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Grain size frequency distributions and modal analyses of Apollo 16 fines

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Abstract—Grain size frequency distributions of 19 lunar fines (less than 1 mm) samples from the Apollo 16 site are bimodal with modes in the 1–4ϕ (500–62.5 μm) and greater than 5ϕ (less than 31.25 μm) ranges. Differences in grain size frequency distribution parameters can be correlated with site geology. Samples collected at Stone Mountain (Stations 4, 5, and 6) appear to contain mixtures of South Ray Crater ejecta and older regolith. Modal analyses of the 74-53, 53-44 and 37-30 micrometer fractions of eight of the samples revealed no appreciable differences among the Stone Mountain samples.

Grain Size Analyses

Grain size analyses of 19 Apollo 16 lunar fines samples (less than 1 mm) have been completed by sieving with an Allen-Bradley sonic sifter and precision sieves. We have controlled the relative humidity in the sieving chamber in order to avoid clumping of the less than 30 micron fraction and have avoided an intense "thumping" action, which lessens the probability of destruction of delicate agglutinates. However, as we have pointed out previously (King *et al.*, 1971), almost any mechanical disturbance is likely to produce a grain size frequency distribution that is slightly finer than that of the undisturbed sample on the lunar surface. We have attempted to analyze all of our lunar samples by exactly the same technique so that comparisons can be made between the individual samples that we have received.

A list of samples analyzed, weight of sample retained on each of the sieves and a brief description of the sampled locality (after Muehlberger *et al.*, 1972, 6-1 to 6-81) are presented in Table 1. Eighteen of the samples were approximately 0.5 gram splits whereas we received approximately 1.96 grams of 68411,13.

A cumulative size frequency distribution plot with probability ordinate for 3 of the Apollo 16 lunar fines samples is presented in Fig. 1. The Apollo 16 lunar fines include the coarsest (67701,16: 116 micrometers) and finest (64811,13: 40 micrometers) lunar fines that we have analyzed. All of the lunar fines that we have analyzed from Apollo 16 and the previous Apollo missions plot within the area outlined by the upper and lower curves in Fig. 1.

In general characteristics, the Apollo 16 fines are bimodal, poorly to very poorly sorted, nearly symmetrical and platykurtic. Graphic mean grain sizes range from very fine sand to coarse silt. Terminology used to describe the grain size frequency distribution parameters is that discussed by Folk (1968). The broad mode in the 1–4ϕ (500–62.5 μm) size range is composed primarily of rock fragments and glass cemented agglutinates. The 4–5ϕ (62.5–31.25 μm) range is relatively depleted in weight fraction of sample and the greater than 5ϕ (less than

Table 1. Weight in grams of size fractions from Apollo 16 samples, grain size frequency distribution parameters and sample locality description.

Micron Sieve Size	60051,2[a]	61141,3[b]	61501,8[c]	63501,30[d]	64421,23[e]	64501,4[f]
841+	0.0143	0.0060	0.0121	0.0131	0.0095	0.0108
420	0.0607	0.0473	0.0462	0.0465	0.0314	0.0371
250	0.0446	0.0485	0.0477	0.0549	0.0432	0.0433
177	0.0329	0.0350	0.0338	0.0534	0.0402	0.0342
149	0.0249	0.0204	0.0201	0.0229	0.0233	0.0179
125	0.0197	0.0224	0.0212	0.0226	0.0210	0.0213
105	0.0234	0.0214	0.0241	0.0197	0.0232	0.0217
74	0.0366	0.0361	0.0353	0.0374	0.0438	0.0360
53	0.0325	0.0299	0.0284	0.0302	0.0294	0.0286
44	0.0228	0.0220	0.0193	0.0252	0.0271	0.0239
37	0.0230	0.0182	0.0182	0.0202	0.0299	0.0175
30	0.0404	0.0373	0.0345	0.0272	0.0408	0.0382
20	0.0352	0.0251	0.0332	0.0331	0.0430	0.0406
10	0.0432	0.0381	0.0372	0.0227	0.0369	0.0392
pan	0.0467	0.0508	0.0455	0.0202	0.0279	0.0501
Total	0.5009	0.4585	0.4568	0.4493	0.4706	0.4604
M_z	3.62 $\phi - 86\ \mu m$	3.75 $\phi - 78\ \mu m$	3.66 $\phi - 84\ \mu m$	3.20 $\phi - 112.5\ \mu m$	3·75 $\phi - 78\ \mu m$	3.83 $\phi - 73\ \mu m$
Graphic Standard Deviation	2.30 ϕ	2.20 ϕ	2.17 ϕ	1.92 ϕ	1.80 ϕ	2.15 ϕ
Graphic Skewness	−0.021	+0.070	+0.080	+0.070	−0.029	+0.023

