changes in the mineral composition of lunar soil due to micrometeoritic impacts (McKay *et al.*, 1971, 1972), microcraters on exterior surfaces of rocks (Gault *et al.*, 1972, 1974), production of isotopes (e.g. Kr^{81}, Ar^{38}) due to cosmic ray interaction (Marti *et al.*, 1973; Kirsten *et al.*, 1973), solar wind implantation of rare gas isotopes (Bogard *et al.*, 1973; Hubner *et al.*, 1973) and neutron induced isotopic changes (Russ *et al.*, 1972), e.g. in gadolinium isotopes.

In the case of Apollo 15 drill core, the gadolinium data suggest a very rapid or an episodic deposition of the top 2.5 m of the core (Russ *et al.*, 1972) in contrast to the slow deposition deduced on the basis of track data. Discrepancies of this type in the deduced deposition model must arise because of major differences in the depth sensitivity for the different "cosmogenic" or other "physical" processes. In most of the methods, except for radioactivity, there exist uncertainties on the time when the physical changes were introduced in the soil sample (e.g. production of tracks and agglutinates or implantation of solar wind). Because of this basic and rather important shortcoming and the marked differences in the depth sensitivity for the neutrogenic and heavy ion produced solid state damage effects, it is possible to entertain a whole range of regolith deposition models which are not mutually consistent. One has to therefore carefully examine the observational data to see if any checks can be made or if any constraints can be placed in order to obtain more specific regolith deposition models.

The purpose of this paper is to apply the FT method to Apollo 17 samples and to study the basic cosmic ray irradiation patterns in the rock and soil samples. This work is based on the analysis of various samples from distinctly different selenological units at the Apollo 17 site. One finds that in the case of soil samples of short FT exposure ages, the exposure ages are generally in good agreement with those of rocks strewn on the surface. Thus, typically, fossil tracks and so also other surface effects (agglutinate production and solar wind ion implantation) seen in soil samples of short FT exposure ages (~10 m.y.) are primarily produced in the most recent exposure history. However, in the case of samples having exposure ages of the order of (50–100) m.y., complexity must arise due to multiple exposure history of individual soil grains.

Based on the present fossil track data for Apollo 17 samples and that published earlier by us for 34 core and 24 scoop fines, we present here typical deposition rates for lunar regolith and for the production rate of agglutinates.

EXPERIMENTAL TECHNIQUES

The experimental procedure followed is the same as described earlier. Briefly, grain mounts of randomly oriented crystals (Arrhenius *et al.*, 1971) were made in the case of soil samples for grains of $>50\ \mu$ diameter; the thick section technique (Bhandari *et al.*, 1972b) has been followed for the rock samples. Alkali etchants are used for feldspar and pyroxene crystals (Lal *et al.*, 1968) and the WN solution (Krishnaswami *et al.*, 1971) has been used for etching olivine grains. Track counting was performed using optical microscopes at (500–1600)× magnification. Surface loss criterion has been used (Bhandari *et al.*, 1973b) to estimate track density (ρ) for $\rho \geqslant 2 \times 10^8\ \text{cm}^{-2}$. Because of the variability in surface loss, depending upon the chemical composition of the grains, the values of track density in this region ($\geqslant 2 \times 10^8$) may be uncertain within a factor of 2. Based on the characteristic differences in track registration parameters (Bhandari *et al.*, 1972b), the measured track densities in olivine grains are scaled up by a factor of 2 for comparing with track data from other mineral species.

RESULTS AND DISCUSSION

Results of fossil track analyses of the Apollo 17 rock and soil samples are presented in Figs. 1 and 2; relevant details of the samples along with the calculated surface exposure ages are summarized in Tables 1 and 2 for rock and soil samples respectively. The implications of these data are discussed below.

Cosmic ray irradiation history of four Apollo 17 rocks

We have analyzed four Apollo 17 rock samples. For one of these, 74275, we received a "through" slice. This rock, collected from the ejecta blanket of the Shorty Crater at Station 4, is a fragment of a small (~20 cm) boulder fractured into three subparallel tablets. The absence of "zap pits" on the lunar bottom of this rock combining with the fact that the Shorty Crater looks relatively young from preliminary geological studies makes this sample very interesting for studying the time averaged flux of very heavy group of cosmic ray nuclei in the last few million years, since one expects this rock to have had a simple exposure history. Besides this sample we have analyzed a part section and also an interior chip of rock 70215; surface chip of rock 73275 and an interior chip of the rock 79215, which was probably ejected in the Van Serg event.

The track density profiles as a function of depth for these rocks are shown in Fig. 1. Among the four rocks the steepest spectrum at depths exceeding a few millimeters is seen in the case of rock 74275, where the track data extend up to ~4 cm. Since the track production rate is extremely depth sensitive, at shallow depths, $\leqslant 10^{-2}$ cm, the relative track density profiles of different rocks are usually similar, resulting from their unshielded surface exposure on the lunar regolith. However, in the presence of continuous chipping off of their surfaces due to fragmentation or because of exposure in different geometries, with or without shielding on the lunar regolith, the resulting track profiles will not be expected to be identical. The rocks having flatter track profiles (at depths greater than few millimeters) are either those which have had significant exposure during their burial within the regolith before outcropping to the surface or those that are a

