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Evolution of lunar soil grain-size and shape parameters

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Abstract—Despite an age difference of possibly as much as 0.4×10^9 yr between substrates at the Apollo 15 and 16 sites the average properties of the soils from the two sites are very similar. The soils have essentially the same graphic mean, graphic standard deviation and graphic skewness. However, the graphic kurtosis of the Apollo 16 soils is slightly but significantly smaller than that of the Apollo 15 soils.

At the Apollo 15 site deeper soil samples are coarser grained, more poorly sorted and more negatively skewed. Kurtosis cannot be interpreted simply in terms of depth below the lunar surface. These trends are consistent with earlier models for an evolutionary sequence. The variations about the mean values for each parameter and the presence of apparently mature soils at depths of up to 2 m in the core suggest that reworking and mixing of the soil is considerable.

At the Apollo 16 site the trend is reversed and grain size and graphic standard deviation both decrease deeper in the soil layer. Simple relationships are not apparent for skewness and kurtosis. The reason for the reversal in trend appears to be the presence of a very-fine-grained well-sorted layer sampled by core segment 60001. Vertical mixing of this soil has produced a sequence of layers that gradually change upward away from the source.

Soil from the bottom of core segment 60001 at the Apollo 16 site is light in color and has unusual grain-size parameters, which suggest that it was sorted during transport in a gaseous medium and may be ray material.

The shape parameters of the Apollo 15 soil particles are determined largely by the glass content and thus the maturity of the soil. The particles with reduced sphericities are concentrated in two narrow zones approximately one standard deviation either side of the mean grain size of the soils.

INTRODUCTION

THE STRATIGRAPHY of the few meters of soil exposed on the lunar surface provides a long record of lunar history. Deep cores returned by the Apollo 15 and 16 missions provide the first extensive sampling of this stratigraphy. The core strings containing the deep cores each consist of six stem segments, which allow a maximum penetration of approximately 242 cm. In the present study, the results of grain size and shape analyses are presented for samples from the Apollo 15 and 16 cores.

GRAIN SIZE

Two methods were combined to determine the grain size distributions. Size fractions larger than 4.5 ϕ (45 μm) were determined by sieving at 0.5 ϕ sieve size intervals. Initially the samples were dry sieved by shaking and then by gently brushing of the sieves finer than 3 ϕ (125 μm). The fines, which had collected in the pan, were weighed and in contrast to previous studies (Lindsay, 1971, 1972), the sieves were washed with double distilled Freon TF. After drying the sieves were shaken again and the residue weighed. The material finer than 4.5 ϕ was analyzed using a Millipore πMC particle measurement computer system. Grain size determined by this method is based on the maximum projected chord rather than on the intermediate dimension of grains as in sieving. Consequently, to make the two methods comparable a correction based on the two dimensional sphericity of the particles is necessary (Fig. 1). The graphic statistical parameters used throughout are those of Folk and Ward (1957).

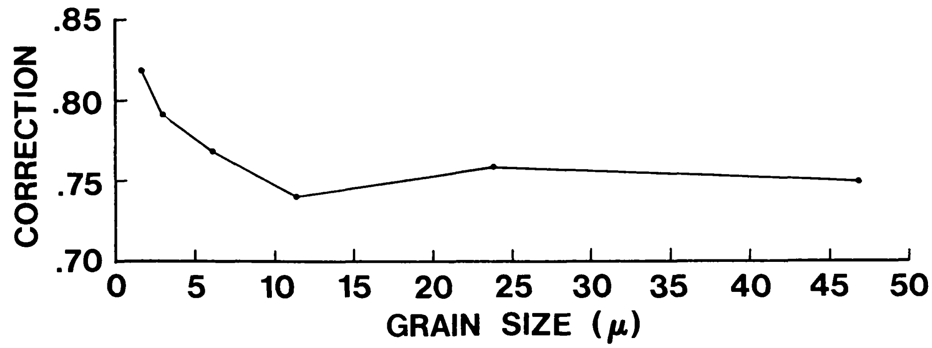

Fig. 1. Plot for correcting grain size determined from maximum chord data to sieve size equivalent.

