MIXING OF THE LUNAR REGOLITH

D. E. Gault, NASA, Ames Research Center, Moffett Field, CA 94035; F.Hörz, NASA, Johnson Space Center, Houston, TX 77058; D. E. Brownlee, Department of Astronomy, U. of Wash., Seattle, WA 98195; J. B. Hartung, Max-Planck Instit. für Kernphysik, Heidelberg, Germany.

Because meteoritic impact is a random process, any given point on the lunar surface has experienced a unique history as compared to any other given point on the surface. Depth of regolith, regolith turnover rates, etc. cannot be described in meaningful terms with "averages" as has been done in the past (Gault, 1970; Shoemaker et al, 1970), particularly as applied to studies of track records of solar and galactic radiation, content and distribution of noble gases, impact produced glass agglutinates, etc.. Stratigraphic layering in all core materials returned by Apollo and Luna missions emphasizes the uniqueness of any given spot on the moon. On the other hand, the dominant role that impact has played in regolith formation suggests that any two spots at a given site on the lunar surface will have experienced similar histories that differ only in details to a greater or lesser degree by the vagaries of the random distribution of the impact events which contributed to the formation at each point. It can be shown that the probability P_u of a given point on the lunar surface remaining undisturbed by (i.e., lying outside) a crater of apparent diameter* D_a in a time interval t is

$$P_u = \exp(-\pi N t D_a^2/4) \quad \text{------------------------------------} \quad 1)$$

where N is the flux of the randomly distributed impacting bodies (per unit area and time) which produce the craters of diameter D_a. Similarly, it can be shown that

$$P_c(n) = P_u\,(\pi N t D_a^2/4)^n/n! \quad \text{-------------------------------} \quad 2)$$

is the probability P_c of a given point on the lunar surface having been covered by (i.e., lying within) exactly n craters of diameter D_a. Equation 2 is the Poisson probability function; values may be found in Molina(1942) for a range n = 0 - 153 and $(\pi N t D_a^2/4) = 0.001 - 100$. We have calculated additional terms up to $n = 10^6$.

Using our "best" estimate of the current meteoritic flux (Gault et al, 1972) Figure 1 illustrates the application of equations 1 and 2 for two sizes of craters based on scaling laws derived from laboratory cratering studies (Wedekind and Gault, 1974). By the time the total area contained within the perimeters of all the craters of a given size is equal to the area of the lunar surface(approximately 3 x 10^5 years for D_a=10cm) overlapping of craters due to random distribution results in approximately 1/3 of the surface remaining undisturbed by craters of the given size, and only 1/3 of the surface is disturbed one time. The remaing fraction of the surface is disturbed two or more times(n=2,20%; n=3, 7.5%; n=4, 2%, etc.). In order to assure that 99% of the

*Apparent diameter D_a is measured with respect to the original (pre-impact) surface, and is 0.8 - 0.9 of the rim diameter for present applications.

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surface has been disturbed at least once, the total area of all the craters produced at a given size must exceed the surface area by a factor greater than 4 (approximately 1.2 x 10^6 years for D_a = 10 cm) with a consequent increase in the number of times the surface is disturbed (e.g., n = 4, 20%; n =10, 2%). Moreover, note that the time required for different sized craters does not scale directly with size; the times for 1 m diameter craters are a factor of 200 greater than for 10 cm craters.

Since each cratering disturbance represents excavation and ejection of regolith material across the lunar surface from a given point, Figure 1 also provides a representation of the probability for the number of times the regolith is turned over at the given point to the depth determined by the size of the cratering events being considered. Accordingly, Figure 2 presents a summary of our interpretation of turnover depths as a function of the number of turnovers in different intervals of time measured from the present. Discontinuous changes in the curves result from changes in the mass-number distributions assumed for the flux of impacting masses(Gault et al, 1972; Latham et al, 1973) and/or changes in the appropriate scaling relationships as determined from laboratory experiments(Wedekind and Gault, 1974; Vedder, 1972, 1974). In particular it should be noted that craters produced in particulate media which simulate the regolith are formed by compaction and direct excavation of the target material. Thus, although the depth:diameter ratio of craters under consideration is about 1:4, the effective turnover depth:diameter ratio of 1:8 has been employed to convert from D_a. Additionally, consideration has been included in Figure 2 to account for the greatly enhanced flux of meteoritic material early in lunar history. The enhancement, of course, is model dependent; it is based on extensive crater count data for the Apollo landing sites (Greeley and Gault, 1974) and Rb/Sr ages reported from the Lunatic Asylum. Regardless of model assumptions the flux may be considered to have been constant during the last 10^9 years in all cases.

