

## A general model for the textural evolution of lunar soil

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**Abstract**—Four dimensional cluster analysis of the grain size parameters (mean, standard deviation, skewness, and kurtosis) of 125 lunar soils from the Apollo 15, 16, and 17 sites has provided a basis for the construction of a general model for the development of textural maturity in the lunar soil. The evolution of textural maturity occurs in two transitional stages: (1) A comminution-dominated stage where the mean grain size of the soil exceeds the average size of agglutinates ( $\sim 2.5 \phi$ ). In this stage, agglutination is ineffective because of a paucity of fines; thus comminution gradually reduces the mean grain size, increases the standard deviation and stabilizes the skewness at zero and the kurtosis at 1.0 (a log-normal distribution). (2) An agglutination—or vitrification—dominated stage where glass is introduced in two narrow size ranges either side of the mean grain size. Transition to this phase occurs when fines are abundant enough to form agglutinates. In this stage, agglutination balances the effects of comminution with the result that the mean grain size and standard deviation both decrease while skewness becomes more negative. When the mean is plotted as a function of standard deviation the two evolutionary stages produce a horseshoe-shaped curve with a reversal of slope at a point where the mean grain size approaches the mean agglutinate size ( $\sim 2.5 \phi$ ). Mixed soils with intermediate characteristics may fall anywhere inside the curve. There is a direct relationship between textural and mineralogic maturity in the comminution dominated stage of soil development. When agglutination begins to dominate textural evolution, the simple relationship disappears as the textural properties of the soil cycles in response to crushing of agglutinates by layer-forming impact events in combination with mixing. Mixing produces a complex relationship among skewness, and mean and standard deviation. The kurtosis of the lunar soils is controlled by the sorting of the fine fraction ( $< 4.0 \phi$ ) which appears to be independent of the effects of meteorite impact. The only alternative mechanism proposed in the literature capable of moving large volumes of fine materials is electrostatic transport. The balance between comminution and vitrification (fusion) of the soil by meteorite impact ultimately produces a soil with a mean and standard deviation that cannot be much smaller than  $\sim 4.0$  and  $\sim 1.5 \phi$ , respectively. This limit is fixed by the restricted grain size range of the glass particles produced during reworking of the soil. A few soils go well beyond this limit possibly as a result of sorting during transport in base surge or grain flow. Both processes produce graded beds, one normally graded, the other reverse graded, respectively. Introduction of pyroclastic materials (similar to the orange soil (74220) from the Apollo 17 site) has minimal effect on the textural maturity of a mature soil. Primitive or comminution dominated soils would, however, be significantly modified by the addition of pyroclastic materials in layers sufficiently thick to reduce the ability of large impacts to excavate new bedrock materials. Texturally the end product would be indistinguishable from a soil produced entirely by impact.

### INTRODUCTION

THE LUNAR SOIL evolves in a regular manner in response to continued reworking by impacting meteorites. The two main dynamic processes responsible for this developmental sequence are (1) comminution and (2) vitrification (fusion). In this paper, an earlier model (Lindsay, 1971, 1972, 1973) is qualitatively expanded to show that it can be applied in a more general sense to large areas of the moon.

## MATURITY: AN INDEX TO THE EVOLUTIONARY PROCESS

Before proceeding to a discussion of the maturity of lunar soils, it is necessary to define the term clearly. Two readily separable concepts of maturity are used in describing the lunar soil: (1) mineralogic maturity and (2) textural maturity. Used in its most general sense, when applied to terrestrial sediments, the term "maturity" generally means mineralogic maturity. "The mineralogic maturity of a clastic sediment is the extent to which it approaches the ultimate end product to which it is driven by the formative processes that operate upon it" (Pettijohn, 1957). This implies that mineralogic maturity is a measure of total energy expended in the formation of the sediment.

Lindsay (1971) first applied the term "maturity" to the lunar soil within the confines of Pettijohn's (1957) definition. The formative processes operating on the lunar soil in large part relate to the meteorite flux at the lunar surface. Each impact on the lunar surface releases a significant proportion of its kinetic energy in the form of heat energy (Gault and Heitowit, 1963; Braslau, 1970). In turn, a proportion of this heat energy is expended in fusing possibly as much as 5% of the mass of the detrital materials excavated by the impact (Lindsay, 1971). Since the lunar soil is continually reworked by meteorites, the glass content of the soil increases with time. However, the rate of increase in the glass content will decline exponentially with increasing glass content (and increasing time) as more energy is expended in remelting preexisting glass. The formation of "soil" or vitric breccias is likewise energy dependent. Consequently, Lindsay (1971) proposed that the proportion of the soil consisting of glass plus vitric breccia fragments be used as an index of mineralogic maturity. The total glass content of the soil is an equally effective measure of mineralogic maturity. Lindsay (1971) tested this model for maturity by using the known radiometric ages of the basaltic substrates at the Apollo 11 and 12 sites. As expected, the soils from the Apollo 11 site, the site with the older substrate, proved to have the highest mean index of mineralogic maturity.

Since the mineralogic maturity of the lunar soil is energy dependent, it could be argued that the textural maturity (i.e. grain size parameters) of the lunar soil may also be energy dependent. This possibility was explored and it was found that instead of a direct relationship between the grain size parameters and the mineralogic maturity of the soil, the soils clustered indicating that mineralogic maturity was insensitive as a measure of textural maturity (Lindsay, 1971). This finding supported the concept of the steady-state soil model in which the effects of comminution are balanced by vitrification (Lindsay, 1971). A strong linear relationship was found between the mean grain size of the lunar soils and the sorting (Lindsay, 1971, 1972, 1973). This indicated that mean grain size decreased as sorting increased and suggested that a subtle evolutionary sequence could be traced for the development of textural maturity. It was found that the mean and sorting were stabilized by the introduction of glass particles in two narrow size ranges approximately one standard deviation either side of the mean grain size (Lindsay, 1972). The particles coarser than the mean are largely constructional

particles (Duke *et al.*, 1970) or agglutinates, the glass particles finer than the mean were found to be irregular in shape and may have been produced by the crushing of the delicate agglutinates or as a fine spray produced by micrometeorite impact (Lindsay, 1972).