Apollo 15

The Apollo 15 deep drill core was taken on the gently undulating but relatively densely cratered mare surface approximately 5 km from the base of the Apennine Front. The soil was thus formed on a basaltic substrate similar to the Apollo 11 and 12 sites but soils derived from the highlands may be mixed with the more typical mare soil. The basaltic substrate has an age of 3.3×10^9 yr (Wasserburg and Papanastassiou, 1971; Compston *et al.*, 1972; Murthy *et al.*, 1971); presumably the soil has had this length of time to evolve.

The drill intersected 42 major morphologic units and a larger number of subunits which range from less than 0.5 cm to almost 20 cm in thickness (Heiken *et al.*, 1972). The samples analyzed all come from the lower three stem sections (samples 15001, 15002, and 15003), that is, from depths of between 120 and 242 cm below the lunar surface. The graphic mean grain size of the soil ranges from 2.689 to 4.445 ϕ with a grand mean of 4.019 ± 0.334 ϕ (Fig. 2). In terms of deviations from the grand mean grain size, there are three broad zones in the lower three core tubes (Fig. 3). The soil in the lowermost zone from depths of 198–242 cm are all coarser than the grand mean. The middle zone from 167–198 cm is characterized by apparently random changes from negative to positive deviations from one morphologic unit to the next. Finally, the third zone from 124–167 cm is characterized by soils that all are finer than the grand mean grain size. The three zones appear to represent a transition from coarse-grained less-mature soil at the base of the core through a mixed zone with alternating units of coarse- and fine-grained soil to fine-grained mature soil in the upper zone of sample 15003.

The graphic standard deviation or sorting of the samples ranges from 1.460 to

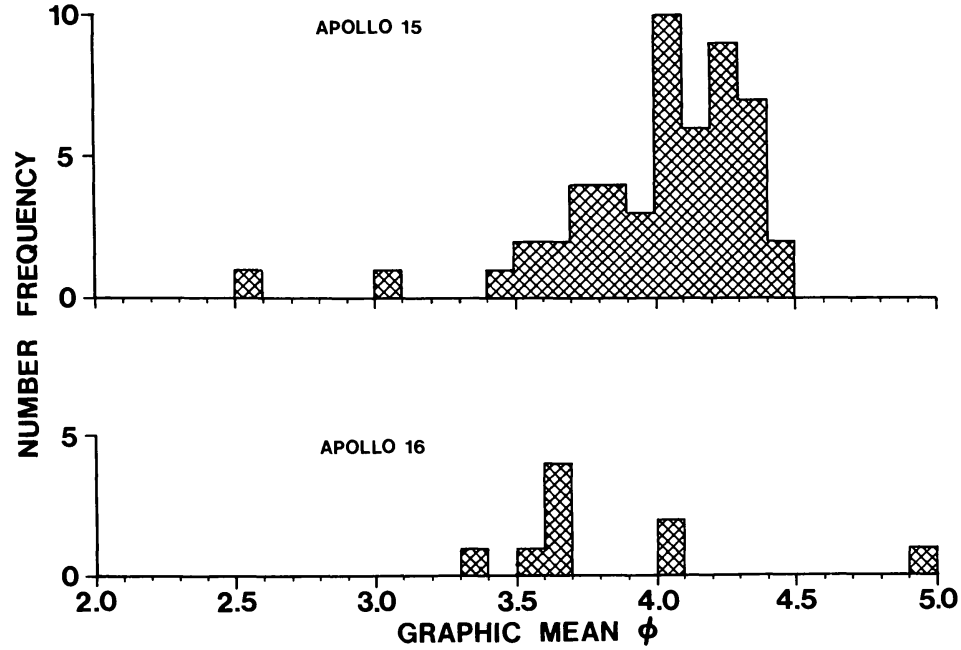

Fig. 2. Frequency distribution of the graphic mean grain size of Apollo 15 and Apollo 16 deep core samples.

2.310 ϕ with a mean value of 1.780 ± 0.213 ϕ. There is a strong linear relationship between the graphic mean and graphic standard deviation ($\rho = 0.765$, $t_{0.05} = 2.000 < 8.401$, $d.f. = 50$) indicating that finer-grained soils are better sorted (Fig. 4). Consequently the same three zones are visible in the sorting curve (Fig. 3) as in the graphic-mean-grain-size curve; the lower segment of the core being more poorly sorted than the mean, the middle segment erratic and the upper segment being better sorted than the mean.

