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SOLAR-FLARE EXPOSURE AND THERMOLUMINESCENCE OF LUNA 24 CORE MATERIAL

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[Plate 1]

Mineral grains from three depths within the Luna 24 drill core (*ca.* 90, 125 and 196 cm) have been examined for solar-flare tracks. Large proportions (55–100%) of grains from all three levels are found to be track-rich (with central track densities $\rho_c > 10^8\ cm^{-2}$), and a substantial fraction (*ca.* 25–50%) of all grains display track-density gradients. These observations indicate that most of the mineral grains have been cycled through the top *ca.* 1 mm of the lunar surface at some time in their history. Some degree of submaturity is observed towards the bottom of the core. The most likely depositional model envisages rapid infall of highly irradiated material into a less mature local component with rather little subsequent reworking. Thermoluminescence (t.l.) studies indicate a lower natural radiation dose in samples from the 196 cm level compared with those from the two upper levels. This can result either from random variations in the local internal radioactivity or from mixing properties of the pre-irradiated material over time scales of less than *ca.* 100 ka. Radiation sensitization of samples suggests a possible use of t.l. sensitivity for the interpretation of lunar radiation history.

1. Introduction

In an earlier paper (Durrani *et al.* (1978), hereinafter referred to as paper I), we have already reported the detailed results of our investigations of Luna 24 drill-core samples with the use of charged-particle track analysis and thermoluminescence (t.l.) methods. Here we propose to present the salient points and significant conclusions emerging from our work to date and to attempt to place them in a wider perspective as established by related studies reported in Merrill & Papike (eds) (1978). Accordingly, details of the experimental procedures and description of samples (already published in paper I) will not be given here. Suffice it to say that samples studied by us came from three depths within the drill core (*ca.* 90, 125 and 196 cm; designated 24090,1; 24125,1; and 24196,1, respectively, with certain subsample end-codes). Mineral grains (150–250 μm and 40–53 μm) were used for track studies, and mineralogically unsorted soil samples (normally less than 75 μm in diameter) were used for t.l. work.

The main purpose of our studies has been to attempt to elucidate the radiation and thermal histories of the lunar regolith. By examining the radiation effects in samples retrieved from different depths below the present lunar surface, one can attempt to establish the soil-mixing and accretion properties of the regolith. The mineral crystals accumulate etchable tracks produced only by ions of charge $Z \gtrsim 20$; these are mainly the 'iron group' ($20 \leqslant Z \leqslant 28$) particles whose chief source at energies less than 100 MeV/nucleon is solar flares. Tracks are generally long-lived and are thus the record of radiation over the last several gigayears (10^9

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TABLE 1. TRACK-DENSITY DATA FOR MINERAL GRAINS FROM THREE DEPTHS IN THE LUNA 24 CORE TUBE

sample no. (and depth)	150–250 μm size fraction: grain no.	mineral	ρ_c† $10^7\,cm^{-2}$	gradient? (type)	40–53 μm size fraction: grain no.	mineral	ρ_c† $10^7\,cm^{-2}$	gradient? (type)
24090,1,9303 (*ca.* 90 cm in the core-tube)	1	pyroxene	20	no‡	1	feldspar	40	slight (anisotropic)
	3	olivine	30	yes (anisotropic) §	2	feldspar	60	no
	4	feldspar + pyroxene	2	no	3	feldspar	100	no
	5	feldspar	20	no	4	feldspar	43	yes (anisotropic)
	6	olivine	10	yes (anisotropic)	5	feldspar	80	yes (anisotropic)
	7	olivine	50	yes (anisotropic)	6	feldspar	60	slight (anisotropic)
	8	pyroxene	20	no	7	feldspar	45	no
	9	pyroxene	10	no	8	feldspar	140	no
	10	pyroxene	100	no	10	feldspar	50	yes (anisotropic)
	11	feldspar	150	slight‖ (isotropic)	11	pyroxene	40	no
	12	olivine	70	no	12	olivine	50	no
	13	glass	1.5	no				
24125,1,9303 (*ca.* 125 cm in the core-tube)	1	olivine	10	yes (anisotropic)	1	olivine	260	no
	2	olivine	10	slight (anisotropic)	2	olivine	80	no
	3	olivine	30	yes (anisotropic)	3	olivine	130	yes (anisotropic)
	5	pyroxene	40	no	4	olivine	140	no
	6	pyroxene	70	no	5	olivine	140	no
	7	pyroxene	40	yes (isotropic)	—	—	—	—
	9	pyroxene	50	no	—	—	—	—
	10	pyroxene	60	no	—	—	—	—
	11	feldspar	60	no	—	—	—	—
	12	pyroxene	100	slight (anisotropic)	—	—	—	—
24196,1,9303 (*ca.* 196 cm in the core-tube)	1	olivine	40	yes (anisotropic)	1	olivine	90	yes (anisotropic)
	2	olivine	90	no	2	olivine	80	yes (anisotropic)
	3	feldspar	2	no	3	olivine	60	no
	4	feldspar	10	no	4	olivine	150	no
	7	feldspar	20	yes (anisotropic)	5	olivine	28	yes (anisotropic)
	8	feldspar	0.03	no	7	olivine	160	no
	10	feldspar	15	yes (anisotropic)	8	olivine	28	yes (isotropic)
	11	feldspar	14	no	9	olivine	90	no
	12	pyroxene	0.05	no	10	olivine	200	yes (isotropic)
	13	pyroxene	30	no	11	olivine	200	no
	14	feldspar	0.5	no	12	olivine	1.3	yes (anisotropic)