In a later definition of maturity, McKay *et al.* (1972) equate the amount of meteorite reworking the lunar soil has undergone with "exposure age or residence time on the lunar surface" and stated "that total glass content cannot be used as an index of exposure age or maturity." McKay *et al.* (1972) based their index of maturity on the agglutinate content of the lunar soil which they show to be related to particle track density and thus the exposure age of the soil. However, Lindsay (1972) found that the agglutinate content of the lunar soils in part determined their mean grain size, standard deviation, and skewness. That is, agglutinate content is related to the *textural maturity* of the soil, not the *mineralogic maturity*. Textural maturity can be measured directly by means of the grain size parameters of the soil.

The formation of glass in the lunar soil is, for practical purposes, an irreversible process. That is, mineralogic maturity changes as a direct function of time. In contrast, textural maturity is a reversible process. Agglutinates in particular are extremely fragile and are readily destroyed due to crushing in larger scale impact events (that is, events too large to produce agglutinates). In this situation, textural maturity (grain size) would be reduced whereas mineralogic maturity would continue to increase. This concept is developed further in a later section.

#### TEXTURAL MATURITY: A MULTIVARIATE MODEL

The meteorite flux, when averaged over a long period of time, should be much the same over large areas of the lunar surface. Consequently, if meteorite impact is the dominant soil forming process on the lunar surface, soil samples from any point on the lunar surface should fit into the same general evolutionary pattern. It should be possible thus to develop a general model for the textural evolution of the soil using samples from several missions and from both the lunar surface and from deep cores.

When grain size parameters of the lunar soil are analyzed on a site by site basis, several simplifying relationships are apparent. These relationships are quite strong frequently and suggest a minimum number of processes operating on the soil. For example, surface soil samples from the Apollo 12 site show a direct linear relationship between median grain size and standard deviation or sorting (Lindsay, 1971). Similarly, soils from the Apollo 15, 16, and 17 sites show strong linear relationships between the inclusive graphic mean and the inclusive graphic standard deviation (Lindsay, 1972, 1973) (Fig. 1). It was also found that a sequence of samples from the Apollo 15 deep core show definite changes in texture with depth (Lindsay, 1973). Shallower soils on average are finer grained, better sorted and more negatively skewed.

To the present time, the writer has analyzed 125 soil samples from the Apollo

15, 16, and 17 sites. Because these samples were all analyzed by the same technique (Lindsay, 1973) the analytical results should be directly comparable. When considered as a whole, the data appear complex and even the simplifying relationships described previously are not readily apparent (Fig. 1). Since several variables must be considered simultaneously in any general model of the soil, the best approach to the problem appears to be to use a multivariate technique to separate the samples into simplifying groups and see if earlier models are upheld.

Cluster analysis is by far the simplest multivariate technique and was found to give the clearest picture. In the present study Euclidean geometry is used; that is, the linear distance between points in four dimensional space is used as a similarity

