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The lunar regolith: physical characteristics and dynamics

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The fine size fraction of the lunar regolith (less than 1 mm mean particle diameter) is composed mostly of particles that owe their origins either directly or indirectly to the impacts of meteoroids on the lunar surface. Comminution of pre-existing rocks and particles is the dominant process affecting the characteristics of the regolith. However, agglutination of pre-existing particles by the glassy, molten spatter and ejecta from small meteoroid impacts is a competing constructive process of low efficiency. Grain size frequency distributions of the less than 1 mm fraction of the regolith tend to be slightly bimodal, with a broad mode in the 1–4ϕ size range (500–62.5 μm) due mostly to agglutination and another mode at approximately 5ϕ (31.3 μm) and finer that appears to be caused by the ballistic influx of fine particles from older (finer) regolith. In general, the size frequency distribution curves are nearly symmetrical and indicate poor to very poor sorting. There is a strong correlation of sample mean grain size (and other size parameters) with the length of time that the regolith has had to accumulate at each landing site. The greater the total length of regolith accumulation time, the greater the comminution by meteoroids, and hence the finer the sample mean grain size and the greater the total agglutinate content. These properties also correlate positively with solar wind implanted carbon and nitrogen contents. Thus, sample mean size, agglutinate content, solar wind nitrogen and carbon, as well as solar particle track densities, can all be used as measures of regolith ‘maturity’. Local sample collection site geology, such as proximity to boulders or recent craters, strongly influences sample modal particle type populations and grain size characteristics. Lunar chondrules of several types have been identified in the regolith and rock samples. Many of these chondrules have textures that are identical with many meteoritic chondrules. The chondrules in lunar surface materials appear to result from lunar impact processes. It may be that chondrules have originated in many meteorites by some of the same processes. If true, this occurrence has important implications for the origin and history of chondritic meteorites.

INTRODUCTION

The exact nature of the lunar surface was a subject of considerable scientific and engineering interest before the landing of Apollo 11 and the examination of the first lunar samples. It was found that the surface of the Moon was covered by a layer of broken and shock metamorphosed rock and mineral fragments. The structure of this fragmental layer, or regolith, appears to be very similar to the structure proposed by Salisbury & Smalley (1964), with numerous ejecta deposits from craters of many sizes overlapping to form a rather complex local stratigraphy. Most of the particles in the lunar regolith owe their origins, either directly or indirectly, to the impacts of meteoroids (King, Butler & Carman 1971). No single particle or volume of particles from the lunar regolith has as yet been proven to be solely of volcanic origin, although it seems almost certain that such particles exist.

PARTICLE TYPES

The common types of particles that occur in the lunar regolith can be classified as follows: unshocked crystalline rock fragments, shocked crystalline rock fragments, unshocked mineral grains, shocked mineral grains, regularly shaped glass (including spheres, other more or less spherical shapes, dumbells, and tear drops), glass fragments of irregular shape, agglutinates (glass bonded aggregates of grains also termed agglomerates or glazed aggregates in the earlier lunar sample literature), and microbreccia fragments. Modal analyses of these and other particle types in various size fractions of the less than 1 cm component of the regolith have demonstrated significant variations in the relative amounts of different particle types present at different landing sites and at different geological settings in the same landing site (King *et al.* 1971; Butler, Greene & King 1973; Heiken & McKay 1974; etc.). Thus, it appears that regolith mixing mostly has been very local since the last big basin-forming events, such as the Imbrian or Orientale events.

However, there is a high probability that a *few* of the grains in any size fraction may have originated from very great distances, i.e. they have been deposited in the regolith as ballistic ejecta from distant craters. This fact was put to good use by four investigator groups who worked with the modal analyses of particle types in the Apollo 11 samples and concluded that the lunar highlands might contain plagioclase-rich rocks because of the occurrence of small numbers of such fragments in the Apollo 11 samples (King, Carman & Butler 1970; Anderson *et al.* 1970; Short 1970; Wood, Dickey, Marvin & Powell 1970). Later Apollo landings in the lunar highlands proved the validity of this interpretation.

There is a continuing effort by a number of laboratories to characterize the small rock fragments in the lunar regolith as the range of rock types represented in these smaller size fractions is much greater than that represented by the larger rocks returned (King *et al.* 1970).