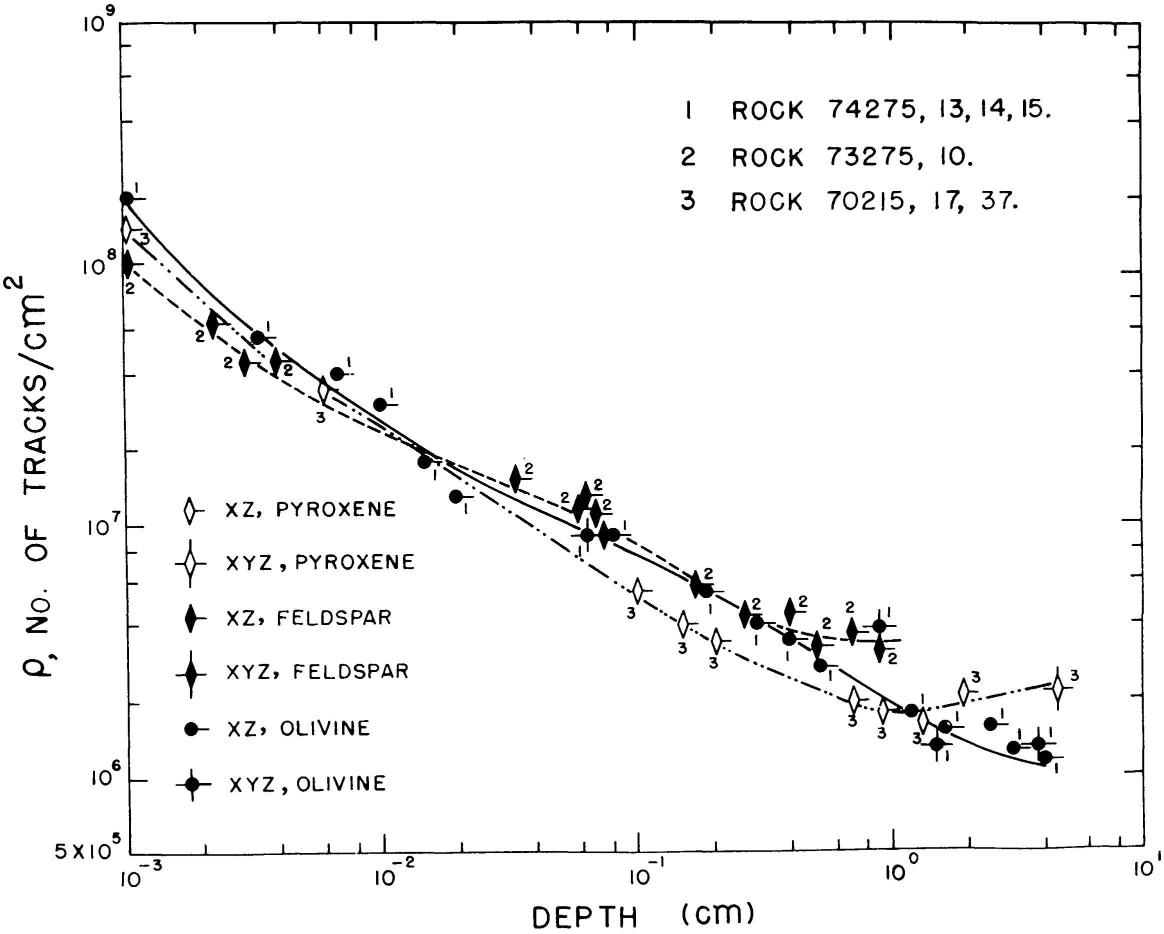

Fig. 1. Observed fossil track density profiles in three Apollo 17 rocks based on data for oriented thick sections. (Few data points based on randomly oriented grains are also included.) All tracks of $>1\ \mu$ were counted using an optical microscope.

remnant of a larger rock which was repeatedly fragmented on the lunar surface so that the exposure geometry (and therefore the shielding) continuously altered during the denudation of the rock. In these cases, the track method allows one to deduce a cumulative exposure age of the rock; this exposure age is designated as subdecimeter age (Bhandari *et al.*, 1972a), since track production becomes insignificant for depths >10 cm.

Based on our earlier work with about two dozen lunar rock samples, we could ascertain in the case of four rocks that they had the simplest exposure history, i.e. consistent with a zero subdecimeter and a finite Suntan exposure age. On this basis we could then obtain the long-term averaged flux of VH group ($Z > 20$) nuclei in cosmic rays (Bhandari *et al.*, 1973c). The analyses of track data in 74275 are consistent with the shape of the energy spectra derived earlier up to ~400 MeV/*n*. Based on St. Severin normalization at 500 MeV/*n* (cf. Bhandari *et al.*, 1971; Lal, 1972) the surface exposure age, designated by us as the *SUNTAN* age, is calculated to be 2.8 m.y. for this rock. (One stage exposure history implies an absence of any subsurface exposure within the first decimeter of the lunar regolith and hence the subdecimeter age in this case is zero, by definition.) As discussed later, the gray soil sample 74260 collected at the same site is found to have a surface residence time of ~2 m.y., which is in good agreement with the rock data.

As mentioned above, the energy spectra derived by us for the VH nuclei for kinetic energy interval 1 MeV/*n* to 1.5 BeV/*n* is consistent with the track data for all Apollo rocks analysed yet by us. However, this is in disagreement with other recent analyses. Yuhas and Walker (1973) have deduced the energy spectra for the energy interval 50–450 MeV/*n* based on one rock (68815) and Hutcheon *et al.* (1974) for the energy interval 1–300 MeV/*n* based on another rock (72315). Yuhas and Walker have obtained the exposure age of the rock on the basis of Kr^{81} data, whereas Hutcheon *et al.* (1974) have obtained the exposure age by using the 2.6 yr average solar flare spectra based on Surveyor glass data. Considering the uncertainties involved in exposure age determination and knowledge of total recordable track length of VH group nuclei in different detectors, the disagreement in VH flux data above 100 MeV/*n*, between the three sets of data does not exceed ~30%. At lower energies the Surveyor based flux of solar VH nuclei are at least an order of magnitude higher than those determined by us on the basis of analyses of lunar rocks. The low-energy part of the spectrum results in production of *track-rich* grains but the discrepancy in the flux of VH nuclei at these energies does not enter into the exposure age calculations which are based on flux data for ⩾100 MeV/*n*. (It may be mentioned that these and other uncertainties such as errors in the measurements of track density (Yuhas *et al.* 1972) can introduce systematic as well as random differences of possibly as much as 30–40% in the exposure age determination.)

The rocks 70215 and 73275 both clearly had multiple exposure history as can be inferred from the flattening of the track profiles at depth >1 cm. In the case of rock 73275, a "SUNTAN" age of 1.2 m.y. has been calculated for the face

Table 1. Exposure ages of Apollo 17 rocks.

Sample Number	Mass (g)	Ellipsoid semiaxes used (cm) ($a \times b \times c$)	Sample details*	Range of observed track densities† ($10^6\ cm^{-2}$)	Fossil track based exposure ages (m.y.)		Surface exposure age (m.y.) based on microcrater counts (face)	Spallogenic exposure age (m.y.)
					Suntan age (Sunny Face)	Sub-decimeter age		
70215,17	8110	11 × 5 × 5.5	Slice	200–2	<1(*B*)	~10	⩾1(*B*)^a	—
,37			I.C.	2.2	—			
73275,10	429.6	5 × 3.5 × 3.5	S.C.	200–4	1.2(*T*)	~8	—	139 ± 11^b
74275,15	1493	8.5 × 6 × 2	Slice I	200–2	2.8(*T*)	0	⩾1(*T*)^a	25^c
,14			Slice II	2–1.2				
,13			Slice III	1.2				
79215,43	553.8	4.5 × 4 × 3.75	I.C.	1.5	—	⩽50	—	—

*S.C. = Surface Chip; I.C. = Interior chip.

†Track densities in near surface region refers to depth ~5 μ.

[a] Fechtig *et al.* (1974).

[b] Crozaz *et al.* (1974).

[c] Eberhardt *et al.* (1974).

73275,10; with a subdecimeter exposure age of ~8 m.y. The feldspar crystals in this metaclastic rock, which is described as an annealed breccia by Morrison and Wilshire (1972, Apollo 17 Catalog), occasionally show deformation features. Our attempts to identify evidence for preirradiated component in this rock did not meet with any success; the negative result is consistent with a high-temperature brecciation of this rock, mentioned above. The "SUNTAN" age of the fine-grained basaltic rock 70215 (face *B*) is <1 m.y. The track density variation as a function of depth, which shows a decrease up to ~1.5 cm and a slow increase afterward may reflect a multiple stage exposure history for this rock. A subdecimeter age of ~10 m.y. has been estimated for this rock. The interior chip of the rock 79215 analyzed by us, is sampled from the bottom face side and lies below the soil line observed in the rock. Although it is not possible to estimate accurately the surface residence time for this rock, the average observed track density of $1.5 \times 10^6\,\mathrm{cm}^{-2}$ implies a *maximum* integrated residence time of 50 m.y. for this rock within the first decimeter of the regolith. The low "SUNTAN" age values ($\leqslant$1–3 m.y.) for the three rocks, 74275, 70215, and 73275 are consistent with our earlier inference for Apollo 12, 14, 15, and 16 rocks that majority of the lunar rocks have "SUNTAN" ages $\leqslant$3 m.y., indicative of a frequent chipping off or tumbling, operative on the lunar surface. It may be noted here that the "minimum" surface exposure ages, based on microcrater counts, for rocks 70215 and 74275 are ~1 m.y. (Fechtig *et al.*, 1974), which is not inconsistent with the track data.