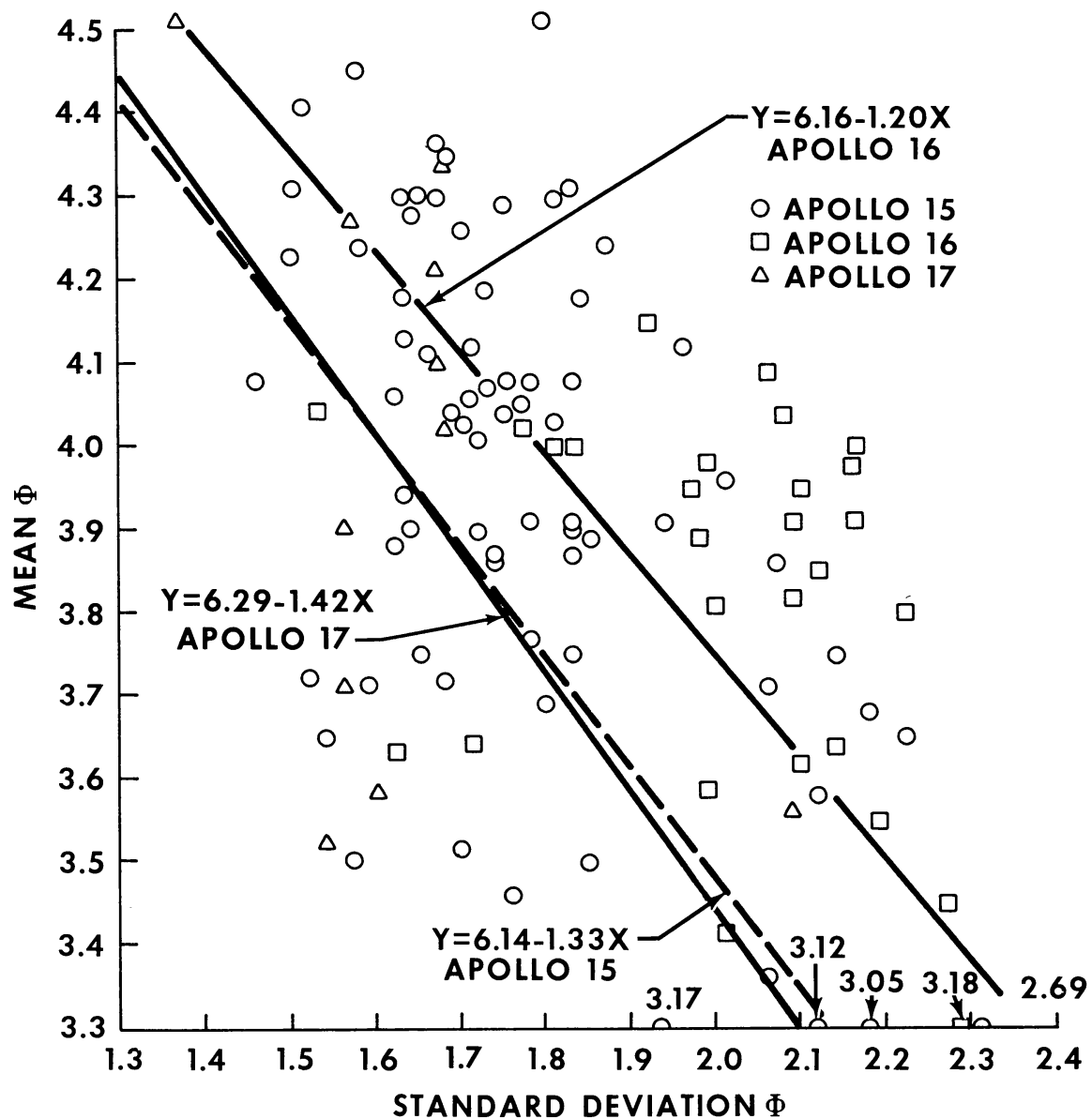


Fig. 1. Mean versus standard deviation for 125 lunar soil samples returned by the Apollo 15, 16, and 17 missions. The correlation coefficients for the three regression lines are all significantly different from zero at the five percent level of confidence or better.

function. The four variables (mean, standard deviation, skewness, and kurtosis) are all similar in magnitude (Folk and Ward, 1957 measures). Consequently, the variables were not normalized, transformed or weighted.

### *Mean and standard deviations*

Cluster analysis produces two clearly defined major groupings including all but seven anomalous samples (Fig. 2). Group I samples on average are coarser grained, more poorly sorted and less skewed than group II samples (Table 1). Group I samples may be broken into two subgroups and group II samples fall into four subgroups. To visualize the significance of the subgroupings the average values of the mean and standard deviations in each group are plotted in Fig. 3. Five of the subgroupings follow a linear pattern similar to that observed on a mission by mission basis, which suggests the possibility that a general model can be established for the evolution of the soil. The sixth subdivision, which contains eight samples, falls to one side of the line.

Lindsay (1972) found that the mean and standard deviation of the lunar soils was controlled largely by the introduction of glass particles in two narrow grain size ranges either side of the mean grain size. In the early stages of textural evolution large rock and mineral fragments will determine the mean and standard deviation to some extent. However, once comminution has broken down these larger particles vitrification and comminution come into balance and the mean and standard deviation are fixed within very narrow limits unless freshly comminuted bedrock is brought to the surface by a large event. On the coarse side of the mean, agglutinates form a prominent mode centered on  $\sim 2.5 \phi$ , whereas angular glass fragments form a mode at  $\sim 6 \phi$  on the fine side of the mean (Lindsay, 1972). Consequently, the mean grain size of the soils is confined to a narrow zone between these two modes and the standard deviation ultimately coincides with them. Thus, a texturally mature lunar soil formed by the normal processes of comminution and vitrification by meteorite impact cannot have a mean grain size

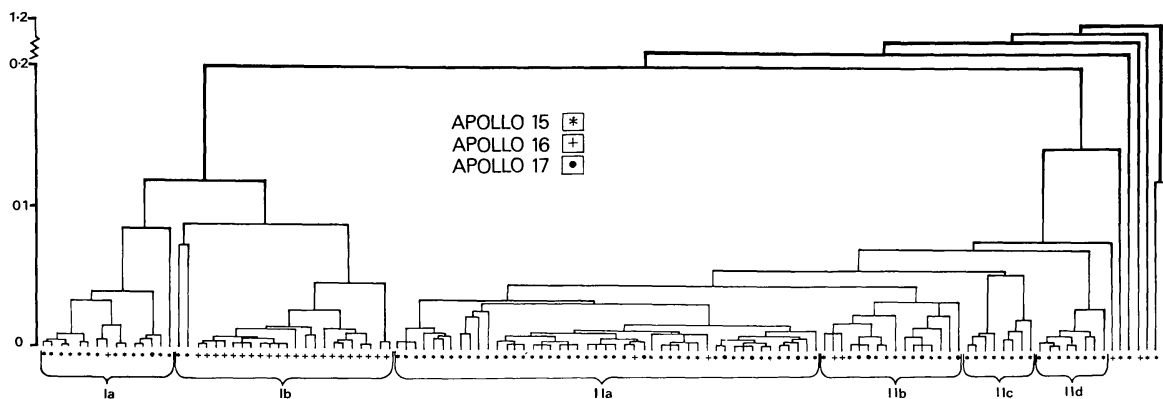


Fig. 2. Cluster analysis dendrogram for 125 samples and four variables (mean, standard deviation, skewness and kurtosis). The units on the y-axis are arbitrary and represent the value of the similarity function (Larger values indicate decreasing similarity). Horizontal tie lines indicate the similarity between samples and groups of samples.

Table 1. Mean value of the four variables for each group and subgroup defined by the cluster analysis.