Note that, taking all three levels together, we find the following statistics for track-density gradients for the 150–250 μm fraction (and the 40–53 μm fraction): no detectable gradients, *ca.* 64 % (*ca.* 56 %); anisotropic gradients, *ca.* 30 % (*ca.* 37 %); isotropic gradients, *ca.* 6 % (*ca.* 7 %). The proportions in grains from each individual level are fairly close to these mean values.

† ρ_c stands for central track density as defined in the text. These values are *uncorrected* for registration efficiencies of the various minerals. All track densities are measured by s.e.m., except those less than *ca.* $1 \times 10^7\,cm^{-2}$ (optical microscopy). Statistical errors are *ca.* 10–20 %.

‡ The statement 'no' throughout this table means that ρ_c and the track density measured at *ca.* 5 μm from the edge are equal within experimental errors.

§ The gradient is taken to be 'anisotropic' if, while being present at some edges, it is absent or significantly less marked on at least one edge of the grain.

‖ 'Slight' gradient signifies that track densities at the edge and at the centre of a grain differ by less than *ca.* 50 %.

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years). Thermoluminescence is the result of stored energy originating chiefly from cosmic rays in the case of near-surface samples and from internal radioactivity in the case of *in situ* deep samples. The temperature of natural storage (and irradiation) plays an important part in governing the equilibrium level of 'trap filling' and the survival of the latent t.l. The time constants involved are such that the natural high-temperature t.l. exhibited by a sample represents its radiation over the preceding *ca.* 100 ka (or less for shallower traps).

2. Track studies

During exposure within the top *ca.* 1 mm of lunar soil, mineral grains rapidly (over *ca.* 10^2–10^6 a, depending on the depth) accumulate high densities (more than 10^8 cm^{-2}) of tracks due to Fe-group solar-flare nuclei. The flux of these low-energy particles (less than 100 MeV/nucleon) falls off very rapidly with depth, so that measurements of track densities in soil layers at different depths within the core tube should allow constraints to be placed on the depositional history of the soil. Also, the presence of track-density gradients, over the outer 10–100 μm of a grain, would indicate almost unshielded exposure on the top lunar surface.

2.1. *Results*

Table 1 shows a detailed breakdown of the data obtained for the 150–250 μm and the 40–53 μm diameter fractions of the mineral grains from all three depths. The 'central' track density refers to that measured at the centre of an arbitrary plane through the core of a crystal. The nature of track-density gradients observed while going inwards from the periphery of a grain is also indicated in the table. The track densities in olivine need to be multiplied by a factor of 2 to allow for its known low registration efficiency compared with that of pyroxene and feldspar (Bhandari *et al.* 1972).

In figure 1, track-density versus depth profiles are shown for some grains from each sample location. Figure 2, plate 1, shows typical photomicrographs of (*a*) a grain with a track-density gradient at one edge, and (*b*) a grain showing a low central track density.

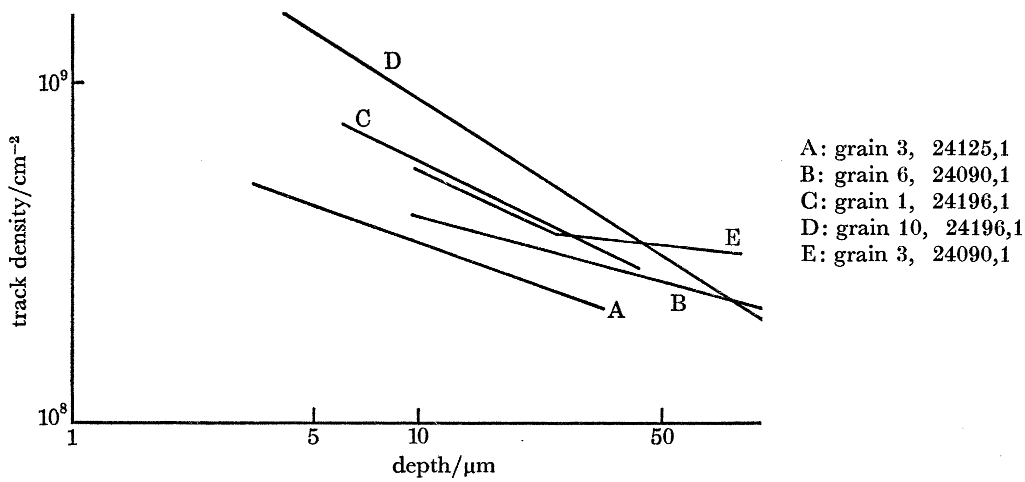

Figure 1. Profiles of track-density against depth within a grain for several Luna 24 grains (150–250 μm fraction). For the sake of clarity, data points have been omitted and only least-squares fits to the data are shown. Profile E was found to be better represented by two such fits, suggesting a change in the exposure conditions of this grain. The individual grains can be identified by reference to table 1. All track densities in this figure are *uncorrected.*