Cosmic ray irradiation pattern in the lunar soil samples from Apollo 17 site

We have analyzed surface fines from all the major selenological units sampled at the Apollo 17 site; samples from the base of North and South Massifs, mantle (dark) material from the valley floor, ejecta samples from the Shorty, Van Serg, and Camelot craters and samples from several depths of a 25 cm trench at the base of the Sculptured Hills.

During their existence on the lunar surface, the cosmic ray tracks are stored in the fines in a very depth sensitive manner. Based on experimental and theoretical studies of the stored tracks, Arrhenius *et al.* (1971) proposed two track parameters for the lunar soil which adequately characterize the surface irradiation pattern and duration: (i) the fraction of grains exposed in the uppermost layer within few hundred microns of the surface—N_H/N (where N_H is the number of grains having high track densities ($\rho \gtrsim 10^8\,\mathrm{cm}^{-2}$) or track density gradient, amidst a total of N grains), and (ii) the quartile track density, ρ_q (a value of the track density such that one-fourth of the total grains analysed in a sample have track densities below this value). We now propose another parameter $Is_{N_H{}^G}/N_H{}^G$ which is the fraction of grains having near surface irradiation characterized by a track gradient from all sides among all grains having track gradient in a given sample. This parameter, in conjunction with the other two track parameters, proves to be very useful in delineating the finer details of near surface transport and gardening processes, as discussed later.

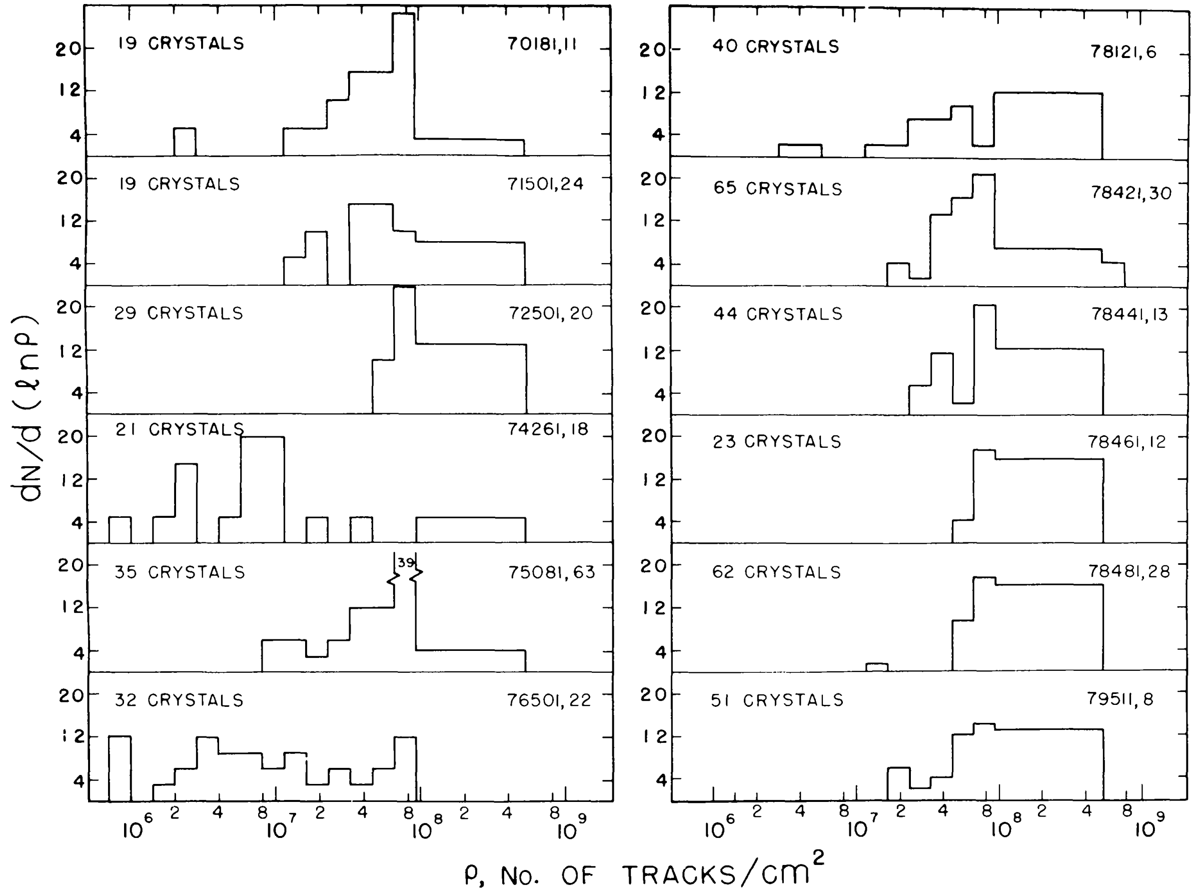

Fig. 2. Histograms showing track density frequency distribution in surface fines from Apollo 17 mission. Each distribution is normalized to 100 grains. (The number of grains analyzed in each case are given on upper left.) Data from all mineral grains are pooled together. (The track density in the olivine grains are scaled up by a factor of 2 to account for their higher threshold characteristics.) Grains having track density values $\geqslant 10^8$ cm^{-2} are shown as distributed uniformly over the interval 10^8 cm^{-2} and 5×10^8 cm^{-2}, by convention.

Below we discuss the exposure ages of three craters at the Apollo 17 site and the nature of regolith dynamics based on track observations.

(A) *Cosmic ray exposure ages of Shorty, Camelot, and Van Serg craters.* Shorty Crater: The discovery of orange glass which was hypothesized initially to be of volcanic origin aroused a great deal of interest in the formation history of this crater. As discussed earlier, the fossil track based exposure age of 2.8 m.y. of the rock 74275 from the Shorty ejecta indicates Shorty to be a young impact crater. We have analyzed the gray soil sample 74261,18 taken from the uppermost centimeter of the Shorty ejecta; this sample shows very low quartile and average track density values of 4.8×10^6 cm^{-2} and 8.5×10^6 cm^{-2}, respectively. The calculated surface exposure age in both cases is ~2 m.y. and is consistent with the "SUNTAN" exposure age of 2.8 m.y. for the rock 74275 from the site. A similar value is reported for the *in situ* galactic cosmic ray exposure age of the orange soil 74220 collected few centimeters below the gray soil at this site

