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MIXING PROCESS OF THE LUNAR SURFACE MATERIALS AND THEIR COSMIC-RAY EXPOSURE AGE

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From the cosmic ray exposure age data, (time scale 10^7 - 10^8 years), of the lunar surface materials, we discuss the mixing process of the lunar surface layer caused by the meteoroid impact cratering. The gardening effect calculated using a crater formation rate slightly modified from the current population data is consistent with observed exposure ages of the lunar samples.

INTRODUCTION

A cosmic ray exposure age of lunar samples has been calculated from the concentration of a cosmic ray-produced nuclide divided by a production rate of the nuclide in the sample. This age provides some information on the history of lunar materials on the surface. Figure 1 shows some data of the exposure ages measured by several groups using Ar, Ne, and Kr methods (Stettler *et al.* 1973; Turner *et al.* 1970, 1972, 1973; Huneke *et al.* 1972, 1973; Kirsten *et al.* 1972, 1973; Husain *et al.* 1972; Heymann and Yaniv 1970; Eberhardt *et al.* 1970). From Fig. 1 we learn that (1) some Apollo 14 samples give relatively longer ages; apart from that, differences due to localizations and sample species are rather minor, and the distribution of the data covers a wide range. Most of them cover the time scale of 10^7 - 10^8 yr; (2) the soil or fine is a mixture of grains having widely scattered exposure ages.

To understand these facts, there must be a *gardening*, that is a material turnover of the lunar surface. In the present paper, we discuss the mixing process of the lunar surface layer caused by the meteoroid impact cratering. Although there are studies of mixing rate of the lunar regolith using a stochastic method, *e.g.*, Gold and Williams (1974) and Arnold (1975), to the authors knowledge few extensive treatments have appeared to date on the question of the gardening of the lunar surface layer and the galactic cosmic ray exposure age of the surface materials.

GARDENING

From a knowledge of solidification or metamorphic recrystallization ages, 30 - 46 x 10^8 yr ago the surface suffered a large scale magmatic activity or extensive impact process by heavy meteoritic falls (e.g., Turner et *al.* 1973;

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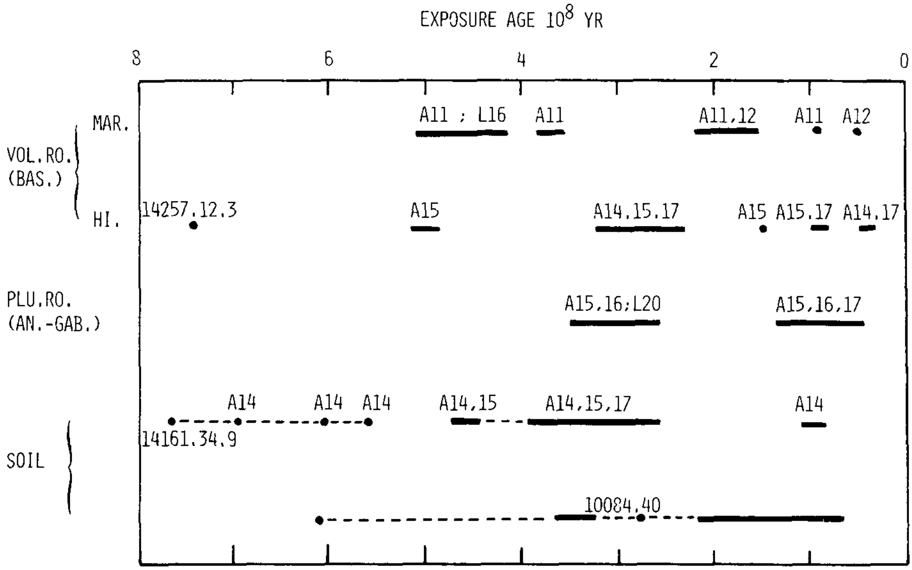

Figure 1. A summary of galactic cosmic-ray exposure age dating data of lunar rocks and soils using Ar, Ne, Kr techniques. Samples from different missions are designated by A for Apollo and L for Luna. Special samples are designated by numbers. Sources for this summary are given in full in the text: Vol. Ro, volcanic rock; BaS, basalt; Mar, mare; Hi, highland; Plu. Ro, plutonic rock; An - Gab, anorthosite - gabbro.