Group	$N$	$M_z\phi$	$\pm\sigma_r\phi$	$Sk_r$	$K_G$	$M_z\phi$	$\pm\sigma_r\phi$	$Sk_r$	$K_G$
I	a	$3.643 \pm .263$	$2.068 \pm .084$	$-0.363 \pm .042$	$0.957 \pm .114$	$3.699 \pm .324$	$2.097 \pm .098$	$-0.172 \pm .164$	$0.874 \pm .110$
	b	$3.734 \pm .357$	$2.115 \pm .104$	$-0.052 \pm .067$	$0.822 \pm .069$				
II	a	$4.046 \pm .220$	$1.729 \pm .069$	$-0.330 \pm .065$	$0.984 \pm .078$	$4.014 \pm .277$	$1.687 \pm .133$	$-0.276 \pm .107$	$0.987 \pm .084$
	b	$4.113 \pm .303$	$1.531 \pm .055$	$-0.292 \pm .059$	$0.986 \pm .095$				
	c	$3.762 \pm .213$	$1.601 \pm .033$	$-0.106 \pm .045$	$0.970 \pm .125$				
	d	$3.875 \pm .413$	$1.833 \pm .052$	$-0.101 \pm .055$	$1.025 \pm .041$				

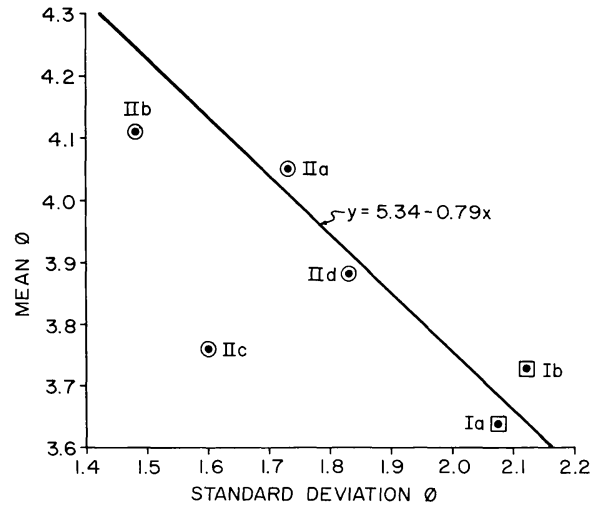


Fig. 3. Mean versus standard deviation for the grand mean values of each subgroup established by cluster analysis. The regression line was determined exclusive of subgroup IIc. The correlation coefficient for the regression line is significantly different from zero at the five percent level of confidence or better.

much finer than  $4.0 \phi$  and the standard deviation cannot be much less than  $\sim 1.5 \phi$ . The actual figures probably depend to some extent on the viscosity of the glass produced by the soil and the strength of the materials forming the soil. Subgroup IIb, which is texturally the most mature subgroup, has a grand mean grain size of  $4.113 \phi$  and a mean standard deviation of  $1.531 \phi$ . Thus, the samples of subgroup IIb can be regarded as texturally mature as further reworking by meteorites will alter their grain size parameters very little. There are rare soils that are finer grained and better sorted than those of subgroup IIb. These anomalous soils, which are discussed in a following section, may be the product of different processes, possibly gaseous sorting (Lindsay, 1974).

Groups I and II are much more sharply defined than are the six subgroups (that is, the value of the similarity function for the group I and II interconnection is large) which may indicate a natural discontinuity in terms of grain size in the sequence of available samples. This suggests that the texturally less mature group I soils are being brought to the surface from considerable depth ( $>2.5$  m) in the soil blanket and are in effect out of sequence. Consequently, they occur interbedded with texturally more mature soils which implies that vertical mixing is sporadic and inefficient.

With such clearly defined subdivisions, terms such as "immature," "submature," and "mature" could be applied (McKay *et al.*, 1974). However, there is evidence that the evolution of the lunar soil is more complex than these subdivisions suggest. All of the lunar soils considered in the multivariate analysis have undergone considerable meteorite reworking and contain high proportions of glass ( $>65\%$ ). Even the texturally least mature of these soils is, in a general sense, relatively highly evolved. That is, a large amount of energy has been expended in its formation.

When grain size data from the Apollo 12 and 14 sites are combined with the

data used in the multivariate analysis, it is found that a small but significant number of samples fall well outside the grain size, range of the more typical soils (Fig. 4). These samples all contain lower than average quantities of glass (Lindsay, 1972) and all are coarser in mean grain size.

One of these coarse grained samples (12028,70) is unique and provides evidence for the early stages in the evolution of the lunar soil. Sample 12028,70 (unit 6 of the double drive tube) consists almost entirely of rock and mineral fragments and only 5% glass (Lindsay, 1971). It contains no agglutinates and appears to be the product of a single impact which penetrated the soil blanket and comminuted the bedrock substrate. Sample 12028,70 has a mean grain size of  $-0.821 \phi$ , a standard deviation of  $1.895 \phi$ , and a skewness of 0.414. This sample is thus much better sorted than would be predicted by extrapolating from the earlier regression model (Fig. 3). It thus seems that the standard deviation of a primitive soil must initially become larger in response to reworking before settling in to the general linear trend described above.

The explanation for this apparent anomaly is simple. The textural maturity of a soil, as defined in the linear model, is determined largely by the production of agglutinates in response to micrometeorite reworking. The importance of agglutinates lies in the fact that they bond together fine-grained material to produce single particles that are larger than the mean grain size of the soil (Duke *et al.*, 1970; Lindsay, 1971, 1972). In the case of primitive soils fine-grained materials, and consequently agglutinates, are in short supply and the mean grain size of the soil is larger than the mean grain size of agglutinates ( $\sim 2.5 \phi$ ). Where the mass of a soil particle is similar in magnitude to the mass of material that can be excavated by a micrometeorite impact, the soil particle will be shattered and molten glass formed by the impact will be dissipated as a fine spray. Consequently, it is unlikely that agglutinates would form in soils with mean grain sizes coarser than the mean agglutinate size. From this it can be concluded that, where the mean grain size of a soil exceeds the mean grain size of agglutinates, agglutination will be progressively less effective and comminution will largely determine the grain size parameters of the soil.

When loose particulate materials, such as the lunar soil, are subject to repetitive fracture the grain size distribution asymptotically approaches a log-normal form (Kolmogoroff, 1941; Halmos, 1944; Epstein, 1947): the mean grain size of the soil decreases, the standard deviation becomes larger, the skewness declines to zero, and the kurtosis moves to 1.0. This process will continue until the mean grain size of the soil approaches  $2.5 \phi$  and fines are sufficiently abundant for agglutination to be effective. Agglutination will then gradually truncate the fine end of the distribution and move more of the mass of the soil closer to the mean grain size, thus reducing the standard deviation. The evolving soil then will conform gradually to the linear relationship which is most obvious at the present time (Fig. 3).