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2.2. *Discussion*

The upper two layers (samples 24090 and 24125 from depths *ca.* 90 and 125 cm) appear to be 'mature' on the basis of the high track densities (i.e. grains with central track densities $\rho_c > 10^8\ cm^{-2}$); the proportion of such grains (N_H) to all grains (N) being *ca.* 0.85 and 1.0, respectively, for the 150–250 μm fraction, and 1.0 at both depths for the 40–53 μm fraction. The deepest layer (*ca.* 196 cm, corresponding to sample 24196) is of lesser maturity, the value of N_H/N being *ca.* 0.55 for the 150–250 μm fraction, and 0.92 for the 40–53 μm fraction. Track-density gradients, indicating almost unshielded exposure, are, however, present in *some* grains from *all* depths.

Track-production rates fall off so rapidly with depth (Blanford *et al.* 1975) that high track densities (more than $10^8\ cm^{-2}$) could not have been produced *in situ* at these depths (*ca.* 1–2 m) over any reasonable time-scale; nor could the steep track-density gradients be explained on that basis. Three possible models for the transport of such track-rich grains from close to the top lunar surface down to their present great depths may be considered.

(i) Irradiation of the soil at the surface of the Moon, followed by considerable reworking to mix this track-rich material with the lightly irradiated local soil at all depths. Bimodal distributions of grain size at most depths, with the two size-fractions exhibiting different degrees of 'maturity' (McKay *et al.* 1978), argue against an extensive reworking of soil. So this model is unsatisfactory.

(ii) Slow deposition of unirradiated material, a layer at a time; its irradiation at the top; and then, subsequently, its reworking to shallow depths to produce highly irradiated layers fairly uniformly with depth in the upper regions.

(iii) Rapid deposition, in one or several discrete events, of pre-irradiated material from elsewhere, which mixes with the *in situ* lightly irradiated layers.

Several research groups employing track techniques have examined track densities in grains from a number of layers within the core-tube, some at depths additional to those accessible to the British workers. They report results similar to ours, i.e. high maturity in general, decreasing somewhat towards the bottom of the core (Blanford & Wood 1978; Crozaz 1978; Chaillou *et al.* 1978; Barber 1978).

The lower maturity of the deepest layers could be explained on the basis of model (ii) if the rate of deposition were assumed to have been more rapid for the lower part of the core (i.e. at earlier times); or on the basis of model (iii) if we postulate an uneven mixing of the pre-irradiated material with a less mature local component.

One puzzle of the Luna 24 core is that the fairly high general maturity of the soils as judged from track densities does not agree with the 'submature to immature' classification indicated by studies such as agglutinate concentration (McKay *et al.* 1978) or ferromagnetic resonance I_s/FeO (Morris 1978), where I_s is the relative concentration of fine-grained metal.

McKay *et al.* (1978) also find evidence, from grain-size distributions, of a mixture of mature and immature components in the soils. This could offer one solution of the puzzle, since track measurements have been made mostly on grains finer than 250 μm. The immature component could predominate in the fraction coarser than 250 μm. However, Barber (1978) finds highly irradiated grains among the 250–1000 μm fraction studied by normal track-etch techniques, and also some lightly irradiated micrometre sized grains viewed by transmission electron microscopy. So the contradictions still remain.