All of the samples studied are coarse skewed. The graphic skewness ranges from −0.505 to −0.047 with a mean of −0.333 ± 0.074. Variations of skewness along the length of the core are more irregular than the variations of mean or sorting, however, the same three zones are present but poorly defined (Fig. 3). In general, deeper samples are more negatively skewed than samples further up the core.

Graphic kurtosis ranges from 0.843 to 1.187 with a mean of 0.954 ± 0.099. Variations in graphic kurtosis are relatively random although the values show a weak tendency to become larger higher in the core (Fig. 3).

It is concluded that, at the Apollo 15 site, deeper soil samples become coarser grained, more poorly sorted and more negatively skewed. Kurtosis cannot be interpreted simply in terms of depth below the lunar surface. It is difficult to say whether these trends can be interpreted directly as evidence of an evolutionary sequence without further samples from the upper three core segments. However, the trends are consistent with the earlier models proposed by the author for an evolutionary sequence (Lindsay, 1971, 1972). The minor deviations about the mean parameters generally coincide with morphologic units—commonly at the boundary between two units. This indicates that each morphologic unit was

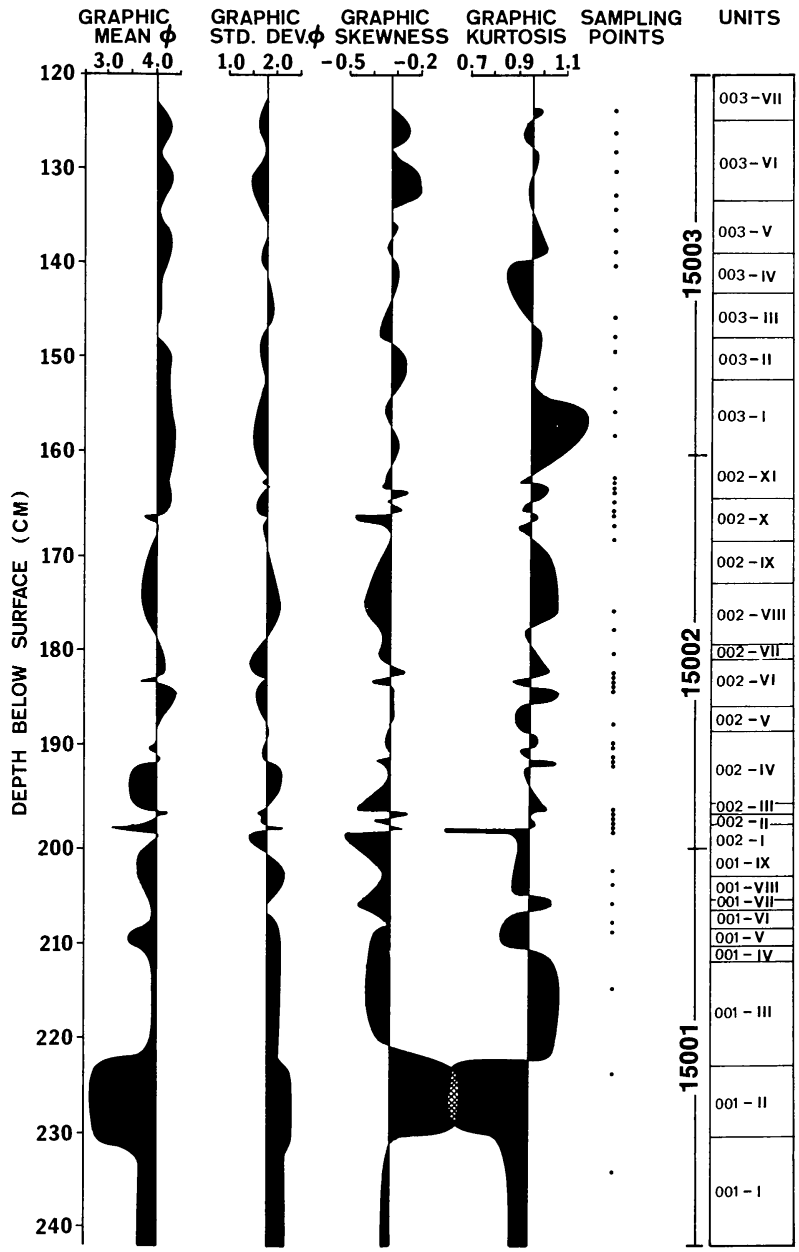

Fig. 3. Grain size parameters for Apollo 15 deep core as a function of depth below surface. Black areas indicate deviations about mean values.

deposited independently and probably represents ejecta from a single impact event. The variations about the mean values for each parameter and the presence of apparently mature soils at depths of up to 2 m in the core suggest that reworking and mixing of the soil is considerable. There is a general tendency for deviations about the grand mean grain-size and the sorting to become less pronounced in core segment 15003. If the same trend continues upward to the surface it would be stronger evidence for an evolutionary sequence. Alternatively, the coarse material in core segment 15001 may simply represent ejecta from a nearby crater which penetrated to bedrock.