Figure 4 shows the approximate position of the full evolutionary path which has an overall horseshoe-shape with a reversal of slope in the region where agglutination (and vitrification in general) begins to dominate or balance comminu-

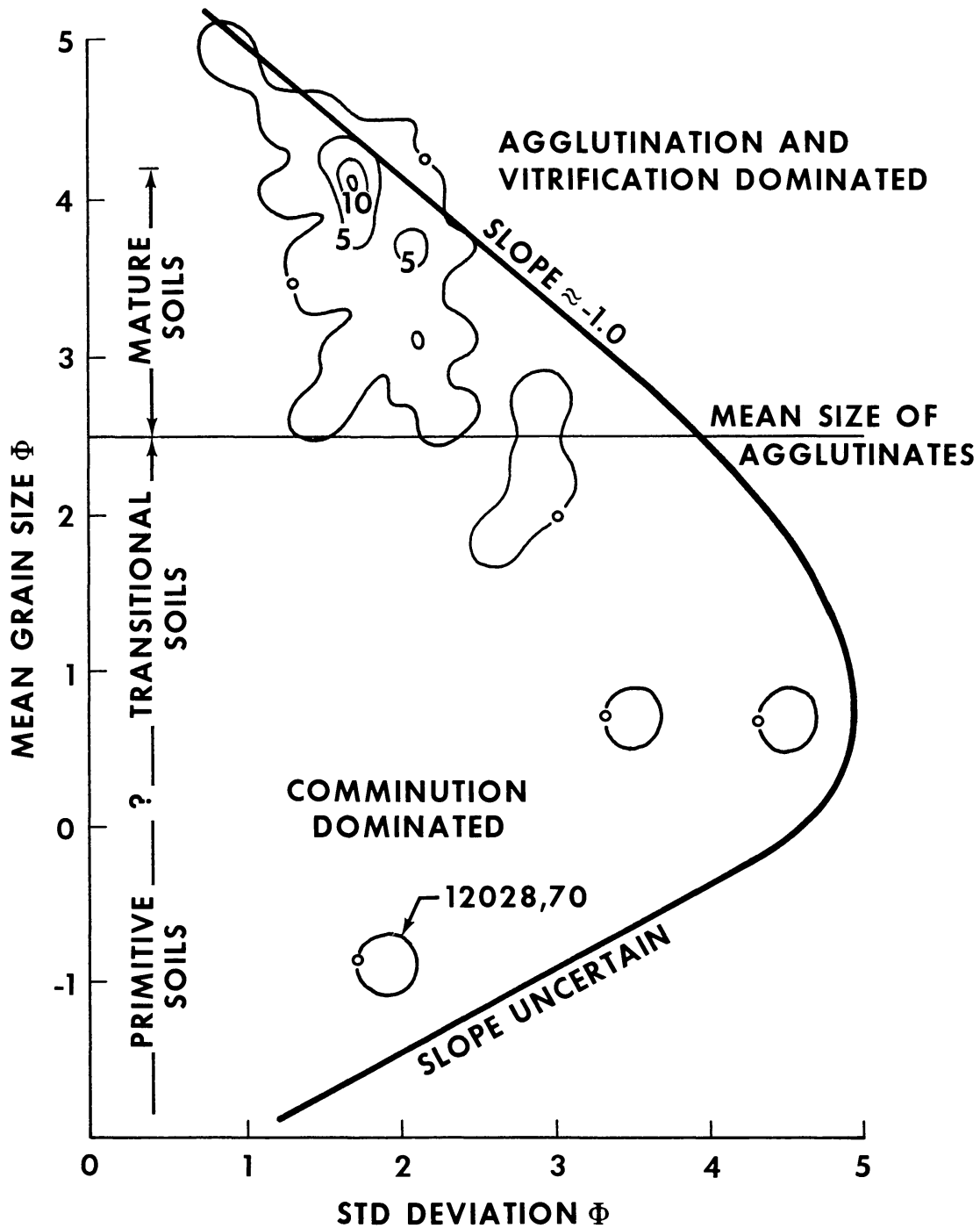


Fig. 4. Suggested evolutionary path for the mean and standard deviation of lunar soils. Primitive soils with mean grain sizes less than  $2.5 \phi$  (the average agglutinate size) are dominated by the effects of comminution and their standard deviations increased with time. Mature soils have mean grain sizes less than the average agglutinate size and are dominated by glass production, particularly agglutinate formation. Their standard deviations decrease with time. Mixed soils with intermediate textural maturities occur along curved paths inside the horseshoe of the evolutionary path. Contours show density in percent of soil samples per  $0.5 \phi$  square. Note that most soils concentrate above the line indicating mean agglutinate size. Also note the high concentration of data points close to a mean grain size of  $4.1 \phi$ . Samples contoured come from Apollo missions 12, 14, 15, 16, and 17.

tion. The curvature of the evolutionary path will depend on the grain size distribution of the freshly crushed bedrock which is in turn determined by the energetics of the meteorite flux. The portion of the lower comminution dominated section of the ideal evolutionary path thus is not known with certainty. However, since Fig. 4 is a log-log plot, the comminution-dominated segment of the curve should be a straight line with a positive slope. The agglutination dominated segment of the ideal evolutionary path is probably also linear as suggested by the regression models. The slope of this segment probably will be similar to the regression models which is close to  $-1.0$ . Between the two linear segments of the curve will be a transition region the width of which can only be estimated from Fig. 4. However, the transitional region cannot extend above the line marking the mean agglutinate size ( $\sim 2.5 \phi$ ).