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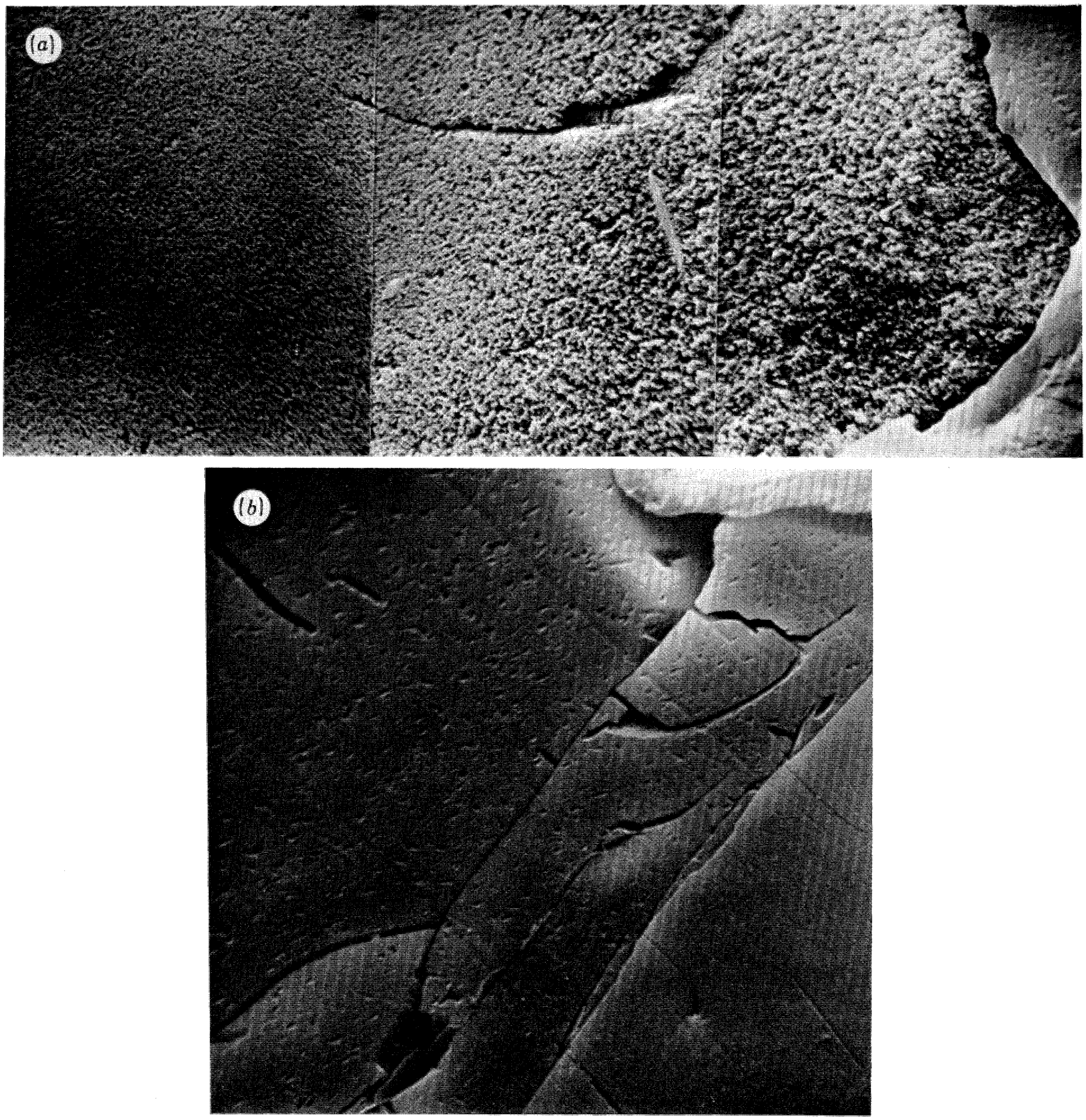

FIGURE 2. (*a*) A composite photomicrograph of an olivine grain showing a track-density gradient from the right-hand corner proceeding inwards. The grain is no. 3 from 24090,1,9303; it was etched in boiling WN solution (Krishnaswami *et al.* 1971) for 30 min. (*b*) A photomicrograph of a composite feldspar + pyroxene grain (no. 4 from 24090,1,9303) showing a low central track density (2×10^7 cm^{-2}) in the feldspar phase. The grain was etched in boiling 40% NaOH solution for 10 min. Tracks in the pyroxene phase (lower right-hand corner) had not yet become visibly etched. Grains in both (*a*) and (*b*) came from the 150–250 μm size fraction.

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Overall, the data are best interpreted on the basis of an irradiation history (model iii) that includes rapid deposition of highly pre-irradiated material (e.g. that from an exposed rock-face, or a mature soil layer from elsewhere) into immature local soil. Measurements of cosmogenic ^{21}Ne content by Bogard & Hirsch (1978) favour such a pre-irradiation model.

One problem remaining with this mixing model is the identification by track measurements of an immature component. Results of Goswami (1978) indicate that olivines from six different Luna 24 core samples show a high proportion of low-track-density grains. McKay *et al.* (1978) have adduced from these observations support for their suggestion that coarse-grained olivine represented the immature components. However, the extensive data of Chaillou *et al.* (1978) reveal no large differences in the mean track density between feldspar, pyroxene and olivine grains other than the factor of *ca.* 2 variation for the latter, which can be understood on the basis of the lower registration efficiency for Fe-group ions in olivine (see, for example, Durrani & Bull 1977). Of the very few Luna 24 grains with $\rho_c < 10^8$ cm^{-2} examined by us, only one is, in fact, olivine (and that in the fraction 40–53 μm). The nature of the immature component is therefore still not clear.