Table 2. Track characteristics of Apollo 17 soil samples.*

Sample	Location	Number of crystals analyzed	Average track density (10^6 cm^{-2}) for crystals of $\rho < 10^8$ cm^{-2}	N_H/N [fraction of grains exposed at the surface]	$(Is_{N_H{}^G}/N_H{}^G)$†	Quartile track density (10^6 cm^{-2})	Integrated surface exposure age (m.y.)‡	Albedo of the site¶ (%)
70181,11	Near L.M. (5 cm scoop)	19	51.2	0.6	>0.4§	27.0	62.0	11–13
71501,24	At Station 11 (4 cm scoop)	19	42.0	1.0	0.76	38.0	70.0	11–13
72501,20	Base of *South Massif* (4 cm scoop)	29	69.4	0.79	>0.4§	76.0	~100.0	~20
74261,8	Near *Shorty Crater* (~1 cm scoop)	21	8.5	0.33	0.86	4.8	~2.0	17–19
75081,63	*Camelot* ejecta	35	53.6	0.85	0.71	38.0	70.0	11–13
76501,22	Rake Soil at *North Massif*	32	20.0	0.50	0.70	3.3	6.0	17–19
78121,6	Ejecta of *S.W.P. Crater*	40	35.2	0.72	0.86	38.0	70.0	13–15
78421,60	*Trench* sample at Station 8 (15–25 cm)	66	54.8	0.79	0.63	54.0	—	—
78441,13	*Trench* sample at Station 8 (5–15 cm)	44	58.0	0.85	0.77	76.0	—	—
78461,12	*Trench* sample at Station 8 (1–5 cm)	23	71.6	1.0	0.66	100.0	—	—
78481,28	*Trench* sample at Station 8 (top 1 cm)	62	68.2	0.93	0.88	76.0	—	13–15
79511,8	*Van Serg* ejecta	51	53.5	0.85	0.88	76.0	~100.0	11–13

*All samples are from <1 mm size fraction.

†Ratio of crystals having all side track gradient to the total number of gradient crystals.

‡Based on the method of Arrhenius *et al.* (1971).

§These values are lower limit due to experimental difficulty involved in observing gradient in high density crystals.

¶Interagency Report: Astrogeology 72.

(MacDougall *et al.*, 1974). This is however at variance with the value of 28 m.y. for this event reported by Fleischer and Hart (1974), based on fossil track data for orange glass. We are at a loss to explain this discrepancy except to point out that so far no accurate method for estimating exposure ages based on cosmic ray track data in glass has been developed. The high value of the cosmic ray exposure age of 38 m.y. (which refers to an integrated exposure up to ~1 m) based on Ar^{38} method and a solicification age of 3.7 b.y. for the orange glass reported by Hussain and Schaeffer (1973a) thus necessitates at least a three-stage process for this material. An example of simplest exposure history is (i) production of orange glass (3.7 b.y. ago) and its immediate blanketting by some regolith material; (ii) exposure at or transported to the present site 38 m.y. ago in a way that the soil is shielded by at least 10 cm thickness of material so that no appreciable track accumulation takes place during this period and lastly; (iii) excavation of this material leading to the formation of what is now called the Shorty Crater, about 2.8 m.y. ago.

Camelot Crater: We have analyzed the surface scoop sample 75081,63 taken on the southwest rim of the Camelot Crater. The fossil track exposure age of approximately 70 m.y. for this sample can be associated with the time of formation of the Camelot Crater. It is interesting to note that the exposure age 85 ± 10 m.y. for the rock 75055 from this site, determined by the Ar^{38} method (Kirsten *et al.* 1973; Huneke *et al.*, 1973), is in good agreement with the deduced fossil track exposure age.

Van Serg Crater: The soil sample 79511,8 collected at Station 9 is located at the ejecta blanket of the Van Serg Crater which is described as a fresh impact crater based on preliminary geological report. But the observed high value of the track parameters, N_H/N and ρ_q, indicates high maturity of the soil which is not typical of a fresh ejecta blanket. The soil seems to have been stirred by reexcavation which is consistent with the observation that most of the Van Serg material is breccia and not the subfloor basalt. Thus, the exposure age for this soil sample corresponds to the integrated exposure age at different depths (<0.1 m) and is not representative of the time of formation of the Van Serg Crater. Therefore, for the Van Serg regolith, the Arrhenius *et al.* (1971) model for calculating regolith growth is not applicable since fresh layers are made up of preirradiated breccia components lying beneath the regolith.

(B) *Distribution of surface exposure ages of Apollo 17 soil samples.* It can be seen from Table 2 that in the case of the Apollo 17 samples, there is a marked deficiency of samples with exposure ages lying between 10 and 60 m.y. This seems to be of significance if we consider this observation in the light of the data on albedo (Interagency Report: Astrogeology 72) and inferred soil maturity on the basis of fossil track data. The low albedo at the Apollo 17 site (Table 2) and the predominance of dark-gray soil is indicative of the fact that a large fraction of the Apollo 17 regolith is exposed and gardened at the lunar surface for appreciable periods of time. Thus, one can understand why ~80% of the soil samples at the Apollo 17 site have integrated surface exposure ages >60 m.y. The low surface exposure ages of soil samples associated with the Shorty Crater and the North Massif base represent recent addition of shielded material by cratering or by surface transport (roll-over) mechanism. The high albedo of the light-mantle material at Station 2, despite being highly mature on the basis of track observation, is probably due to major mineralogical differences (Heiken and McKay, 1974); the light-mantle material presumably consists mainly of anorthositic breccia compared to the ilmenite-rich basalt in valley floor material.

(C) *Surface transport processes of lunar soil.* The macroscopic dynamical processes operating on the lunar surface can be studied in detail from observations of density distribution of cosmic ray tracks in individual grains of the lunar fines, both average track densities as well as gradients in track densities at different faces of the grain. For instance, if the regolith growth involves primarily transportation by roll over on the surface with time periods greater than or comparable to the erosion equilibrium time scales (Bhandari *et al.*, 1972a), one would expect a majority of the grains to show an isotropic track irradiation pattern characterized by a high value of the parameter $Is_{N_H^G}/N_H^G$, and, also a high value of N_H/N indicating that a large fraction of the soil grains had a near-surface exposure. On the other hand, if the regolith growth involves primarily a deposition by the "throw-out" mechanism and subsequent micrometeorite induced vertical mixing, one may expect to see a large number of grains to have an anisotropic irradiation and also a lower fraction of grains to have near-surface exposure, i.e. low N_H/N and $Is_{N_H^G}/N_H^G$ values, if surface exposure periods are $\leqslant 10^6$ yr, as in the previous case. Thus, the absolute values of these parameters should serve to provide information about the prominent regolith growth mechanisms.

The measured values of N_H/N, $Is_{N_H^G}/N_H^G$ and ρ_q for different Apollo 17 samples along with the sample locations are shown in Fig. 3 and Table 2.