GRAIN SIZE ANALYSES

The grain size frequency distributions of lunar regolith samples have been determined most thoroughly on the less than 1 mm size fraction because this is the size fraction most widely and generously distributed by N.A.S.A. for various types of analyses. The grain size frequency distributions of this size fraction can be characterized as generally bimodal, poorly to very poorly sorted and nearly symmetrical (Butler & King 1974; and earlier papers cited therein). Raw grain size data for the less than 1 mm size fraction of the lunar regolith have been published in a number of papers (King *et al.* 1971; King, Butler & Carman 1972; Butler, King & Carman 1972; Butler *et al.* 1973; Butler & King 1974). Representative grain size frequency distribution curves illustrating the basic features seen in most such curves for lunar samples are shown in figure 1. King *et al.* (1971) suggested that the mean grain size of the less than 1 mm size fraction might decrease as the total regolith accumulation time at site increases, thereby providing greater opportunity for comminution by meteoroids. For landing and sample collection sites of clearly different surface ages, hence different lengths of time of regolith accumulation, there is a good correlation (figure 2). Although some authors have suggested that there is a 'dynamic equilibrium' in the regolith such that after sufficient meteoroid bombardment the constructive process of agglutinate formation and the destructive comminution by meteoroids tend to balance each other and the mean grain size will remain essentially constant, we do *not* find any evidence to support this contention.

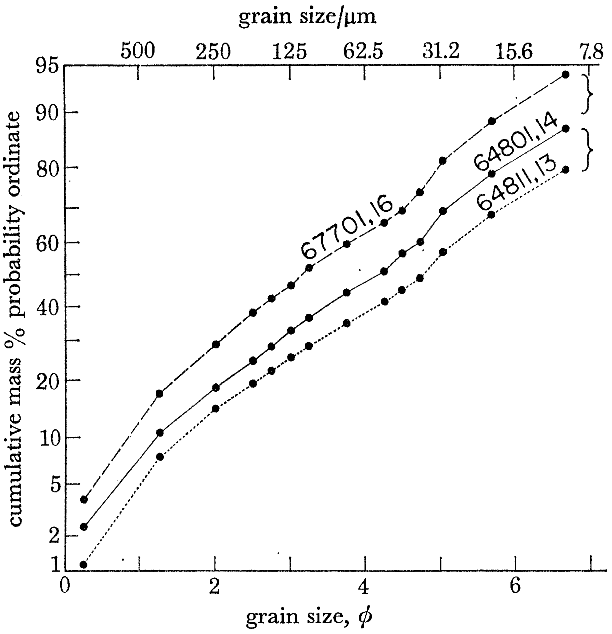

FIGURE 1. Grain size frequency distribution curves for three Apollo 16 samples illustrating the features present in most lunar regolith samples. These curves are for the less than 1 mm size fraction only. Note the broad mode in 1–4ϕ size interval and the narrower mode at approximately 5–6ϕ. The solid dots indicate the sieve sizes used. (From Butler *et al.* (1973), courtesy of Pergamon Press.)