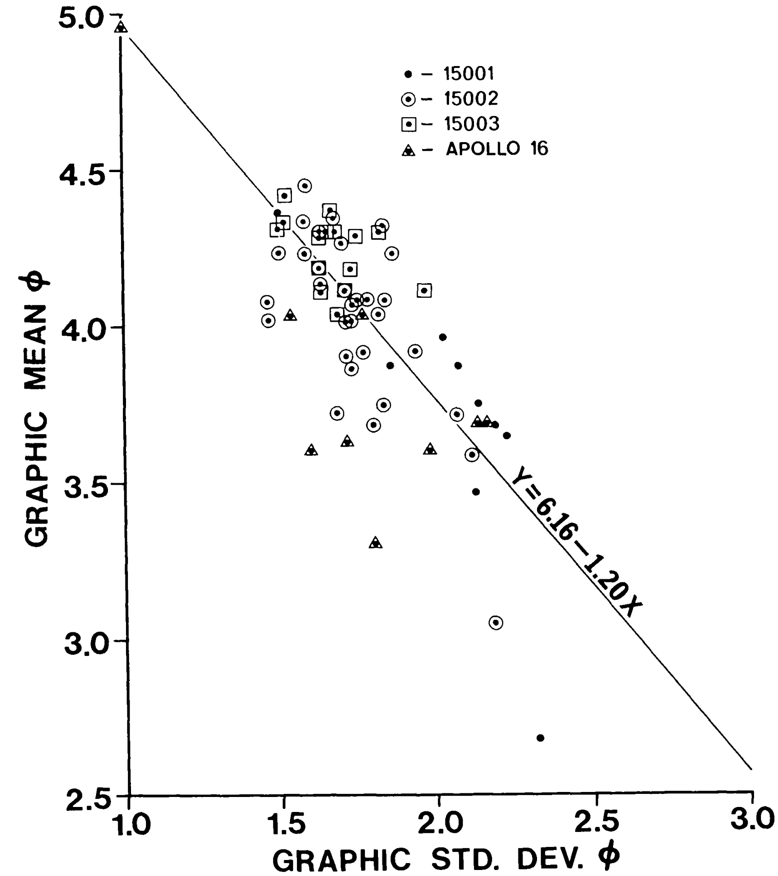

Fig. 4. Graphic mean grain size as a function of graphic standard deviation. The Apollo 16 data are not considered in the regression line.

Apollo 16

The Apollo 16 deep core sampling locality lies at the foot of the Descartes Mountains between North Ray and South Ray craters on the undulating Cayley plains, which overlie the Cayley Formation (Apollo Lunar Geology Investigation Team, 1972). Rays with a high albedo extend from both North Ray and South Ray craters towards the sampling locality. At the sampling locality the rays are not clearly defined and appear to be modified by lower albedo soils than overlie them. The Cayley Formation consists of breccias that appear to be the product of a large scale impact event. This is consistent with Eggleton and Marshall's (1962) interpretation that the Cayley Formation is a facies of Imbrium Basin ejects, thus the Apollo 16 soil may have had as much as 0.4 billion years longer to develop than the Apollo 15 soil.

Seven of the nine samples studied from the Apollo 16 site come from the ends of the six core stem segments. The remaining two samples are surface samples from the vicinity of the coring site close to ALSEP.

The graphic mean grain size of the samples ranges from 3.314 to 4.969 ϕ with a grand mean of 3.840 ± 0.478 ϕ (Fig. 2). Comparison with the Apollo 15 site shows no significant difference between the graphic mean grain size at the two sites

($t_{0.05} = 2.000 > 1.326$, $d.f. = 59$). Overall, the grain size of the soil decreases with depth (Fig. 5).