Figure 4 offers a very direct explanation for the anomalous position of subgroup IIc in relation to the mean and standard deviation of the other subgroups (Fig. 3). Ideally, as a soil evolves texturally it would follow the horseshoe-shaped curve depicted in Fig. 4. However, the soil is continually being mixed such that soils with intermediate grain size characteristics are continually being formed. Thus, in a texturally mature soil blanket such as was sampled at all of the Apollo sites, it is possible to have mixed soils with means and standard deviations lying inside the horseshoe outlined in Fig. 4. The mixtures are presumably formed when larger meteorites excavate material from deep in the soil blanket or penetrate the soil and comminute bedrock. As the soil blanket increases in thickness, the probability that it will be penetrated by an impact declines such that mixed soils are dominated more and more by the texturally mature component. That is, most of the mixed soils will have a mean grain size finer than the  $2.5 \phi$  agglutinate size. Subgroup IIc thus includes mixed soils lying within the horseshoe.

It may appear that soils of intermediate textural maturity could be obtained by mixing varied proportions of soils with grain size parameters lying either side of the mixed soil (McKay *et al.*, 1974). However, this holds true only on straight line segments of the evolutionary path. Mixtures will have intermediate characteristics which lie along a curve joining the two end-members of the evolutionary path. On a straight line segment the mixing curve and the evolutionary path coincide but where the mixing curve crosses between the agglutination- and comminution-dominated zones the mixed soils will lie well off the ideal evolutionary path. The degree of curvature of the mixing curve will be controlled by the standard deviation of the mixture which in turn is determined largely by the distance between the mean grain size of the end-members. This accounts for the broad scatter of points about the regression lines in Fig. 1. Most, if not all, soils are mixtures. The mixing picture is even more complex when skewness is considered.

### Skewness

Skewness measures the asymmetry of the grain size curve. In the case of the lunar soils, the asymmetry appears to be determined in large part by the introduction of agglutinates on the coarse side of the mean grain size. This

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suggests that as the soil matures texturally, the grain size distribution should become more negatively skewed (Lindsay, 1971). Samples from the Apollo 15 drill core conform to this pattern (Lindsay, 1973). However, skewness is not as strongly related to the mean grain size as is the standard deviation which implies that additional variables may be operating on skewness.

Subgroups Ia and Ib essentially differentiate Apollo 15 and 16 samples. These two subgroups have very similar mean and standard deviations and differ mainly in that subgroup Ib, which consists largely of Apollo 16 deep core samples, has a skewness close to zero as compared to the large negative skewness for subgroup Ia (Table 1). This suggests that while a general model may be established for mean and standard deviation, there are some local variations in the soil which affect skewness. The deep core samples all appear to be mixtures of normal texturally mature lunar soil and a well-sorted layer (60001,10) that may be ray material (Lindsay, 1973). Sample 60001,10 has a skewness close to zero with the result that the overlying mixed soils all have more symmetrical distributions than would be expected.

Variations of skewness within subgroup II provide some indication of the complexity of the mixing problem. Here the sequence of increasing textural maturity according to mean and standard deviation is IId, IIa, IIb. However, from Table 1 the subgroups become more negatively skewed in the sequence IId, IIb, IIa. If the evolving soil were simply migrating along the agglutination-dominated zone, then the processes of reworking and mixing would produce a simple relationship between mean, standard deviation, and skewness. To some extent, the simple relationship was observed in the Apollo 15 deep core. As the soil matures, agglutinates are added and the size distribution becomes more negatively skewed. However, as discussed, mixing is not that simple. The end-members producing the mixture may come from any point along the evolutionary curve of Fig. 4 and there may be just two end-members or a large number. If the progress of an ideal maturing soil is followed along the evolutionary path, skewness would first begin to approach zero as the soil progressed along the comminution-dominated zone and then begin to become negatively skewed as it entered the agglutination-dominated zone. A texturally mature soil mixed with a less mature soil from the agglutination-dominated zone and with a soil from the comminution-dominated zone could produce soils with similar mean grain sizes but with completely different skewness values. The mixture containing the soil from the agglutination-dominated zone would have an intermediate skewness in keeping with the linear trend of this section of the curve. The mixture containing the soil from comminution-dominated zone would have a skewness much closer to zero. Skewness thus offers considerable information about the mixing of the soils. Fine-grained soils with large negative skewness values result from mixing soils from within the agglutination-dominated zone only. Fine-grained soils with skewness values lying closer to zero are mixtures of soil from the comminution- and agglutination-dominated zone. Consequently, a simple relationship could not be expected between the mean grain size and the skewness or between the standard deviation and skewness. Instead, skewness must be a complex function of both mean and standard deviation.

### *The kurtosis anomaly*

It has not been possible to find a relationship between kurtosis and any other variable at any of the Apollo sites (Lindsay, 1973). The multivariate model does not help to clarify the picture. Group II samples have a slightly higher kurtosis than group I samples. Except for subgroup IID, all subgroups are platykurtic. However, no consistent relationship could be established between kurtosis and the other variables. This suggests that kurtosis may be independent of the processes which determine the other grain size parameters. It may be that kurtosis is not controlled directly by meteorite impact. The effects of sample handling are also difficult to evaluate.

Kurtosis essentially compares the sorting of the tails of the grain size distribution to the sorting of the central portion of the curve. The coarse tail of the grain size distribution consists almost entirely of rock and mineral fragments. Consequently, the sorting of the coarse tail is controlled by comminution and is relatively constant. Further, any variation in the sorting of the coarse tail should relate to the textural maturity of the soil by way of the mean and standard deviation. Sorting of the coarse tail is always very similar to the sorting of the center of the distribution. The fine tail of the soil consists largely of angular mineral fragments and at first thought could be expected to relate to the effects of comminution. However, the sorting of the fine tail is far from constant. Generally, the sorting increases sharply in grain sizes finer than  $3.5\text{--}5.5\phi$ . Butler and King (1974) have suggested that this change in sorting is an artifact due to the changing of analytical techniques from sieving to particle counting. However, this change in technique occurs at  $4.5\phi$ , whereas the change in sorting may occur at up to  $1\phi$  either side of this point. In some samples there is no change in sorting at all. Further, the same changes in sorting of the fine tail are recognizable in samples analyzed entirely by sieving (e.g. Butler *et al.*, 1973, Fig. 1).