Iriyama 1975). During this period rare gases have been lost and the exposure to cosmic rays has not been memorized in the samples. As far as rare gas exposure ages are concerned, we may treat the history of the surface materials during the past 30 x 10^8 yr. A simple model may be constructed considering an effective gardening depth and an effective cosmic-ray production thickness, 0 - 1 meter. From the profile of Mn-53 produced from Fe (Imamura et al. 1974), the mean absorption depth, 1/e thickness, for the production is estimated to 230 g/cm^2 or about 1.3 m thick soil layer.

If we also assume a vertical component for the mean velocity of materials, we can illustrate the situation schematically in Figure 2 (Iriyama and Honda (1975; Iriyama *et al.* 1976). The straight line having a slope of 45^o indicates the limit to the parameters due to the finite thickness of the cosmic ray effect. Near the limiting condition, observed ages will be scattered widely, whereas with faster rates, the ages will be uniform and simply express an inverse function of the effective gardening depth. In the latter case materials appear many times in the exposed surface and the content of the products is homogenized.

CRATER FORMATION AND EXPOSURE HISTORY

The principal mechanism of the movement of the lunar surface must be attributed to crater formation in the past. We may introduce a more realistic gardening model, considering the effects of cratering produced by meteorite falls. For the distribution of present craters which has been observed from telescopes and from

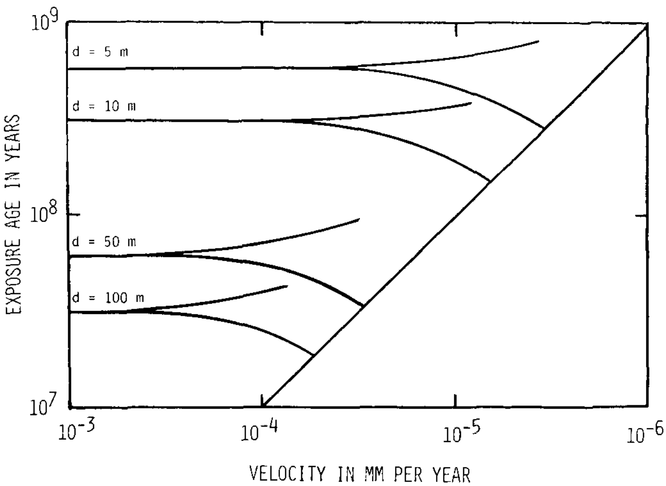

Figure 2. Changes in galactic cosmic-ray exposure age with mixing velocity of lunar surface materials for different gardening depths.

the photographic survey of lunar orbiters, formulae in the form of

$$\log N\ (>D) = \log y - x \log D \qquad (1)$$

could be used to summarize the population (*e.g.*, Kopal 1969; Shoemaker *et al.* 1970), where N is the cumulative number of craters which have ϕ (size) > D km in a 10^4 km^2 lunar area.

In the mare region, Hartmann (1965) gave log y = 2.0 and x = 2.4 to cover a wide range of the crater. First we may take this equation for an estimation of crater formation rate. Next, considering a higher possibility of disappearance of smaller craters (D < 1 km) caused by multiple formations in the same area, the above equation has been modified to some extent. Keeping y = constant, x may be increased stepwise, from 2.4 to 3.3. Here we also assume a constant rate of meteorite fall on the surface during 30 x 10^8 yr, as well as a constant cosmic ray flux.

In an estimation of the gardening rate, we assume that a cratering of ϕ = D causes a removal of D/6 thick materials from the interior. As a result, a new surface appears in the area of the crater circle. Simultaneously the materials are ejected and deposit evenly covering the neighborhood of the crater extending ϕ = 3D region. This implies that near the crater freshly formed, a thin surface layer, D/(6 x 8), appears. The cosmic ray age of the sample will reflect the period of its stay at a depth shallower than that effective for the production of the nuclides. The results of a simple examination using equations postulated above are listed in Table I.

A mean time for the sample to appear at less than 1.3 m, could be obtained from a turnover multiplicity of the renewal of the area per unit lunar surface in the past 30 x 10^8 yr caused by the formation of craters of D $\geq$ 7.8 m. The multiplicity M above mentioned may be calculated as 1 + (No. of surface renewals), because it is reduced to one when there has been no gardening effect at all.