[a]60051,2—ALSEP—Station 10.
[b]61141,3—Traverse from Plum.
[c]61501,8—Crater rim, rake.
[d]63501,30—Station 1.
[e]64421,23—Station 4.
[f]64501,4—Station 4.

Table 1. (continued).

Micron Sieve Size	64801,14[g] Weight	64811,13[h]	65501,2[i]	65701,5[j]	65901,6[k]	66031,2[l]
841+	0.0111	0.0266	0.0092	0.0013	0.0052	0.0096
420	0.0409	0.1253	0.0291	0.0280	0.0307	0.0319
250	0.0381	0.1293	0.0317	0.0350	0.0396	0.0350
177	0.0306	0.1036	0.0263	0.0346	0.0299	0.0281
149	0.0156	0.0533	0.0141	0.0174	0.0159	0.0162
125	0.0200	0.0650	0.0178	0.0199	0.0169	0.0177
105	0.0222	0.0743	0.0176	0.0236	0.0211	0.0201
74	0.0372	0.1282	0.0351	0.0440	0.0393	0.0320
53	0.0318	0.1005	0.0264	0.0321	0.0290	0.0236
44	0.0250	0.0853	0.0230	0.0267	0.0350	0.0173
37	0.0133	0.0663	0.0162	0.0169	0.0171	0.0196
30	0.0494	0.1680	0.0423	0.0461	0.0710	0.0299
20	0.0455	0.2271	0.0461	0.0452	0.0282	0.0309
10	0.0403	0.2114	0.0503	0.0454	0.0326	0.0220
pan	0.0616	0.3963	0.0897	0.0618	0.0353	0.0176
Total	0.4826	1.9605	0.4749	0.4780	0.4468	0.3515
M_z	4.08 ϕ − 60 μm	4.72 ϕ − 40 μm	4.60 ϕ − 44 μm	4.23 ϕ − 56 μm	3.88 ϕ − 71 μm	3.46 ϕ − 95 μm
Graphic Standard Deviation	2.22 ϕ	2.52 ϕ	2.45 ϕ	1.95 ϕ	1.90 ϕ	1.85 ϕ
Graphic Skewness	−0.079	−0.050	−0.060	+0.030	−0.142	−0.028

[g] 64801,14—Station 4.
[h] 64811,13—Station 4.
[i] 65501,2—Station 5.
[j] 65701,5—Station 5.
[k] 65901,6—Station 5.
[l] 66031,2—Station 6.

Table 1. (continued).