Since the sorting of the coarse fraction is relatively constant, the kurtosis of lunar soil is determined almost entirely by the fine fraction of the lunar soil. If a normal curve with the same mean and standard deviation as the lunar soil is subtracted from the grain size distribution of the lunar soil, a fine-grained residual remains. When recalculated, the grain size distribution of the residual has some unusual properties. Regardless of the mean and standard deviation of the soil sample being considered, the fine residuals have a mean grain size and a standard deviation of their own which falls within a very narrow range. The mean ranges from approximately  $6.1\text{--}6.5\phi$  ( $11\text{--}15\mu\text{m}$ ). In contrast to the lunar soil, the fine residual may be moderately sorted and always falls within the range from  $\sigma_I = 0.88\phi$  to  $\sigma_I = 1.05\phi$ . The size distribution of the fine fraction is always close to symmetric and platykurtic. In short, the fine fraction must be produced by a single very uniform process otherwise its size distribution would not be so constant.

Evensen *et al.* (1974) have investigated the nature of what they call the "exotic component" of the lunar soil. The exotic component is necessary to account for differences in trace element and isotope chemistry between the soil and its

substrate. Evensen *et al.* (1974) found that the exotic component, which is compositionally similar to KREEP, progressively increases in the finer fractions of the soil. In particular, they associated the exotic component with plagioclase in the fine fraction and suggested that it was derived from some distant source possibly in the vicinity of the Imbrium Basin.

The combination of the grain size data and the chemical data presented by Evensen *et al.* (1974) suggest that considerable masses of fine-grained material are being transported over large distances on the lunar surface by some process other than meteorite impact. There is no doubt that meteorite impact is capable of moving material in stages almost anywhere on the lunar surface. An exotic component moved in this way would gradually be reduced in size by comminution as it moved further from the source. However, the effects of agglutination and vitrification in general are such that fine materials are gradually incorporated into larger particle (agglutinates) close to the mean grain size. Consequently, the exotic component could be expected to occur in similar proportions in the fine fraction and in the vitric fraction close to the mean. This suggests that the process transporting the fines is relatively independent of agglutination process and thus may not be related to impact.

An alternative transport mechanism must be capable of transporting large volumes (up to 10% of the soil mass) of fine materials over long distances. The only possible mechanism thus far proposed is electrostatic transport (Gold, 1955; Heffner, 1965; Singer and Walker, 1962; Criswell, 1972, 1973). Criswell (1972, 1973) suggests that electrostatic transport could move  $10\ \mu\text{m}$  (diameter) and smaller particles between dark and light areas in active zones of the lunar terminator at a rate of  $10^{-3}\ \text{g cm}^{-2}\ \text{yr}^{-1}$ . The rate of movement is far in excess of the mean accumulation rate of the soil by meteoritic processes ( $\sim 10^{-7}\ \text{g cm}^{-2}\ \text{yr}^{-1}$ ) and the grain size indicated by Criswell (1972, 1973) is very similar to the mean grain size of the fine residual.

### *Pyroclastic materials*

There is little solid evidence to suggest that volcanism has played a major role in the development of the lunar soil. However, the possibility should not be overlooked in that reworking of the soil since the cessation of volcanism may have masked the presence of a significant pyroclastic contribution. For example, Carter and Padovani (1973) conclude that glass spheres with a basaltic composition from Apollo 16 soils are volcanic in origin. McKay *et al.* (1973) reached a similar conclusion for Apollo 15 green glass spheres. Pyroclastic particles may have formed a significant contribution to the lunar soil in the immediate post-mare flooding phase of soil development.

Reid and Lofgren (1973) have concluded that the Apollo 17 orange soil from near Shorty Crater (74220) is volcanic in origin and has erupted in lava fountains along the margins of the mare basins. The orange soil (74220) has a mean grain size of  $4.506\ \phi$ , a standard deviation of  $1.387\ \phi$ , skewness of  $-0.223$  and a kurtosis of  $0.993$ . The grain size parameters are thus little different from a mature soil and in

fact the sample clusters with subgroup IIb. This implies that in the case of a texturally mature soil, the introduction of late stage pyroclastic materials would have little effect on their grain size parameters. Pyroclastic material similar to the orange soil would significantly change the grain size parameters of primitive soils. However, with time as the textural maturity increased due to reworking, the effect would not be recognizable.

Addition of pyroclastic material to the lunar soil is most likely to be effective if it significantly increases the thickness of the soil layer and shields the bedrock from larger meteorites. In this way, the growth of the soil blanket would be slowed and more of the kinetic energy of the impacting meteorites would be directed to reworking the soil. A pyroclastic contribution to the lunar soil would also anomalously increase its mineralogic maturity.

#### *Other processes and variables*

The multivariate model for the textural evolution of the soil readily accounts for general trends observed in the lunar soil. However, the seven samples which are not included in the two major groups require at least some explanation. The anomalous soils fall into two groups which are not accounted for by the multivariate model. The soils are either fine grained and better sorted than average or coarser grained than average and within the normal range for sorting. The fine-grained better sorted soils may be the product of (1) gaseous sorting most probably in a base surge (Lindsay, 1973). This produces normally graded beds. (2) Grain flow which may result either from meteorite impact or thermally induced slumps. This mechanism tends to produce reverse graded beds. The possible effects of base surge and grain flow on the sorting of the soils are discussed in more detail elsewhere (Lindsay, 1974).