Our finding of a decrease in maturity in the sequence (24090 ≈ 24125) > 24196, based on track data as well as on t.l. studies (§3.2.2), is to some extent supported by the work of Pillinger *et al.* (1978) on hydrolysable carbon contents and magnetic susceptibilities of the Luna 24 samples, who find a maturity sequence 24090 > 24125 > 24196.

3. Thermoluminescence studies

The natural t.l. retained by a sample is governed both by the radiation received by it and by its ambient temperature. Each of these parameters varies with depth below the lunar surface in a complicated way. In what follows we study both the natural and the artificial t.l. of Luna 24 samples in an attempt to shed light on their environmental history.

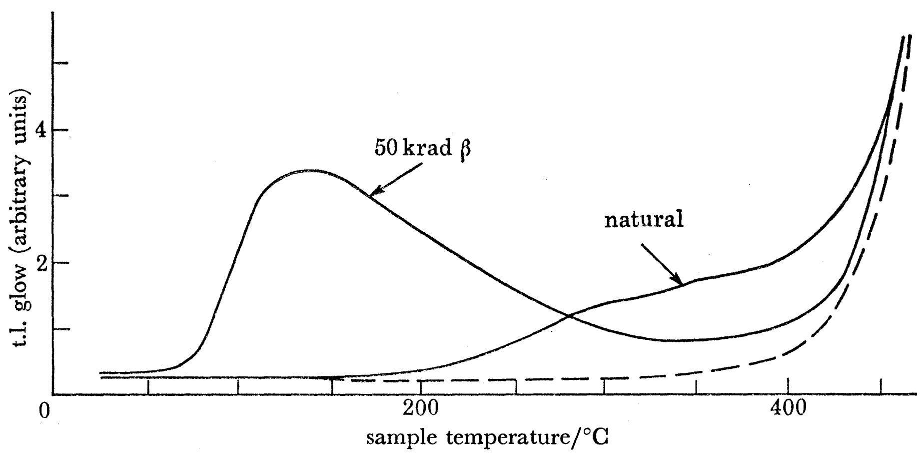

Figure 3. Artificial glow curve from 24196,1,9601, obtained by irradiating the sample with 50 krad of ^{90}Sr β particles after its natural t.l. had been drained in a previous readout. The natural glow curve and the black-body signal (broken line) are also shown. Notice the prominent low-temperature peak (centring at *ca.* 135 °C) induced by artificial irradiation and missing in the natural curve probably because of the storage of the sample at room temperature for 12 months.

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3.1. *Results*

Figure 3 shows typical glow curves, both natural and that resulting from a 50 krad† dose of ^{90}Sr β particles (subsequent to t.l. drainage during a previous readout), for one of the Luna 24 samples (24196,1,9601; grain size less than 75 μm). Glow from the fraction finer than 75 μm from the other two depths, as well as the 75–106 μm fraction from the 125 cm depth, was very similar to that in figure 3. (The 75–106 μm fraction, unlike the fraction finer than 75 μm, had not been subjected to the heat-drying treatment; see paper I for details.) Absence of natural glow below *ca.* 160 °C is notable.

In figure 4 we plot the normalized (natural) t.l. against depth for Luna 24 samples from the three depths *ca.* 90, 125 and 196 cm. Normalizing the glow (by dividing the natural t.l. intensity observed at 324 °C by the corresponding intensity resulting from a 50 krad β dose imparted to the drained sample) helps to eliminate the effect of differences in t.l. phosphor content between samples.

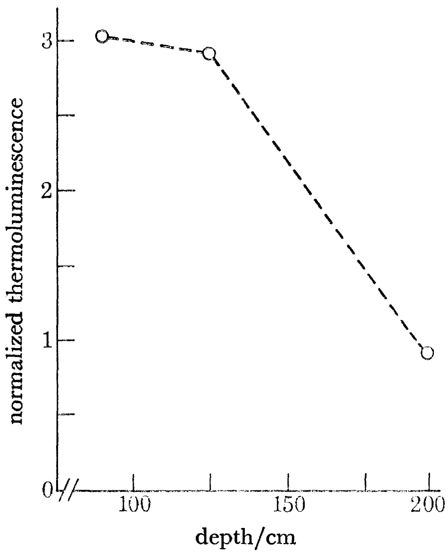

FIGURE 4. Profile of the normalized t.l. against depth in the core-tube. The normalized t.l. in this instance is taken as the ratio of the natural t.l. intensity to that induced by a 50 krad dose of β particles, at a glow-curve temperature of 324 °C, after allowing for the standardization of sample masses. The normalized t.l. is seen to fall with depth, especially between 125 and 196 cm.

Figure 5 demonstrates the 'plateau test' (see discussion in §3.2.2) for the t.l. samples (*a*) 24090,1,9601 and (*b*) 24196,1,9601: the normalized (natural/test-dose induced) intensity is plotted as a function of readout temperature. Both curves appear to be tending towards a constant normalized t.l. value (a 'plateau') beyond *ca.* 430 °C. Samples 24125,1,9601 and 24125,1,9503 (from 125 cm depth) gave curves similar to (*a*) (from 90 cm depth).