Micron Sieve Size	66041,15[m] Weight	66081,13[n]	67701,16[o]	68501,33[p]	68841,13[q]	69941,15[r]	69961,14[s]
841+	0.0031	0.0025	0.0172	0.0025	0.0154	0.0000	0.0122
420	0.0334	0.0308	0.0666	0.0383	0.0437	0.0408	0.0370
250	0.0351	0.0403	0.0597	0.0451	0.0447	0.0413	0.0393
177	0.0295	0.0292	0.0410	0.0432	0.0322	0.0333	0.0310
149	0.0194	0.0145	0.0193	0.0178	0.0180	0.0173	0.0198
125	0.0180	0.0205	0.0210	0.0200	0.0203	0.0211	0.0207
105	0.0211	0.0202	0.0294	0.0221	0.0218	0.0228	0.0218
74	0.0350	0.0350	0.0341	0.0401	0.0367	0.0365	0.0362
53	0.0259	0.0305	0.0255	0.0265	0.0294	0.0287	0.0322
44	0.0258	0.0234	0.0218	0.0251	0.0251	0.0237	0.0227
37	0.0152	0.0196	0.0209	0.0254	0.0195	0.0114	0.0192
30	0.0436	0.0418	0.0380	0.0309	0.0402	0.0488	0.0417
20	0.0481	0.0521	0.0329	0.0508	0.0387	0.0315	0.0386
10	0.0447	0.0458	0.0269	0.0355	0.0423	0.0433	0.0404
pan	0.0612	0.0638	0.0311	0.0313	0.0453	0.0525	0.0435
Total	0.4591	0.4700	0.4854	0.4546	0.4733	0.4530	0.4563
M_z	$4.23\phi - 56\mu m$	$4.27\phi - 54\mu m$	$3.13\phi - 116\mu m$	$3.70\phi - 81\mu m$	$4.13\phi - 58\mu m$	$4.00\phi - 62.5\mu m$	$3.87\phi - 68\mu m$
Graphic Standard Deviation	2.20ϕ	2.17ϕ	2.00ϕ	1.90ϕ	2.20ϕ	2.20ϕ	2.15ϕ
Graphic Skewness	−0.045	−0.060	+0.100	0.000	0.000	0.000	−0.023

[m] 66041,15—Station 6.
[n] 66081,13—Station 6.
[o] 67701,16—Station 11.
[p] 68501,33—Station 8.
[q] 68841,13—Station 8.
[r] 69941,15—Station 9.
[s] 69961,14—Station 9.

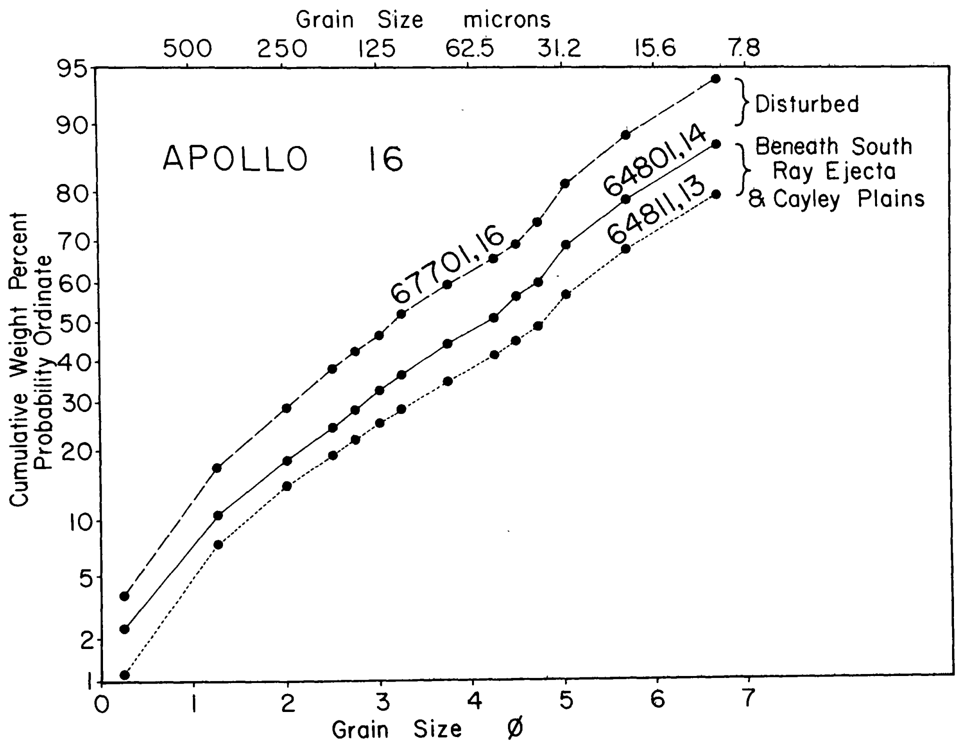

Fig. 1. Size frequency distribution curves for 3 Apollo 16 samples.