The scoop samples 71501 and 75081 are obviously cases representing impact

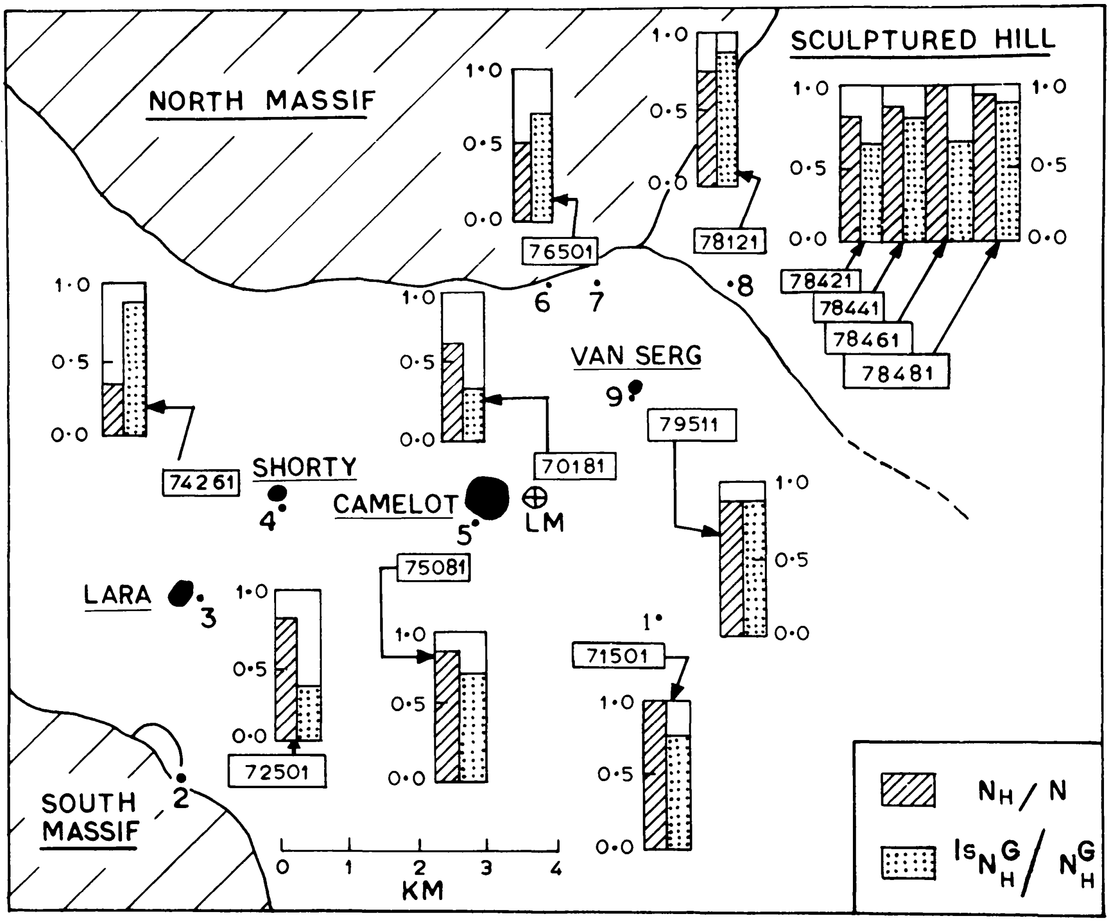

Fig. 3. The observed track parameters, N_H/N (fraction of grains having track densities $\geqslant 10^8\,\mathrm{cm}^{-2}$ and/or track density gradients) and $Is_{N_H^G}/N_H^G$ (ratio of number of grains having track gradients on all sides, to the total number of grains having track gradients) for different Apollo 17 scoop samples are shown along with the sample locations (Station number) at the Taurus-Littrow region. The positions of the major craters at the site are also shown.

gardening of soil for long periods of time leading to high values for all the three parameters: N_H/N, ρ_q, and $Is_{N_H{}^G}/N_H{}^G$. A similar inference can be drawn for the sample 70181 (scooped from a depth of 5 cm), where these parameters are all relatively large. Of particular interest here are the soil samples 76501 and 72501 collected at the base of North and South Massif and the trench and surface samples taken at Station 8. The sample 76501 has a low ρ_q value but relatively high N_H/N and $Is_{N_H{}^G}/N_H{}^G$ values indicating a recent accumulation of the soil by surface transportation during the last few millions of years. Considering the fact that this sampling site had a downslope of ~11° (Interagency Report: Astrogeology 72), the most plausible process of growth of sample 76501 seems to be a rapid downslope transport of the North Massif material. The presence of fillets on the upslope side of the rock and boulder samples at the base of North Massif (AFGIT, 1973; Schmitt 1973) is in fact indicative of a continuous downslope movement of the North Massif material. Similarly, for the scoop sample 72501 (see Table 2) from the light mantle material at the base of South Massif, the high ρ_q (combined with the small spread in ρ_q values; Fig. 2) and N_H/N values are also compatible with a downslope movement at this site, but this implies either a slow transport over a long period of time or an appreciable irradiation after the avalanche, for ~100 m.y. The latter process has been suggested in view of the depression observed at the base of South Massif (AFGIT, 1973, Schmitt 1973).

All the trench soil samples from various depth up to 25 cm at Station 8 show high values for all the three parameters; see Table 3 where data on the carbon and agglutinate contents of the samples as well as the albedo of the sampling site are also given. These data clearly indicate an appreciable near surface exposure in all the cases. It is important to note here that no visible layering could be observed on the trench walls and that the soil sample 78121,6 which was collected at the ejecta of S.W.P. crater (and therefore must have included soil from at least 2 m below

Table 3. Surface correlated parameters for the Apollo 17 trench and scoop samples at the base of sculptured hills (Station 8).

Sample Number	Location	Quartile track density (10^6 cm^{-2})	N_H/N	$(Is \cdot {}_{N_H{}^G/N_H{}^G})$	Agglutinate content* (%)	Carbon content† (μg/g)	Albedo‡ (%)
78121	S.W.P. Crater ejecta	38	0.72	0.86	—	125	13–15 (Sampling site: Station 8)
78421	Trench sample (15–25 cm)	54	0.79	0.63	46	165	18 (Average of the sculptured hill region)
78441	Trench sample (5–15 cm)	76	0.85	0.77	—	155	
78461	Trench sample (1–5 cm)	100	1.0	0.66	—	180	
78481	Trench sample (top ~1 cm)	76	0.93	0.88	—	180	

*McKay *et al.* (1974).
†Moore *et al.* (1974).
‡Interagency Report: Astrogeology 72.

the surface) also shows characteristics similar to the trench samples. Although the observed high maturity of these soil samples can result from a continuous gardening of a shallow regolith over a long period of time, the expected regolith thickness of $\geqslant 10$ m at this site, inferred from the absence of any boulder or subfloor material at the slope and base of sculptured hills, rules out this as the only process responsible for the observed track parameters. Considering the slope due south at the sampling site, one can infer that at least some part of the soil at this site should have been accumulated as a result of transport from the sculptured hills over long periods of time. However, this does leave one with the following dilemma. The albedo observed in the sculptured hill region is very low $\leqslant 18\%$ (see Table 3) and is not compatible with a downslope movement at this site which will expose fresh material at the top of the hills. Thus, one is confronted with the problem of the origin of highly mature soil at this site. One way out, as suggested in the preliminary geologic investigation report (Interagency Report: Astrogeology 72), would be that mature (dark) material from sources lying east or southeast region of Taurus-Littrow Valley was brought to the site.

In the case of the gray soil sample 74261, the high value of $Is_{N_H{}^G}/N_H{}^G$ with low ρ_q and N_H/N values is consistent with repeated micrometeorite induced gardening of the uppermost layer (~2 mm) of the regolith in time scales of the order of a few million years. The agreement between the calculated surface exposure age for rock 74275 (2.8 m.y.) and the gray soil 74261 (~2 m.y.) indicates that the latter must have been emplaced very soon after the Shorty event.