The effect of repeated irradiation of the same sample after successive readouts has been described in detail in paper I. It is shown there that the t.l. from the low-temperature (*ca.* 150 °C) as well as the high-temperature regions (*ca.* 378 °C) of the glow curve shows 'supra-linear' growth with γ-ray dose. The t.l. in the 378 °C region (unlike that in the 150 °C region) showed no trend towards saturation even after an individual γ dose of 2.27 Mrad had been given to a sample that had been subjected to several readout and irradiation cycles.

† 1 rad = 10^{-2} Gy (gray) = 10^{-2} J kg^{-1}.

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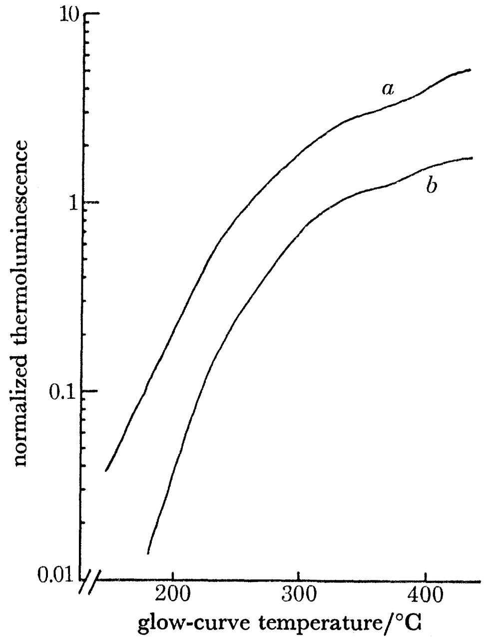

FIGURE 5. A 'plateau test' of normalized t.l. (i.e. natural t.l. divided by t.l. induced by 50 krad of βs) against glow-curve temperature for (*a*) 24090,1,9606 and (*b*) 24196,1,9601. Both curves appear to be reaching a plateau (beyond *ca.* 430 °C) at approximately the same glow-curve temperature. This is taken to indicate that the difference in the normalized t.l. levels between the samples is not predominantly the result of differing amounts of thermal drainage at the two depths (90 and 196 cm, respectively) from which they come.

3.2. *Discussion*

3.2.1. *Preservation of low-temperature t.l.*

The fact that the natural t.l. in the low-temperature readout region (less than 160 °C) of the initially cold Luna 24 samples (from a depth of 90 cm or greater) has failed to survive has been attributed by us to their storage at room temperature for 12 months before our experiments (see paper I for details). This has prompted us to make the recommendation that part or all of any future deep-core material from Luna missions be placed in a deep freeze as soon after retrieval as possible. The Royal Society of London has communicated this recommendation to the U.S.S.R. Academy of Sciences.

3.2.2. *Thermoluminescence and depth*

At any given depth below the lunar surface, a state of dynamic equilibrium is eventually reached between the rates of radiation-filling and thermal-emptying of charge traps in the samples. The 'normalized t.l.' (i.e. natural t.l. divided by test-dose induced t.l.) at first increases rapidly with depth; this is because over the first 10–20 cm the diurnal heat-wave is attenuated sharply. Beyond this depth, the t.l. decreases slowly with increasing depth owing both to the attenuation of the galactic cosmic-ray flux and to the outward heat-flow at greater depths. Hoyt *et al.* (1971) estimate that there is a temperature rise of (2 ± 2) K/m with increasing depth, beyond *ca.* 20 cm, within the lunar regolith. The precise shape of the resultant t.l.–depth profile will therefore depend not only upon the heat-flow balance governed by the input temperatures and the effective thermal conductivity of the material at a particular depth (Durrani & Hwang 1974) but, more importantly, on the particular readout interval of the t.l.

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glow curve used in the analysis. Thus, because of the great thermal stability of the traps involved, there is no observable depth-dependence of t.l. beyond *ca.* 1 cm below the surface at glow-curve temperatures above *ca.* 500 °C, and little, if any, in the glow-temperature interval 300–400 °C (Nash & Connel 1971; Hoyt *et al.* 1972). Our t.l.–depth profile (figure 4) has been based on the height of the glow curve at 324 °C. If the results of the authors quoted above are true, the steep fall in normalized t.l. observed by us at a depth of 196 cm is unexpectedly large: a drop in t.l. by a factor of *ca.* 3 from the t.l. value at 90 cm cannot be accounted for on the basis of a temperature gradient of *ca.* (2 ± 2) K/m.