31.25 μm) range constitutes a second mode composed primarily of mineral fragments and colored glass. We have suggested previously that the finer mode may contain a higher proportion of particles derived from distant sources (Butler *et al.*, 1970; King *et al.*, 1971) and that samples from near the maria-highlands contacts should be strongly bimodal. The bimodal nature of the Apollo 16 lunar fines similarly could be caused by an influx of fine particles although, as will be discussed, it is likely that most of the Apollo 16 fines that we have analyzed contain at least a small component of the relatively coarse ejecta from either the North Ray and/or South Ray craters.

We have noted previously a tendency for the graphic mean grain size (in micrometers) to be negatively correlated with the total sample weight for those samples for which we had more than one split available (King *et al.*, 1971). Samples 64801,14 (0.48 grams—60 micrometers) and 64811,13 (1.96 grams—40 micrometers) illustrated in Fig. 1 exhibit the same relationship. This variation could be fortuitous or it could reflect size sorting of particles during sample collection and handling prior to our receipt of the samples.

Variation of graphic mean grain size

Throughout our analyses of lunar fines we have maintained that site geology influences the size frequency distribution parameters of the less than 1 mm fraction of samples collected within a few centimeters of the lunar surface. As noted previously, the suite of samples that we have analyzed from Apollo 16 covers a considerable range of graphic mean grain size—116 to 40 micrometers. Discussions of the preliminary geologic investigations of the Apollo 16 landing site (Muehlberger *et al.*, 1972, 6-1 to 6-81) emphasized the complexity of the areas sampled and it appears likely that the samples we have examined contain information concerning several categories of surficial deposits:

(1) Ray materials from North Ray Crater.
(2) Ray materials from South Ray Crater.
(3) Materials representative of units that predate the ray materials (either the Cayley and/or Descartes units). These units may be overlain by ray material at many of the sample stations.

The map of the ejecta distribution in the Apollo 16 landing site area (Muehlberger *et al.*, 1972, Fig. 6-5, page 6–10) and the discussion of the sample stations suggests that many of the samples that we have analyzed contain mixtures of at least two of the above categories of surficial debris. We believe that our observed range in graphic mean grain size and other size parameters is real and is the result of differences in the size frequency distributions of the materials sampled. The Apollo 16 traverses and locations of the sites sampled are reproduced in Fig. 2.

Samples from Stations 11 and 13 (67701,16 and 63501,30 respectively) were collected from within the North Ray Crater ejecta and are very coarse (116 and 112 micrometers graphic mean grain size respectively). These two samples possess grain size frequency distributions that are similar to the Apollo 14 Cone Crater ejecta sample that we have described previously (King *et al.*, 1972).

South Ray Crater ejecta at Station 1 is thought to be quite thin (if present at all) and it was believed that samples from this station had the highest probability of being "... representative of the upper units of the subjacent bedrock of the Cayley Plains ..." (Muehlberger *et al.*, 1972, 6–19). Our samples from Station 1 have graphic mean grain sizes of 78 and 84 micrometers (61141,3 and 61501,8 respectively). The single sample we have analyzed from Station 10 (60051,2) was collected from an area within distinct South Ray Crater ejecta and has a graphic mean grain size of 86 micrometers.

Stations 4, 5, and 6 were located on the northern flank of Stone Mountain. Two separated areas were sampled at Station 4. Samples 64421,23 and 64501,4 have graphic mean grain sizes of 78 and 73 micrometers respectively and were collected within a small (15 meter) doublet crater. In addition to the doublet crater, a 20 m subdued crater was sampled at Station 4. Indurated regolith samples from the block-free west and north west crater rim might have been derived partly from underlying Descartes materials (Muehlberger *et al.*, 1972, 6–27 to 6–28). Our samples from the 20 meter crater—64801,14 and 64811,13—have graphic mean grain sizes of 60 and 40 micrometers respectively. Two samples from Station 5—65501,2 and 65701,5—have graphic mean grain sizes of 44 and 56 micrometers respectively. Sample 65901,6 was collected from approximately 15 cm below the lunar surface and has a graphic mean grain size of 71 micrometers. Our analyses of Apollo 12 and Apollo 14 trench samples (King *et al.*, 1972) similarly indicated