Thus, combining the knowledge of the geological setting of a particular site and the track density distribution pattern in individual grains from the site, one can delineate the macroscopic lunar surface transport processes.

We may note here that the existence of local topographical effects on the growth of lunar regolith, was inferred earlier in the case of Luna 16 site (Bhandari *et al.*, 1973b). The roll-over mechanism may have wider occurrence on the moon.

Synthesis of cosmic ray track observations in rocks and fines from different Apollo sites

Several important features of the evolution and dynamics of the lunar regolith are summarized below, based on analysis of cosmic ray track record of 34 core fines, 36 surface scoop samples and several rock samples from the Apollo 12, 14, 15, 16, and 17 sites.

A comparison of exposure ages for rocks and soil samples, based on the fossil track and other methods. Based on detailed geological investigations several sampling stations at different Apollo sites have been shown to be associated with extensive deposits arising from crater ejecta. In some cases, consistent cosmogenic Ne^{21}, Ar^{38}, and Kr^{81} dates have been obtained for different samples. In order to check on the internal consistency between the exposure ages calculated by the fossil track method and those based on cosmogenic gases we have searched for suitable samples (among those studied by our group) for such a comparison. In

Table 4 we present the surface exposure ages based on the track, the rare gas and other methods. A good agreement can be seen between the ages derived by different methods which gives credence to the fossil track based exposure ages. (It should be emphasized that such a comparison can be made only in the case of crater ejecta, because, whereas the fossil track method allows one to deduce surface or subdecimeter ages, the rare gas method gives integrated exposure for dwell of the sample within depths of about a meter; in the case of ejecta sample, the two methods in general dates the age of the crater.)

Surface correlated parameters (*agglutinates and solar wind, etc.*) *and chronology of lunar soil.* A general correlation has already been observed between the surface correlated parameters, e.g., the fraction of track-rich grains, agglutinate content, solar wind implanted rare gases, nitrogen and carbon compounds. (cf. McKay *et al.*, 1971, 1972; Cadogan *et al.*, 1972; Crozaz *et al.*, 1972; Goel *et al.*, 1974). We show in Fig. 4 a correlation plot for the parameters, N_H/N and the total carbon content in lunar soil samples from several Apollo missions. The data on total carbon content are taken from Moore *et al.* (1972, 1973, 1974); these represent values for bulk sample analyses only. The correlation plot indicates that most of the carbon in lunar soil is solar wind implanted as has already been suggested by Moore *et al.* (1972). The deviations from a linear trend observed for certain samples are possibly due to the variation in the amount of indigenous lunar

Table 4. Exposure ages of lunar rocks and fines from different "ejecta" sites.

Sample location	Exposure age (m.y.) based on				
	Fossil tracks*		Cosmogenic rare gases	Agglutinate content†	Microcrater counts
	Fines	Rocks			
1. Apollo 14					
(i) Station 'C' Crater	7	—	20[a]	6.5	—
2. Apollo 16					
(i) Buster Crater	6	2.5	2–100[b]	50	3[f]
(ii) North Ray rim	24	—	25–35[c]	28	—
(iii) North Ray ejecta	≤100	50‡	50[d]	56	—
3. Apollo 17					
(i) Shorty Crater	2	2.8	—	3	>1[g]
(ii) Camelot ejecta	70	—	85±10[e]	65	—

*The fossil track data except for the rock sample from North Ray ejecta are from the present work. Yuhas and Walker (1973).

†Agglutinate data are from McKay *et al.* (1972, 1973, 1974). The exposure ages are based on the revised production rate (see text).

[a] Lugmair and Marti (1972).

[b] Lightner and Marti (1974).

[c] Hussain and Schaeffer (1973b); Jordan *et al.* (1974).

[d] Marti *et al.* (1974).

[e] Kirsten *et al.* (1973); Huneke *et al.* (1973).

[f] Morrison *et al.* (1973).

[g] Fechtig *et al.* (1974).

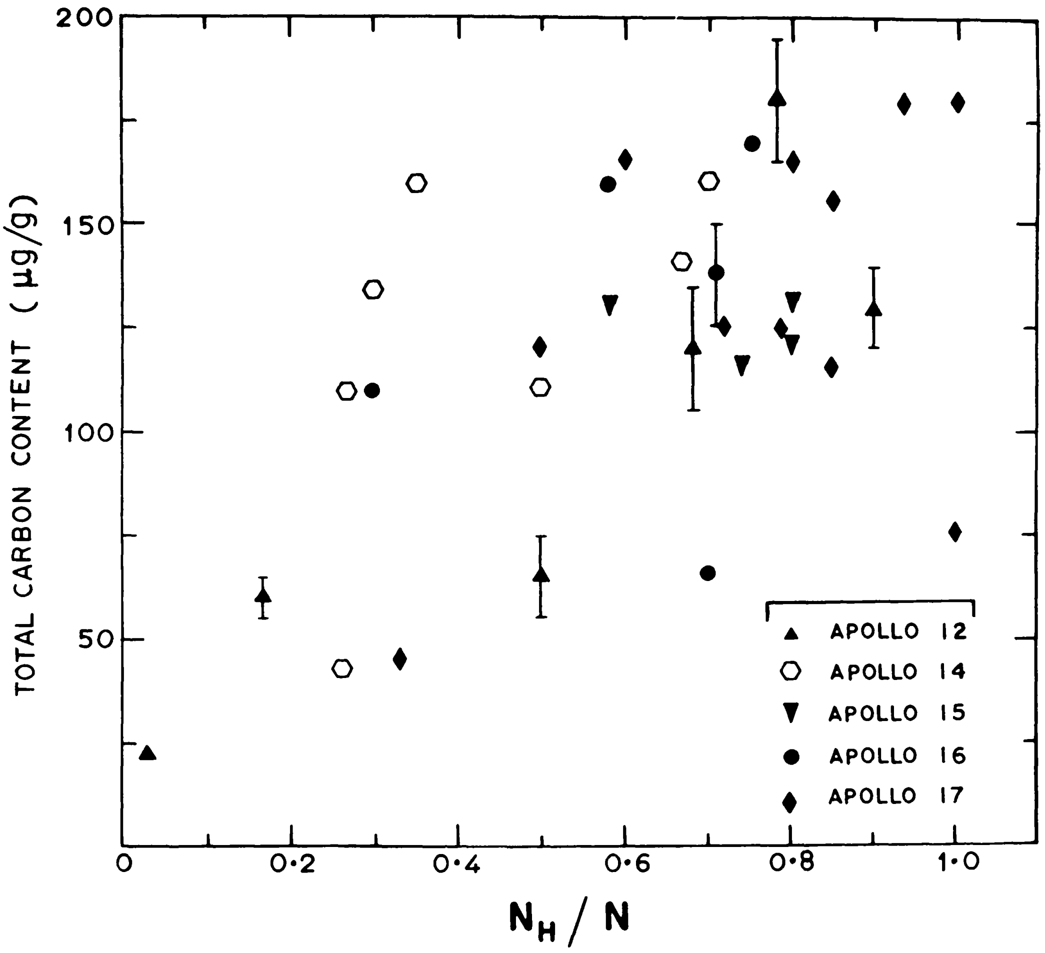

Fig. 4. Total carbon content in lunar samples from different Apollo missions is plotted as a function of N_H/N (fraction of grains having track densities $\geq 10^8\,\mathrm{cm}^{-2}$ and/or track gradients). The total carbon content data are from Moore *et al.* (1972, 1973, 1974).

and/or meteoritic carbon in these sample, and also the variations in the trapping efficiency of different types of mineral grains (Moore *et al.*, 1973).