Typical of the coarse-grained soils from the anomalous group is sample 67711, which comes from the rim of North Ray Crater. This sample has a mean grain size of  $2.720 \phi$  and a standard deviation of  $2.850 \phi$ . These coarse-grained soils all fall close to the comminution dominated zone and their means scatter around the agglutinate value ( $\sim 2.5 \phi$ ) (Fig. 4). That is, they are primitive soils with only small admixtures of more mature soil. Because most of the soils sampled by the Apollo missions are very mature in both textural and mineralogic terms, most of the truly primitive soils occur as mixtures falling between the two extremes—thus the reason for subgroup IIc which falls between the textural zones dominated by comminution on the one hand and vitrification on the other.

#### MATURITY RECONSIDERED

In the light of the model established for the evolution of textural maturity, it is necessary to reevaluate the relationship between textural and mineralogical maturity. Two lines of evidence lead to some understanding of the complexity of this relationship. First, it is obvious that the total glass content of the lunar soil must continually increase with time as meteorites continually rework the soil. At

first thought, it could be argued that continued application of energy to the soil would likewise increase the textural maturity of the soil along with mineralogic maturity (Lindsay, 1972). Returning to the ideal evolutionary path outlined in Fig. 4, it can be seen that the interpretation is partly correct. A soil migrating along the comminution-dominated segment of the soil evolves in direct response to energy applied. The glass content of the soil must increase as the grain size of the soil decreases and the standard deviation increases. Since agglutination is ineffective along this segment of the curve, it can have no effect on textural maturity. Why then is it not possible to say the same about the agglutination dominated zone? As energy is applied, the agglutinate content increases and the textural maturity and mineralogic maturity of the soil should both increase.

This brings us to the second line of evidence. For a soil to move the full length of the idealized evolutionary path a time period of the order of  $10^9$  yr (the age of the substrate) is available. McKay *et al.* (1972) suggest that agglutinate content of the soil is a direct function of the exposure age of the soil. It thus appears that agglutinates form at the lunar surface in response to micrometeorite reworking. Arrhenius *et al.* (1971), upon whose data McKay *et al.* (1972) base their conclusions, places the exposure ages of the soils studied at  $10^8$  yr or less. If textural evolution is a unidirectional irreversible process, this implies that an evolving soil migrates along the whole of the agglutination-dominated segment of the curve in  $10^8$  yr or possibly less. The fact that so few primitive soils from the comminution-dominated zone were sampled suggests that progress along this portion of the evolutionary path was also relatively rapid when compared to  $10^9$  yr. Since progress along the comminution-dominated zone is unidirectional (ignoring the mixing process), some process must be operating in the agglutination-dominated zone which causes the soil to recycle backward and forward along this segment of the curve in time periods of the order of  $10^8$  yr.

The process involved in recycling is simple to understand. Agglutinates are extremely fragile, low-density particles which are readily destroyed by crushing. The exposure ages given by Arrhenius *et al.* (1971) are effectively the exposure ages of the individual layers of soil. If it is assumed that each layer represents a single depositional event (that is, a single ejecta blanket), it could be argued that each time a soil layer is formed the fragile agglutinates are destroyed by crushing. Since agglutinates are so abundant in the soil and the grain size parameters are sensitive to their presence, the textural maturity of the soil would be modified. Mean grain size would thus be reduced and standard deviation increased. In conjunction with continuous mixing with texturally less mature soils, the soils would appear to fluctuate backward and forward within a narrow area along the agglutination-dominated zone. This model readily explains the high concentration of data points toward the top of Fig. 4.

Thus in the early stages of soil development, textural and mineralogic maturity could be expected to increase in a direct relationship. However, once soils cross the transitional region into the agglutination-dominated zone, mineralogic maturity will continue to increase while textural maturity cycles backward and forward in response to larger layer-forming impact events. Since most of the soils sampled

by the Apollo missions are texturally mature the clustering of data points encountered when Lindsay (1972) plotted grain size parameter as a function of mineralogic maturity is predictable.

#### CONCLUSIONS

(1) The mean grain size and standard deviation of the lunar soil can be used as general indicators of the textural maturity of the soil anywhere on the lunar surface.

(2) The textural maturity of the lunar soil evolves in two well-defined stages: (a) The primitive or comminution-dominated stage where the mean grain size gradually decreases as the standard deviation increases. This stage is terminated when the mean grain size approaches the mean size of agglutinates ( $\sim 2.5 \phi$ ). (b) The mature or agglutination-dominated stage where the mean grain size continues to decrease but the standard deviation decreases also as glass particles form in two narrow size ranges either side of the mean.

(3) The ultimate mean and standard deviation of mature lunar soils are limited to approximately 4.0 and 1.5  $\phi$ , respectively. This results from glass particles being formed in two narrow size ranges lying either side of the mean.

(4) Mixed soils may occur with grain size parameters lying inside a crescent formed by the horseshoe-shaped curve followed by the ideal maturing soil and a mixing curve linking the extreme ends of the ideal curve. In thick soil blankets the mixtures tend to be dominated by the texturally mature component.

(5) In the early stages of soil development, mineralogic and textural maturity increased in unison. In the later stages of soil development when agglutination becomes effective, textural maturity cycles backward and forward in periods of the order of  $10^8$  yr while mineralogic maturity continues to increase.

(6) Pyroclastic contributions similar to the orange soil from the Apollo 17 site (74220) would have minimal effect on the textural maturity of a mature soil blanket. They would, however, significantly affect the textural maturity of a primitive soil particularly when the contribution is large enough to retard penetration of the soil blanket by larger meteorites. The mineralogic maturity would be increased anomalously.

(7) Transportation by base surge or grain flow may produce soils that are finer grained and better sorted than the ultimate mature soils. These soils are in small numbers and should not significantly modify the overall textural maturity of the soil blanket.

(8) Skewness is complexly related to mean grain size and standard deviation. The relationship is determined by mixing of soils from the comminution and agglutination-dominated zones.

(9) Kurtosis cannot be related to any other soil parameter which suggests that it may be determined by a process independent of the meteorite flux. The only transport mechanism yet suggested that fulfills the requirements of moving large volumes of fine-grained materials long distances is electrostatic transport.

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