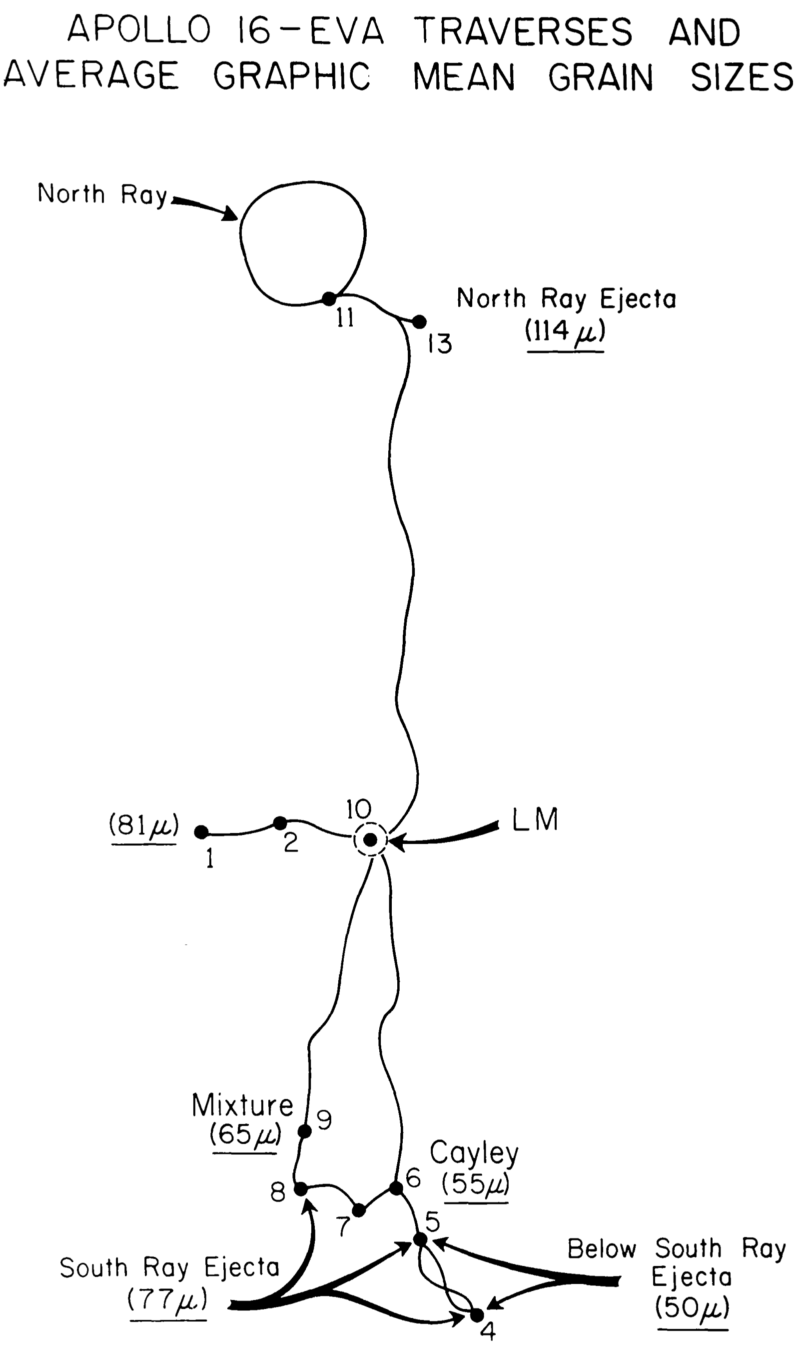

Fig. 2. Apollo 16 traverses and location of sample stations.

that trench samples are coarser than nearby surface samples. This trend apparently does not characterize the Apollo 16 regolith as sampled by the deep core (Lindsay, 1973).

Samples 66041,15 and 66081,13 are very similar in size frequency distribution properties (Table 1) even though 66041,15 has been described as a "... unique white splotch of indurated soil..." (Muehlberger *et al.*, 1972, 6–29) and 66081,13 as a gray soil.

Thus, there is a considerable range in graphic mean grain size among the Stone

Mountain samples. After careful consideration of available information we find it difficult to categorize these samples except to note that they are finer than those collected from Stations 1 and 10. We believe that the Stone Mountain suite represents a mixture of South Ray ejecta with older, underlying regolith units. On the basis of grain size data alone it would be impossible to assign this underlying material to either the Cayley or Descartes units.