The minimum surface exposure time required for saturation of carbon in a soil layer (assuming a saturation value of ~150 µg/g in the total carbon content; Moore *et al.*, 1972), is similar to the time scale required for a majority of the grains in a soil layer to have near surface exposure, as most of the samples having such carbon content also have N_H/N value ≥ 0.8. From an analysis of track parameters we have deduced this time scale to be ~20 m.y. A similar time scale has also been deduced from a correlation study of track data and solar wind implanted rare gases specially Ar^{36} and Ne^{20} (M. N. Rao, private communication).

Agglutinates, being a product of micrometeorite impact (McKay *et al.*, 1971), are produced during exposure of the soil on the lunar surface and hence serve as an indicator of the "surface exposure." The agglutinate method was first attempted by McKay and Heiken (1973), who proposed an averaged value for agglutinate production rate of 4×10^{-3} agglutinate grains/(grain · million year).

Based on the fossil track data, Goswami and Lal (1974), deduced an agglutinate production rate of $(2.4 \times 10^{-2}/d)$ agglutinate grains/(grain · million year) for a soil sample of thickness d (in cm) in the $<200\,\mu$ size fraction. It should be emphasized here that we have invoked the layer thickness in the agglutinate production rate. The situation here is very similar to the production of grains having high track densities; for a thicker layer, the fraction of agglutinates or N_H/N is lower for a given exposure time. (Although, in the case of scoops, one can have a soil sample representing more than one layer, the typical scoop penetration depths are small ≤ 3 cm, so that only one layer is sampled generally.) We show in Fig. 5 a correlation between "surface exposure ages" for lunar surface soils from different Apollo sites, based on fossil track data (Arrhenius *et al.*, 1971; Bhandari *et al.*, 1972a, 1973a; Goswami and Lal, 1974) and agglutinate content (McKay *et al.*, 1971, 1972, 1974; McKay and Heiken 1973). It can be seen that the value adopted for the production rate leads to a good correlation for a majority of the samples (within 10% error). Thus, for constructing a relative chronological sequence for the regolith, one should combine data on all surface correlated processes, e.g. tracks,

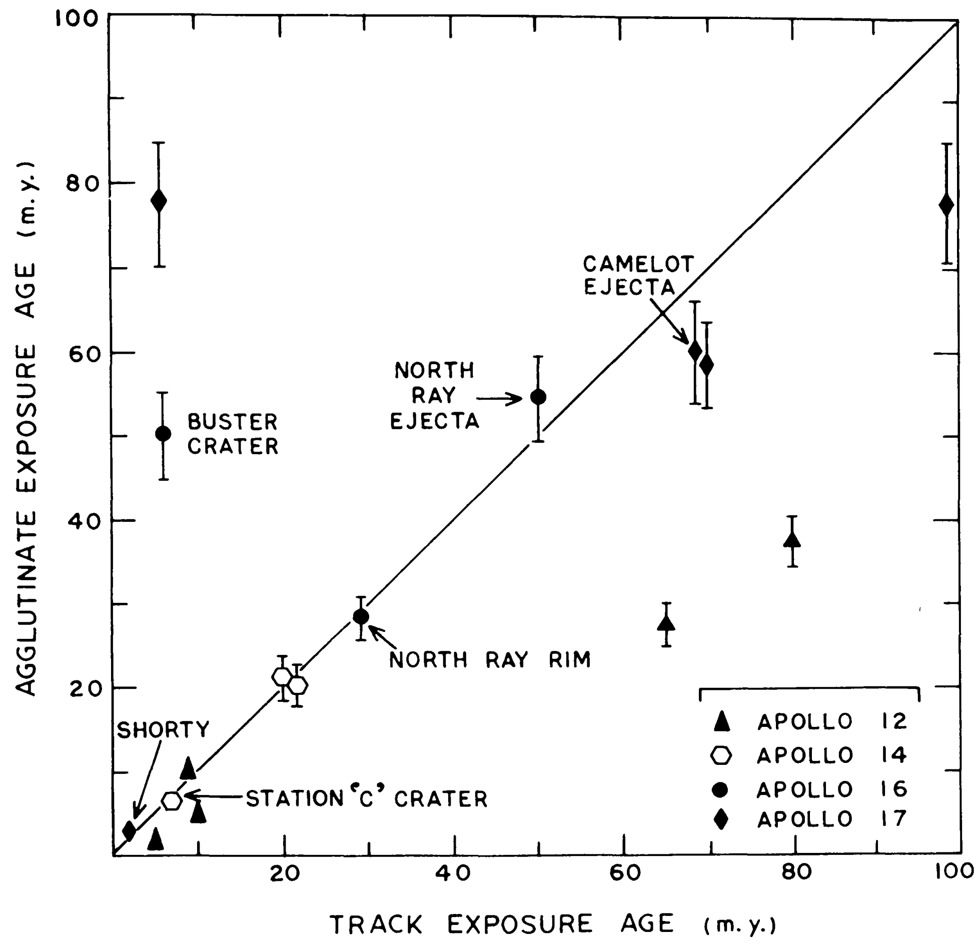

Fig. 5. Correlation plot between track exposure age and calculated exposure age based on agglutinate content (see text). A good linear correlation can be observed between the track and agglutinate based ages, within an uncertainty level of about 10% (indicated by the error bars). The agglutinate data are from McKay *et al.* (1972, 1973, 1974).

agglutinate content as well as rare gas concentrations to preclude special histories of soil samples.

Temporal variations in micrometeorite influx rates. It has been discussed earlier (Bhandari *et al.*, 1973a) that the surface exposure indicative fossil track parameters are a very sensitive function of micrometeorite influx rate. Also, it has been found that the observed track density distribution for lunar soil samples differs markedly from that at production due to vertical mixing as a result of micrometeorite impacts (Arrhenius *et al.*, 1971). As an example, see Fig. 6 where we have given observed track density distribution pattern for the soil sample 74261 and also that expected in absence of mixing. We have also shown in this figure the number of track-rich grains having high track densities, or track density gradients, indicative of their exposure on the lunar *surface* (Arrhenius *et al.*, 1971). Thus, if the rate of vertical mixing changes due to a change in the micro-