Although Keihm & Langseth (1973) report a steeper temperature gradient over the top *ca.* 60 cm of the regolith on the basis of their direct heat-flow measurements, our observations suggest that the differences in the normalized t.l. with depth between *ca.* 1 and 2 m do not stem primarily from temperature effects. This can be demonstrated by looking at the 'plateau test' for the 90 and 196 cm samples (figure 5). Differential fading of t.l. from traps that do not have thermal stability at the ambient temperature results in a non-constant value for the normalized t.l. when plotted against readout temperature. The region of thermally stable traps is indicated by a constant value of the normalized (natural/artificial) t.l., i.e. a 'plateau'. In figure 5, curves for both samples exhibit the onset of a 'plateau' at readout temperatures beyond *ca.* 430 °C. Below this temperature, some degree of thermal fading of t.l. from the traps concerned at the local temperature on the Moon is indicated, the fading being greater the shallower the trap (i.e. the lower the glow-curve temperature). However, if thermal effects alone had been responsible for the observed levels of normalized t.l. at the two depths, 90 and 196 cm, then the two samples should have given the same *plateau* level (which corresponds to readout regions where no noticeable thermal fading had taken place), even though this level would have started at different readout temperatures.

From our observations it would therefore appear that the low value (by a factor of *ca.* 3) for the normalized t.l. from sample 24196 is due to that sample having received a substantially lower natural dose than either 24090 or 24125.

Our profile of normalized t.l. glow (at 324 °C) against depth for the three levels shown in figure 4 broadly parallels our track-density–depth data discussed in §2.2. There are two possible explanations for the t.l. profile with depth. The first is that the effect is due to random differences in the dose imparted by internal radioactivity to those relatively few grains that are responsible for the majority of the t.l. exhibited by a sample. Walker & Zimmerman (1972) have drawn attention to the anomalous behaviour of t.l. from bulk fines (as in the present work; see also the local fluctuations in the normalized t.l.–depth curve for the top 40 cm of lunar regolith in Hoyt *et al.* 1971). The other possible explanation for the profile in figure 4 is in terms of our rapid soil-deposition and reworking model (iii) of §2.2 above. This explanation would imply that a substantial part of the t.l. exhibited by soil from depths up to *ca.* 2 m is due to the external radiation dose received either *in situ* (from galactic cosmic rays) or when it was originally near the top (from solar flares). A corollary of the last statement is that the burial of the soil to its present depth must have taken place over periods of less than *ca.* 100 ka for the t.l. memory of its solar-flare exposure to have been retained. With the limited data available at present, however, it would be unsafe to assert a genuine correlation between our t.l. and track data, because random variations in internal dose, as discussed above, could account for the t.l. behaviour.

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3.2.3. *Radiation sensitization of samples*

Previous studies of lunar-sample thermoluminescence (see, for example, Hoyt *et al.* 1971, 1972; Walker & Zimmerman 1972; Crozaz & Plachy 1976) do not suggest an obvious correlation between t.l. sensitivity and radiation damage. Walker & Zimmerman (1972) attribute differences in t.l. sensitivity to the amount of t.l. activators present in different samples; they consider the activator content to be the real cause of an apparent correlation between the t.l. sensitivity and U content of samples.

Geake *et al.* (1972) report variations of a factor of *ca.* 10 in luminescence efficiency from lunar fines, and attribute these to differences in the phosphor content and possibly in radiation histories. Since the lunar t.l. emission occurs strongly at *ca.* 450 nm (Lalou *et al.* 1972; Durrani & Hwang 1974), which coincides with one of the prominent lunar luminescence emission bands (Geake *et al.* 1977), it is reasonable to assume that the two phenomena are related to the same phosphors.

The supralinear growth of t.l. response with the imparted dose reported in paper I (and noted in §3.1) suggests a radiation-sensitization of the samples by virtue of their being subjected to repeated irradiation and t.l. readout.

Indeed, it was discovered by giving 50 krad test doses of β particles to a sample that the imparting of a total γ ray dose of 8.27 Mrad during the reirradiation and reheating cycles had enhanced its t.l. sensitivity in the 378 °C region by a factor of 18. This increase in the t.l. sensitivity is probably not entirely due to the repeated thermal cycling of the sample, if our allied work on meteoritic samples is a guide.

We thus conclude that the t.l. sensitivity of a lunar sample may serve as a pointer to its natural-radiation history, but that this effect may become easily swamped by large differences in the 'intrinsic' t.l. sensitivity of the mineral constituents of different samples.

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4. Conclusions

The solar-flare track densities in the samples from depths of *ca.* 90, 125 and 196 cm in the core tube indicate that the Luna 24 soils are mature, with some degree of submaturity towards the bottom of the tube. The deposition model most compatible with data obtained by ourselves as well as by other groups is the one that postulates rapid deposition of pre-irradiated material mixed-in with a less mature local component.

Our thermoluminescence observations also indicate a lower normalized t.l. glow from the soil at the 196 cm level compared with that from the two upper levels. These observations would be compatible with the soil-deposition model just mentioned, provided that soil burial to a depth of *ca.* 2 m could have taken place over a time scale of less than *ca.* 100 ka. Alternatively, they might merely reflect random variations due to differences in the local internal radioactivity dose received by the most sensitive t.l. phosphors. Radiation-sensitization of the samples suggests a possible use of t.l. sensitivity for the interpretation of lunar radiation history, if inhomogeneities of t.l. phosphor content of samples can be allowed for. Deep freezing of at least a part of deep-core material from future Luna missions would be an advantage.