Muehlberger *et al.* (1972, 6–30) concluded that most of the surface material collected from Stations 8 and 9 is ejecta from South Ray Crater, although they noted that both younger and older material was evident. Our analyses of samples from these stations are similar to those previously discussed for the Stone Mountain stations (Table 1) and we believe that these samples are mixtures of South Ray Crater ejecta and material from underlying units.

We would expect that the South Ray ejecta component of these mixtures is coarser than the component derived from the underlying units. Therefore, the mean grain size of the less than 1 mm fraction may be a useful, although crude, index of the extent of mixing. Unfortunately, we do not have sufficient data to be able to estimate the sorting or the mean grain size of either component.

Further interpretation of Apollo 16 grain size data must await resolution of ambiguities in the interpretations of site geology and more sophisticated numerical analysis.

Modal analyses

Modal analyses of the 74-53, 53-44 and 37-30 micrometer fractions of 9 of our Apollo 16 samples have been completed. Approximately 750 grains per fraction were counted and identified using oil immersion techniques. Results of the modal analyses are presented in Table 2. For illustrative purposes olivine, pyroxene and plagioclase have been lumped into a "mineral grains" component.

The nine samples analyzed were selected to cover the range of the graphic mean grain size of the less than 1 mm fraction. Modes of the North Ray ejecta sample from Station 11 (67701,16) and three coarse samples from Stone Mountain (65901,6, 64421,23, and 64501,4) are illustrated in Fig. 3. Glass and mineral grains increase in abundance as grain size decreases. Welded fragments (including glassy agglutinates) decrease in the finer fractions and essentially are absent in the less than 10 micrometer fraction. The North Ray Crater ejecta sample contains almost twice as many rock fragments as do the Stone Mountain samples. This may reflect a real difference between the North Ray and South Ray ejecta or the dilution of the South Ray ejecta samples from Stone Mountain with underlying regolith.

Modal analyses for 5 of the finest samples from Stone Mountain (66041,15, 66081,13, 64811,13, 64801,14, and 65501,2) are illustrated in Fig. 4. Again, there is a trend of increasing glass and mineral grains at the expense of welded fragments in the finer fractions. It is difficult to recognize any modal differences within the coarse and fine Stone Mountain samples (Fig. 3 and 4). We have not been able to find a means of separating these samples into groups using what amounts to a Q-mode analysis of the modal analyses data. It is possible, however, that there are

Table 2. Summary of modal analyses of Apollo 16 lunar fines.

Sample Number	Location	Olivine %	Pyroxene %	Plagioclase %	Glass %	Rock Fragments %	Welded Fragments %
64421,23							
74-53 μm	South Ray	0.6	1.1	13.6	10.6	22.9	52.6
53-44 μm		0.6	0.7	14.8	14.4	23.9	45.9
37-30 μm		1.0	3.6	22.1	12.0	21.9	39.3
64811,13							
74-53 μm	Regolith	1.1	3.2	23.2	10.0	28.0	34.3
53-44 μm		3.1	6.5	26.2	13.9	21.2	29.1
37-30 μm		2.1	8.8	25.4	16.3	27.8	19.5
64501,4							
74-53 μm	South Ray	0.7	1.7	28.2	6.5	26.0	36.8
53-44 μm		0.8	1.7	27.8	8.9	36.0	24.8
37-30 μm		0.5	6.4	32.1	10.9	24.8	25.4
64801,14							
74-53 μm	Regolith	1.4	1.4	12.3	5.9	21.7	57.4
53-44 μm		1.1	3.6	16.5	10.8	25.9	42.1
37-30 μm		0.5	3.7	19.2	15.5	17.1	44.0
65501,2							
74-53 μm	Regolith	1.6	3.1	11.0	8.5	42.5	33.5
53-44 μm		1.1	6.8	13.4	6.1	46.6	25.6
37-30 μm		1.0	8.5	16.5	10.8	35.0	28.3
65901,6							
74-53 μm	South Ray	0.7	1.8	10.9	19.7	33.5	44.4
53-44 μm		0.6	1.9	8.3	15.5	32.0	41.7
37-30 μm		0.5	10.0	17.6	17.0	33.7	21.1
66041,15							
75-53 μm	Cayley Pl.	1.9	3.5	12.4	9.0	30.4	42.8
53-44 μm		1.0	1.4	12.9	14.4	30.2	39.7
37-30 μm		0.7	4.0	13.4	12.4	35.3	34.2
66081,13							
74-53 μm	Cayley Pl.	1.4	1.4	9.7	4.3	28.1	55.1
53-44 μm		0.9	2.0	12.8	9.5	31.6	43.2
37-30 μm		1.6	4.2	19.0	13.3	37.2	24.8
67701,16							
74-53 μm	North Ray	1.3	2.3	15.6	2.1	48.4	30.4
53-44 μm		0.9	4.2	17.9	3.6	51.1	22.3
37-30 μm		0.7	5.5	24.3	6.4	43.6	19.6