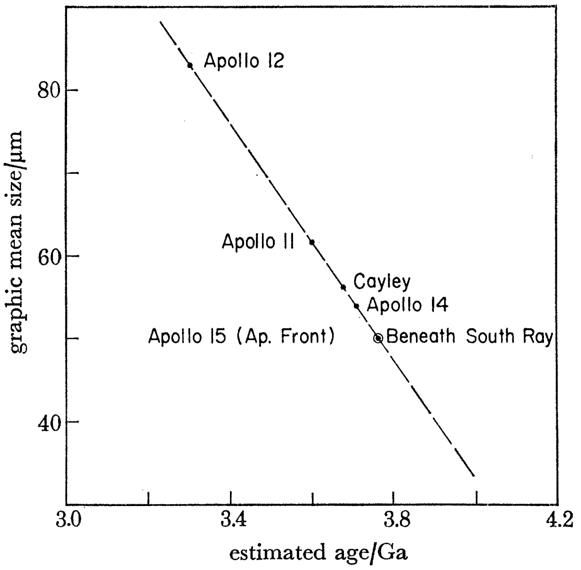

FIGURE 2

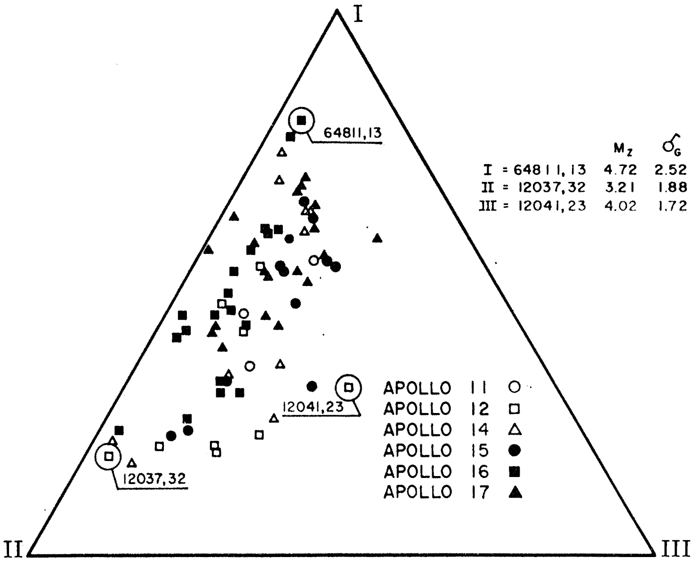

FIGURE 3

FIGURE 2. The approximate relation between sample mean size, for the less than 1 mm size fraction of lunar regolith samples, and total regolith accumulation time at various lunar sites. The dashed line is only an approximation established by extending the line established by the Apollo 11 and Apollo 12 data. However, it fits the observed ages rather well. There are theoretical reasons to believe that the curve should not be rectilinear and this figure should be used only to illustrate the observation that the mean size of samples decreases as their total regolith accumulation or meteoroid exposure time increases.

FIGURE 3. Plot of the normalized first three rotated components derived from Q-mode factor analysis of the mass percent grain size data for 72 regolith samples from all Apollo missions. Samples with the greatest component I content have the greatest grain size maturity. (From Butler & King (1974), courtesy of Pergamon Press.)

A Q-mode factor analysis of 72 lunar sample grain size frequency distributions including samples from each of the Apollo missions was reported by Butler & King (1974). Each of these samples was handled in exactly the same way and the grain size analyses were accomplished by the same technique such that the data are internally comparable. The object of the analysis was to account for the greatest amount of the data with the fewest dimensions or factor axes. The Q-mode factor analysis selected three components for what can be considered as a mixing model (figure 3).

Sample 64811,13 (closest to factor I) is very fine grained, only slightly bimodal, and very poorly sorted. This sample is typical of some of the oldest regolith collected by the Apollo missions and it is believed that the factor I content of the sample can be used as an indicator of *grain size* maturity. Samples that plot near this corner of the triangle also tend to have large total agglutinate contents.

The factor II component, as illustrated by sample 12037,32, is strongly bimodal, relatively coarse grained, poorly sorted and nearly symmetrical in its grain size frequency distribution. Closely associated with this end member in the plot (figure 3) are samples from Cone, North Ray, Elbow, Head and Surveyor craters. Furthermore, modal analyses of these samples tend to have large amounts of rock fragments and low agglutinate contents. Thus, the factor II component can be considered as fresh crater ejecta.

The interpretation of the factor III component is less clear, but samples with large factor III contents, such as 12041,23 and 15271,92 tend to have a pronounced mode in the 5ϕ or finer size range, which several investigators (Duke *et al.* 1970; King *et al.* 1971; and others) have suggested might represent an exotic, perhaps very old highlands regolith, component.

The fact that all samples tend to plot close to the factor I–II side of the triangle is further confirmation that comminution by meteoroids is the dominant process affecting the grain size frequency distribution (and most other properties) of fine grained regolith samples. Mixing by ballistic influx of material with different grain size characteristics is a process that is clearly of secondary importance.

Maturity

The term 'maturity' has been used by many investigators in characterizing lunar regolith samples. The important fact to note is that these various measures of 'maturity' mostly are measuring somewhat different things. The measure of maturity using agglutinate content of a highly restricted size range (McKay *et al.* 1972; and later papers by the same laboratory) is measuring a different kind of maturity than is the grain size maturity (Butler & King 1974; and earlier papers by this laboratory). Both of these measures of maturity tend to correlate well with solar wind implanted carbon and nitrogen, solar particle track densities, etc., but they are measuring somewhat different processes. Perhaps one of our most valuable tools in understanding the rate and dynamics of regolith processes will be the quantitative intercorrelation of these various maturity indices.