Residence time of sample in the exposed surface layer, 0 - 1.3 m, is given by: (3 x 10^9) / M(d >1.3 m) when a higher multiplicity observed at less than d

TABLE I

CRATER FORMATION RATE AND RESIDENCE TIME OF SAMPLE IN EXPOSED SURFACE LAYER, DEPTHS BETWEEN 0 AND 1.3 m, AND MEAN EXPOSURE TIME FOR SURFACE SAMPLE SHOWING M = 3 AT DEPTH, d

x*	2.4	2.7	3.0	3.3
Residence time at 0 - 1.3 m: 10^8 yr	11	6.3	2.7	1.0
Depth at M = 3: meters	1	3	5	10
Mean exposure time: 10^8 yr	(11)	4.5	2.1	1.3

*log N (>D) = 2.0 - x log D

meter, the mean exposure time of the surface sample is given by $(3 \times 10^9) / (d / 1.3) \times M(> d)$.

The cumulative surface area A_c exposed by formation of craters is given by

$$A_c\ (>D^*) = \int_{D^*}^{\infty} X dD, \tag{2}$$

where $X = 10^{-4}\pi(D/2)^2\ dN/dD$. (3)

The cumulative surface area A_s exposed by sedimentation caused by cratering is given by

$$A_s(>D^*) = \int_{8D^*}^{\infty} 8X(1 - D^*/D)dD + \int_{D^*}^{8D^*} X(D/D^* - 1)dD, \tag{4}$$

where the equation takes into account the previously exposed layers and the surface thickness, $d = D^*/6$. In general $A_s > A_c$ by a factor of 2 to 5, independent of the depth.

The multiplicity of surface renewal below $d = D/6$ is calculated as

$$M(>d) = 1 + A_c + A_s. \tag{5}$$

Based on this model a calculation to obtain a reasonable exposure age may be possible.

Apparently a part of materials located at a shallower depth may appear on the exposed surface many times. By multiple exposures down to a certain depth, d, the concentration of the products may be seen to be homogeneous. For example, from equation (1) with x = 3.3, craters of deeper than 5 m will already occupy more than 100% of the lunar surface and for about 10 m the multiplicity is 3 already. Therefore cosmic ray products may be fairly homogenously mixed. The mean surface exposure time of 1.3×10^8 yr will result from these circumstances.

Although the analyses must be extended furthermore to calculate the most probable age of the samples and their distributions based on more realistic cratering effects, the current crater population, with x = 2.4, does not seem enough to explain the observed exposure ages of the samples.* The formation rate seems to be slightly steeper than the current one in respect to crater size, *i.e.*, x = 2.7 - 3.0.

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Lunar materials which may contain fossil records of between 30 - 46 x 10^8 yr ago may be distributed down to much deeper layers. To detect their presence we could use non-volatile cosmic ray products, stable nuclides as well as K-40 from Ca as a reference.

Referee's remark: *It happens that x* is *around 3 to 3.3 for diameters less than 2 km because of secondary ejecta and secondary craters. So these results* do agree *with observations after all.*

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DISCUSSION

WHIPPLE: In 1942 I first asked the question: "Does the Moon Lose or Gain Mass by Accretion?" Do you have an answer? If the moon is not gaining or losing mass, then the asteroids with lower gravity should all be losing mass.

IRIYAMA: I think that 4.6 x 10^9 *years ago the moon grew to its present mass and radius very rapidly by an accretion process. I think that after the lunar formation its mass has been a constant. We show that by circulation of the material within the moon, the observed exposure ages of the lunar samples can be obtained.*

CHAPMAN: The subject of this paper might seem to have little to do with the question of the interrelations among asteroids, meteorites, and comets. Yet studies analogous to those just described for the moon would be very important if applied to the asteroidal case. There is increasing evidence that a large proportion of the meteorites were formed as impact breccias in a regolith *similar to that on the moon. That requires very deep regoliths to be present on asteroids, such as Anders believes to be present. Yet my own calculations suggest that asteroidal regoliths are probably far too thin. Indeed, Dollfus has just described his interpretation of asteroid polarization properties in terms of dust-covered rocks, suggesting very thin regoliths. Because of the importance of this question for the origin of meteorites on parent-body surfaces, it would be helpful if the numerous researchers who have been studying the lunar regolith would turn some of their attention to modelling the asteroidal cases.*

IRIYAMA: We discussed the mixing process of the lunar surface layer caused by the impact cratering of meteorites with various masses. Our gardening model may be applied to the estimate of meteorite flux or crater formation rate at the asteroids and the thickness of asteroidal regolith.