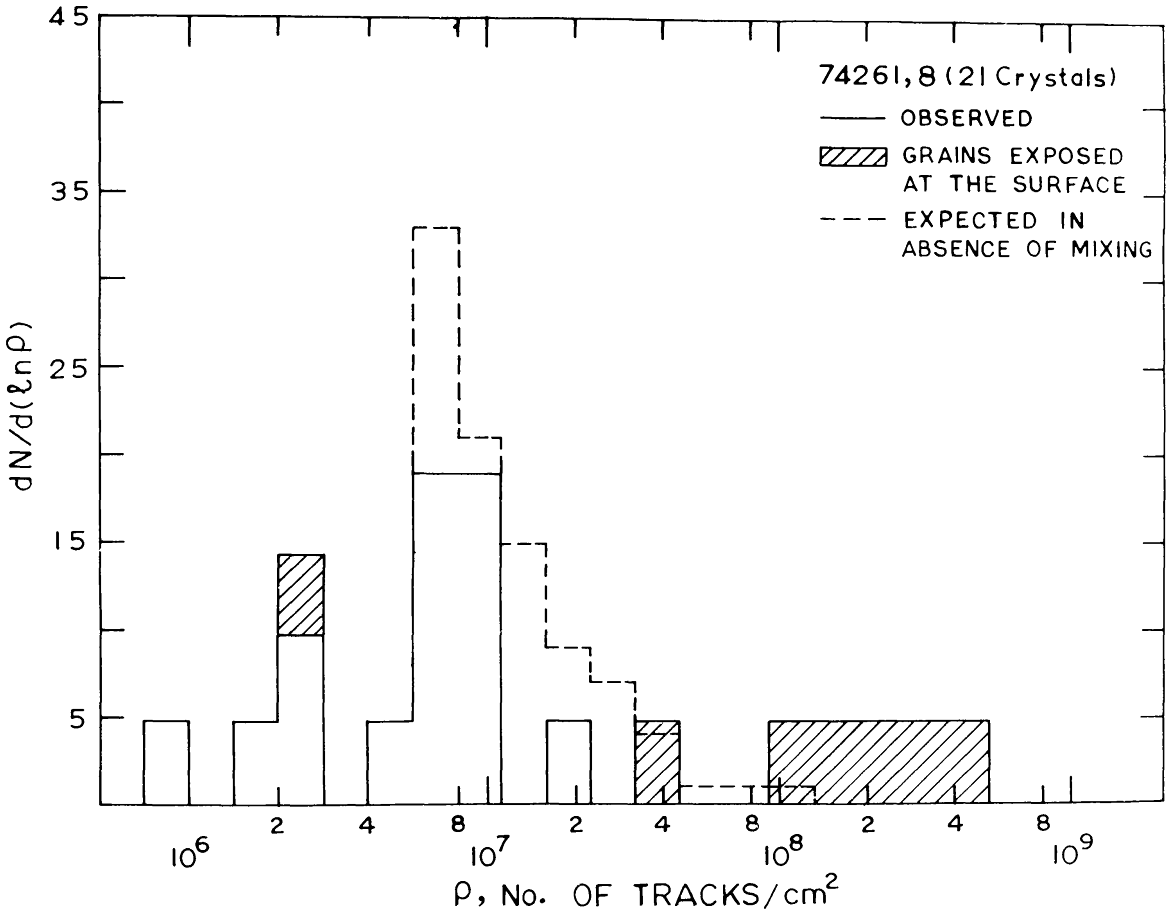

Fig. 6. Histograms showing the track density frequency distribution in the gray soil 74261,8 collected at Shorty Crater ejecta from the uppermost centimeter of the regolith. The grains exposed at the surface, characterized by a high track density ($\geq 10^8$ cm^{-2}) or track density gradients are also shown. The dotted line is the expected track distribution for a one cm thick layer, which remain, undisturbed for 2 m.y., the calculated exposure age of this soil sample; the calculations are based on a uniform grain size of 100 μ. The number of grains have been normalized to 100.

meteorite influx rate, it will lead to a change in the production rate of the *track-rich* grains. For instance, if the vertical mixing increases (due to increase in the micro meteorite flux), the number of track-rich grains will also increase because more grains will be brought to the surface and exposed to low-energy solar cosmic rays. In order to see if there is any evidence in the fossil track data for a change in the micrometeorite influx rate, we have plotted in Figs. 7a and b, N_H/N as a function of ρ_q (which is indicative of the surface exposure age of a sample; Arrhenius *et al.*, 1971), for scoop and core fines, respectively. Data from two successive samples from a core have been combined together for a meaningful comparison with the surface scoop data. The general trend in the N_H/N versus ρ_q plot for the scoop samples (Fig. 7a) is indicative of the time-averaged micrometeorite influx rate over the last hundred million years. In Fig. 7b we have shown by envelopes marked 1 and 2 the core samples which deviate appreciably from this trend. These respectively refer to samples in the Apollo 11 and 12 cores lying between depths (4.5–8.0) cm and (42–56) cm. This should possibly be taken to indicate a change (decreased by a factor of 2–3) in the micrometeoritic influx rate during the deposition of these layers as compared to the long-term averaged value. Assuming a deposition rate of 0.4 g/cm^2 m.y. the two depth intervals refer to time spans of 25–45 m.y. and 200–250 m.y. before present. (It should be remembered that the time brackets quoted may be in error, since besides the statistical uncertainties, cumulative errors in the calculation of ages of different layers can arise if one of the overlaying layers had a significant preirradiation history.)

In view of the above, it seems important to examine samples from similar depth intervals from the Apollo 15 deep drill core. It seems relevant to note here that the smaller time bracket of low micrometeorite influx rate also coincides with the well-known period of paucity of stone meteorites having exposure ages >30 m.y. (Zahringer, 1968).

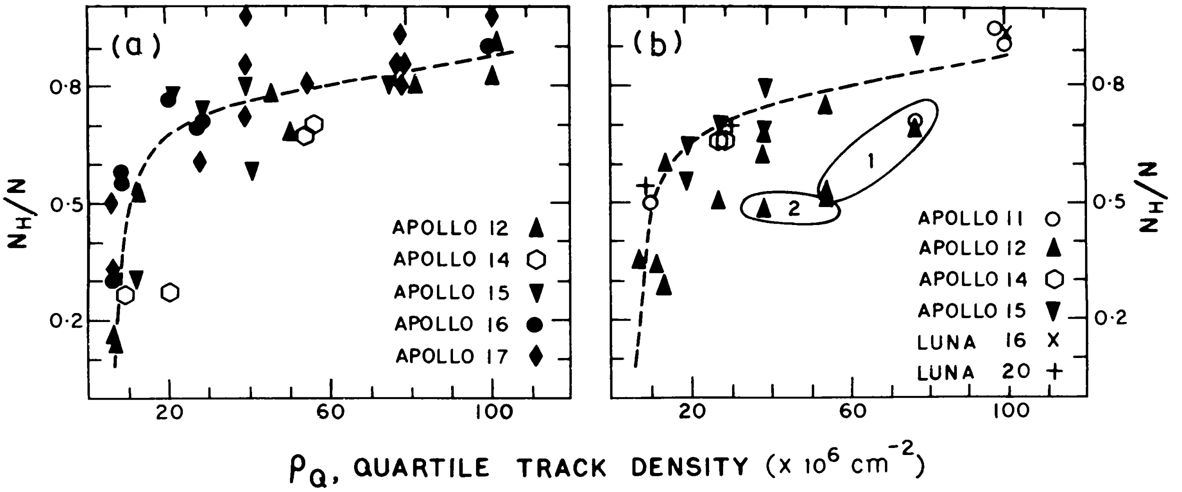

Fig. 7. The track parameter, N_H/N plotted as a function of the quartile track density, ρ_q, for the different surface scoop samples (Fig. a) and core samples (Fig. b) from various Apollo and Luna missions. (See text for discussion of the points inside the envelope marked 1 and 2.)

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