The graphic standard deviation ranges from 0.990 to 2.166 ϕ with a mean of 1.747 ± 0.359 ϕ. The samples on the whole have the same graphic standard deviation as the Apollo 15 soils ($t_{0.05} = 2.000 > 0.023$, $d.f. = 59$). Except for sample

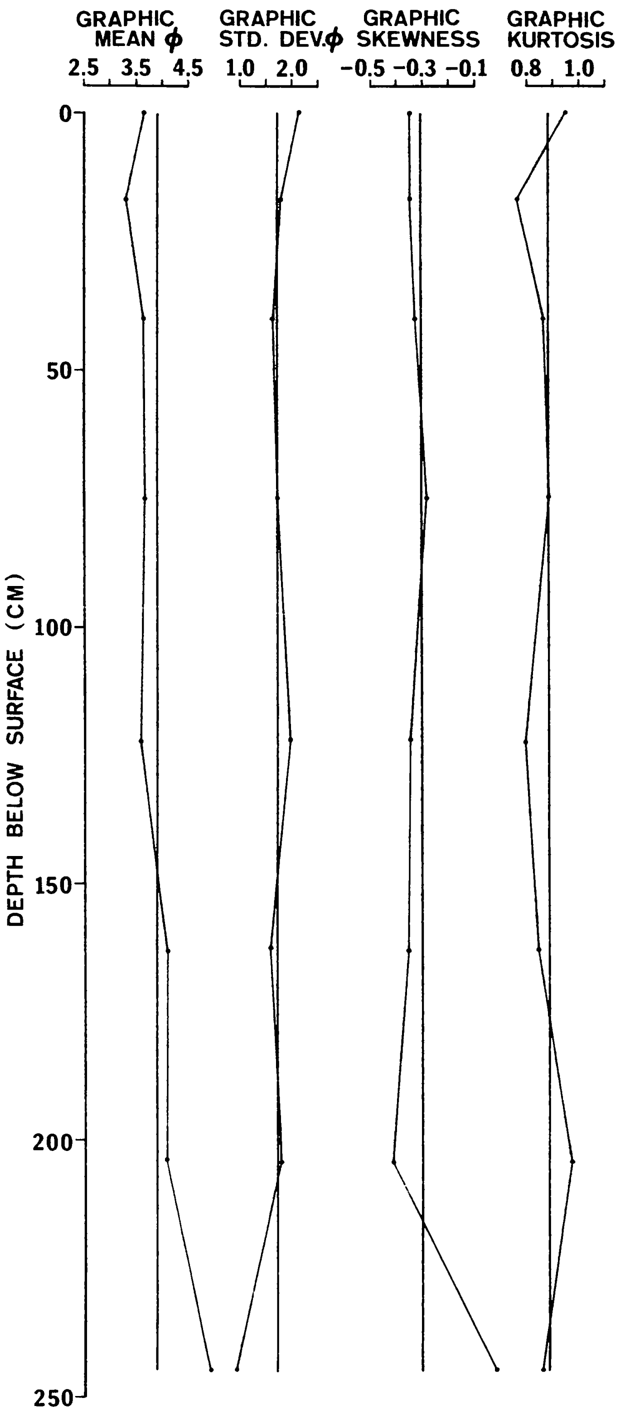

Fig. 5. Grain size parameter for Apollo 16 deep core samples as a function of depth below surface.

60001,10 at the base of the core the graphic standard deviation of the samples deviates very little from the mean value (Fig. 5). In general, deeper soils are better sorted. The same linear relationship appears to exist between the graphic mean and graphic standard deviation for the Apollo 15 soils (Fig. 4).

As for the Apollo 15 core samples all of the Apollo 16 samples are negatively skewed. Graphic skewness values range from -0.417 to -0.030 with a mean value of -0.310 ± -0.110. The Apollo 16 soils are skewed to the same degree as the Apollo 15 soils ($t_{0.05} = 2.000 > 0.773$, *d.f.* = 59). Except for sample 60001,10 at the base of the core the samples from the top and bottom of the core are more negatively skewed than those from the middle of the core (Fig. 5).

The graphic kurtosis of the samples ranges from 0.763 to 0.991 with a mean of 0.879 ± 0.079. A t-test of the means suggests that different populations were sampled at the Apollo 15 and 16 sites ($t_{0.05} = 2.000 < 2.061$, *d.f.* = 59). That is, the graphic kurtosis of Apollo 16 soils is lower than that of the Apollo 16 soils.