The most significant result from the calculations shown in Figure 2 is thelarge number of turnovers which occur in the upper 1 mm of the surface as compared to deeper layers. It is 99% probable that the upper 0.5mm is turned over almost 100 times in 10^6 years while even at the 50% probability level the 1 cm depth has yet to be disturbed; it requires 10^7 years to assure (99%) that the surface has been turned over to a depth of 1 cm at least once. Time scales for one turnover at 10cm to 1 m depths are measured in 10^9 year units, and it is not surprising that the A-15 drill core material returned from more than 2 meter depth had lain undisturbed for about 500 million years(Russ et al, 1973). As pointed out previously(Gault et al, 1972), it is only the upper 0.5 - 1 mm of the lunar surface that is subjected to intense churning and mixing by the meteoritic complex at the present time. This thin veneer of regolith should be considered a primary mixing layer of lunar materials from all points on the moon and a major source for impact melts, agglutinates, and vapor products.

REFERENCES: Gault(1970), Radio Science,5,2, 273-291; Gault et al(1972), Proc. 3rd LunSciConf, 3, 2713-2734; Greeley and Gault(1974), in preparation; Latham et al(1973), Lunar Science IV, 457-459; Molina(1942), "Poisson's Exponential Binomial Limit", Van Nostrand; Russ et al(1973), Lunar Science IV, 642-644; Shoemaker et al(1970), Proc. A-11 Conf, 3, 2399-2412; Vedder(1972),JGR, 77,23,

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4304-4309; Vedder(1974),Pers.Commun.; Wedekind and Gault(1974), in preparation.

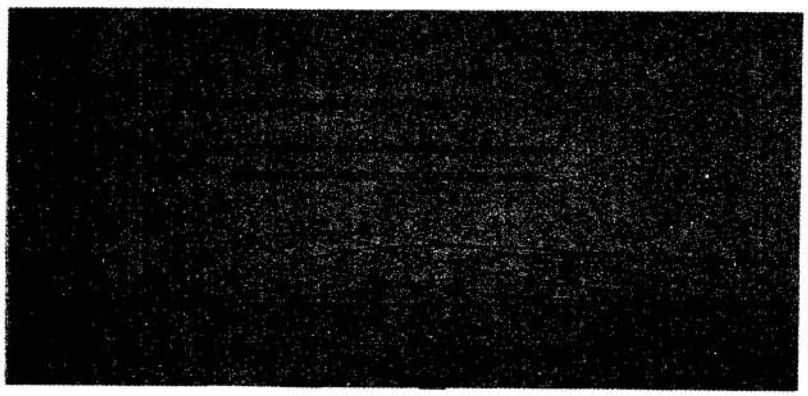

Figure 1.-Temporal veriation of probability P_u and $P_c(n)$ expressed as fraction of surface area covered by randomly distributed craters. Impact Velocity, 20km/sec.

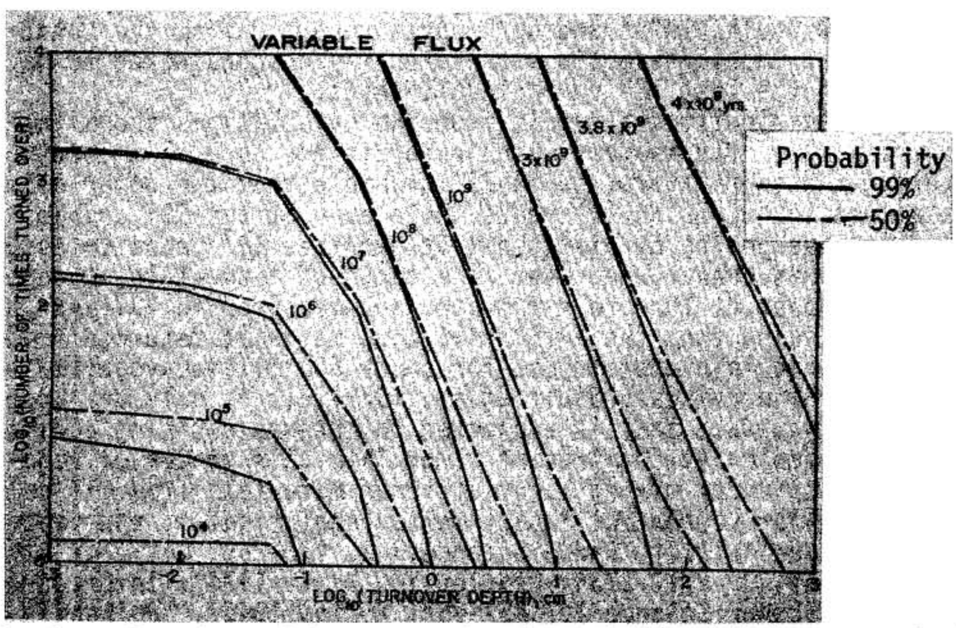

Figure 2.-Variation of number of turnovers to given depth with turnover depth. Time measured from the present. Impact velocity, 20km/sec.