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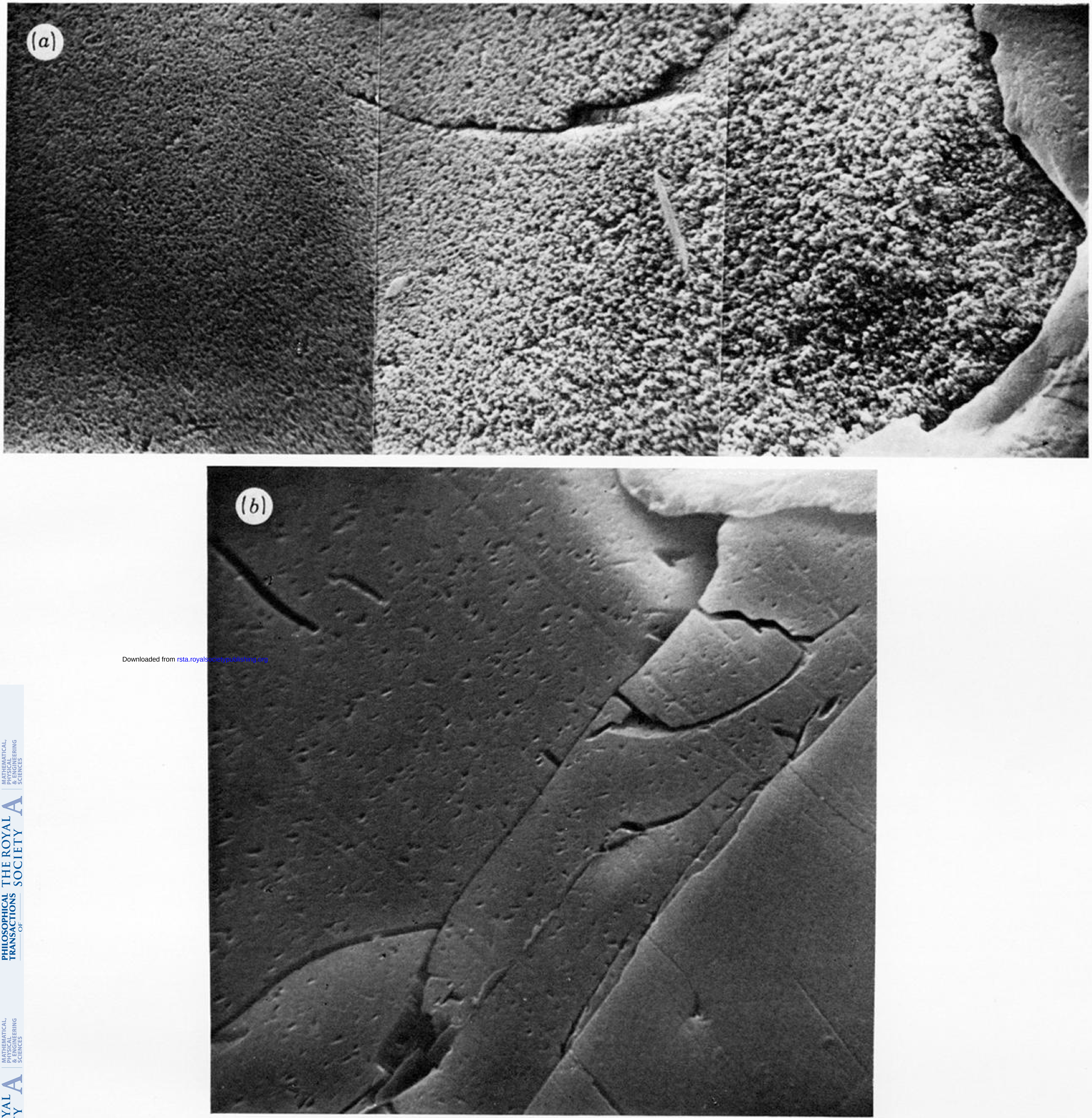

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FIGURE 2. (*a*) A composite photomicrograph of an olivine grain showing a track-density gradient from the right-hand corner proceeding inwards. The grain is no. 3 from 24090,1,9303; it was etched in boiling WN solution (Krishnaswami *et al.* 1971) for 30 min. (*b*) A photomicrograph of a composite feldspar + pyroxene grain (no. 4 from 24090,1,9303) showing a low central track density (2×10^7 cm^{-2}) in the feldspar phase. The grain was etched in boiling 40 % NaOH solution for 10 min. Tracks in the pyroxene phase (lower right-hand corner) had not yet become visibly etched. Grains in both (*a*) and (*b*) came from the 150–250 μm size fraction.

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