Sample 60001,10 from the bottom of the core (Fig. 5) is much lighter in color than any of the other samples and has by far the smallest mean grain size of any soil examined (4.969 ϕ). More important than the mean grain size is the fact that the soil is moderately sorted (0.990 ϕ) and the grain size distribution is near symmetrical (graphic skewness $= -0.030$). A soil with these characteristics could not be produced by comminucation or vitrification—the two major processes involved in the formation of lunar soil. Immature soils and freshly derived bedrock materials are very poorly sorted. For example, two soils from the area surrounding Cone Crater at the Apollo 14 site have graphic standard deviations of 3.700 ϕ and 4.800 ϕ (Lindsay, 1972). It has been found further that the mature soils tend to stabilize with graphic standard deviations of approximately 2.0 ϕ (Lindsay, 1972). Sample 60001,10 is not fresh bedrock material nor could it have been derived from these source materials by the normal process of comminution and vitrification by meteorite impact. The light color of the soil plus its grain size parameters suggest that sample 60001,10 has been sorted in a gaseous medium and is possible ray material. The sample may represent a ray from North Ray or South Ray craters, however, its depth in the soil suggests an earlier event.

Mixing of this fine-grained soil with soil layers subsequently ejected onto the surface has produced a sequence of soils that gradually increase in grain size higher in the sequence as they are further removed from the source of the fine materials by burial.

Particle Shape

Two dimensional sphericities (Lindsay, 1972) were determined for a minimum of 500 particles for each of the four Apollo 15 surface samples and nine samples from the lower three segments of the Apollo 15 deep drill core. As in an earlier study (Lindsay, 1972) the sphericity of the particles was found to vary sinusoidally in relationship to grain size. In general, the lower sphericity values coincide with concentrations of highly irregularly shaped glass particles. Thus, the particles of more mature soils have lower mean sphericities overall and more complex size-shape distributions than their less mature counterparts.

Two dimensional sphericity has been contoured as a function of grain size (longest dimension) and depth below the lunar surface (Fig. 6). The same size-shape relationships are present in the core samples as in the surface samples. Two zones of reduced sphericity are present in the soils approximately one standard deviation either side of the mean grain size of the soils (Fig. 7). The two zones occur between 0 to 2 ϕ and 5 to 7ϕ. The 0 to 2 ϕ zone coincides with concentrations of complex agglutinates, but the 5 to 7 ϕ zone coincides with concentrations of small irregularly shaped glass spatter particles. The 0 to 2 ϕ zone is relatively uniform in width however the 5 to 7 ϕ zone widens gradually upwards and finally the two zones join at a depth of about 125 cm. This is consistent with an overall model for soil development in which soil samples closer to the surface are more mature in responses to more prolonged reworking of meteorite impact. More deeply buried soils are protected to some degree from small meteoroid reworking. Overall, the samples from the lower three core segments have a grand mean sphericity of 0.783 compared to a grand mean of 0.753 for the surface samples. This indicates that the same gradual decline in sphericity continues into shallower depths also.