Lunar chondrules

Lunar chondrules were identified in the Apollo 14 lunar regolith and breccia samples by several laboratories. The history of observations and papers related to lunar chondrules has been summarized by King *et al.* (1972). There are at least three separate types of lunar chondrules that have been found in the Apollo 14, Apollo 15 and Apollo 16 samples that are identical

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

in texture and general petrography to meteoritic chondrules. These are: (1) roughly spherical fluid drops that have supercooled and partially crystallized or have been devitrified by annealing in hot crater ejecta deposits; (2) abrasion rounded lithic fragments; and (3) types 1 and 2 above or angular to rounded clasts that are surrounded by aureoles and diffusion and/or recrystallization haloes. Such lunar chondrules have been figured by King *et al.* (1972); King, Carman & Butler (1972); Butler *et al.* (1972); King, Butler & Carman (1972*a*); Kurat, Keil, Prinz & Nehru (1972); Nelen, Noonan & Fredriksson (1972); and others. The occurrence of lunar chondrules in these samples and not in the Apollo 11 or Apollo 12 samples is thought to be related to the ejecta from the large basin-forming events. The Apollo 14 landing site was on the Fra Mauro Formation which has been interpreted as ejecta from the Imbrian event. It appears that the chondrules are formed by melting, abrasion and other processes accompanying the impact, transport and deposition of large crater ejecta (King *et al.* 1972).

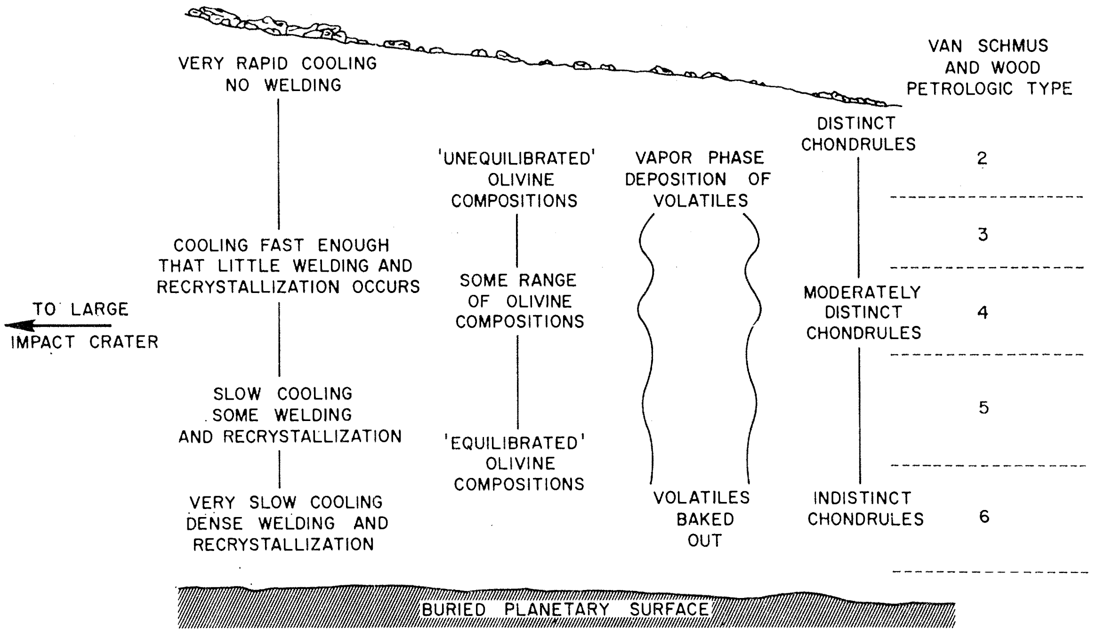

Figure 4. Schematic diagram of impact-implaced hot base surge and fall-back deposits, somewhat similar to a cooling unit of an ash-flow tuff. Some of the possible relationships between various petrologic and chemical variations in chondritic meteorites used in the classification scheme of Van Schmus & Wood (1967) are indicated. (From King *et al.* (1972), courtesy of the M.I.T. Press.)

The important implication for chondritic meteorites is that if some fraction of meteoritic chondrules have formed by the same processes, then chondritic meteorites may, in part, represent impact formed ejecta from the surface of other planetary bodies. Thus, impact-implaced base surge and fall-back deposits may have been the environment of origin of chondritic meteorites in a model similar to that of an ash flow tuff (figure 4). This type of model might also account for some of the petrologic and chemical variations that have been used to classify meteorites by Van Schmus & Wood (1967), as has been suggested by King *et al.* (1972). There is, of course, the opportunity for many impacts on any planetary surface and it is not suggested that chondritic meteorites might originate from a single event but from a number of such events as is demonstrated by the petrography of chondrites.

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