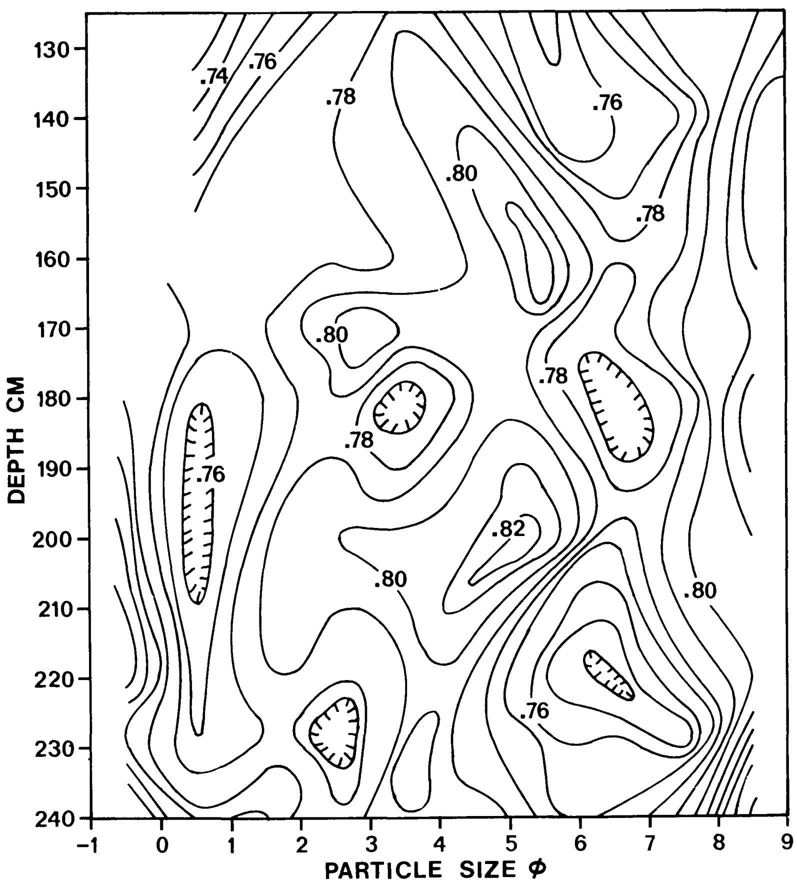

Fig. 6. Two dimensional sphericity of Apollo 15 soil particles contoured as a function of particle size and depth below lunar surface. Contour interval 0.01.

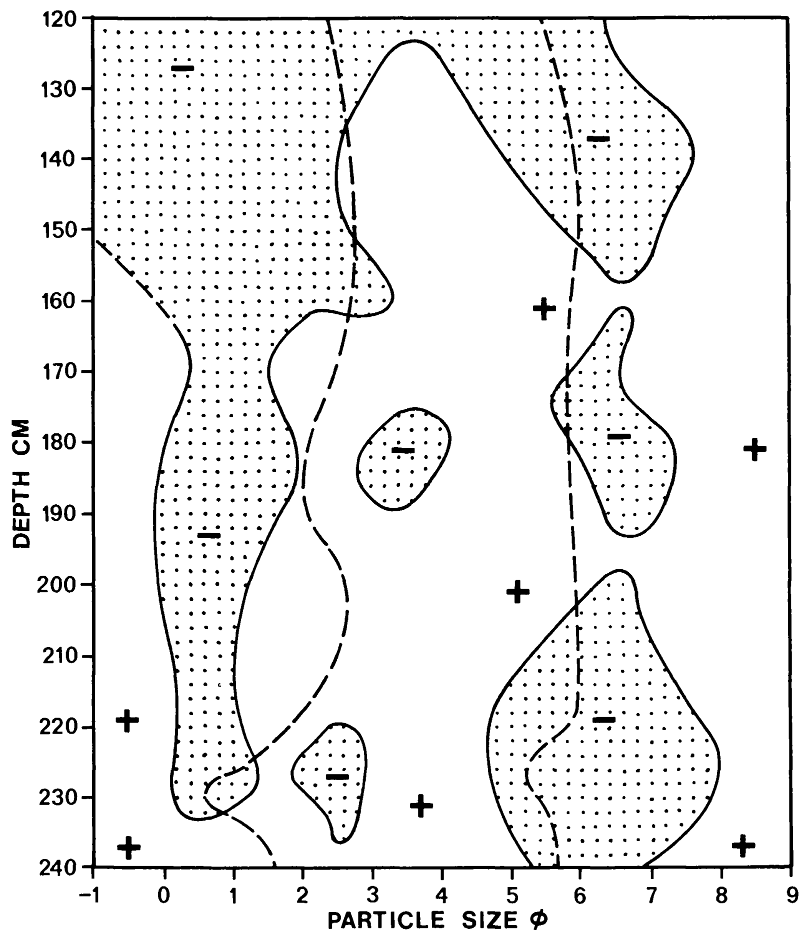

Fig. 7. Same as Fig. 6 but all contours except the mean value of 0.78 removed. Stippled areas represent negative deviations from the mean sphericity, blank areas positive. Dashed lines indicate a zone one standard deviation either side of the mean grain size of the soil.

Despite the possible difference in the age of the substrates the average properties of the Apollo 16 soils are not significantly different from the Apollo 15 soils analyzed in this work. In detail, however there are substantial differences. At the Apollo 16 site the soil stratigraphy has been modified substantially, possibly by the introduction of ray material.

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