differences between the Stone Mountain samples with respect to the types of rock fragments present. We have experienced difficulty in establishing suitable criteria to be used in working with these very small fragments and have not attempted to subdivide the rock fragment category.

We have used the Pearson product moment correlation coefficient as a measure of the similarity between variables for the modal analyses data. The raw data matrix consisted of 27 entries (9 samples and 3 analyzed fractions per sample) and 6 variables. These data are percentages and hence constitute a set of closed data.

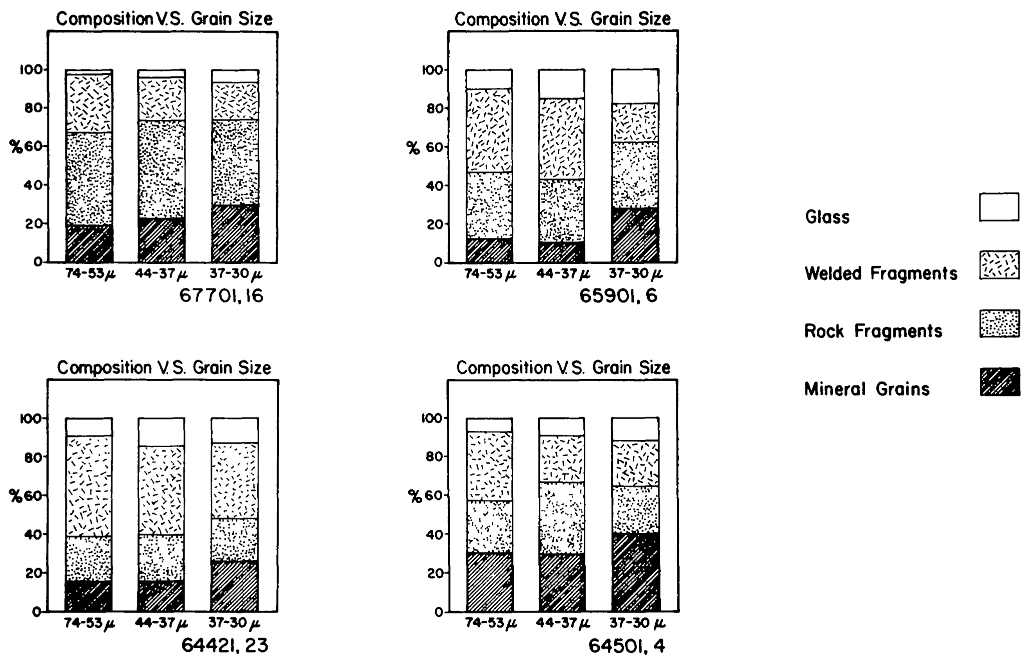

Fig. 3. Modal analyses of Apollo 16 fines from Stone Mountain.

Therefore, a null value of zero is not appropriate for use in the standard test for estimating departures from randomness. Closure correlations were computed according to the methods of Chayes and Kruskal (1966). The hypothetical open variances are all positive and, assuming that individual correlations can be tested for significance, only two of the correlations are significant at the 95% level: (1) pyroxene versus welded fragments and (2) rock fragments versus welded frag-

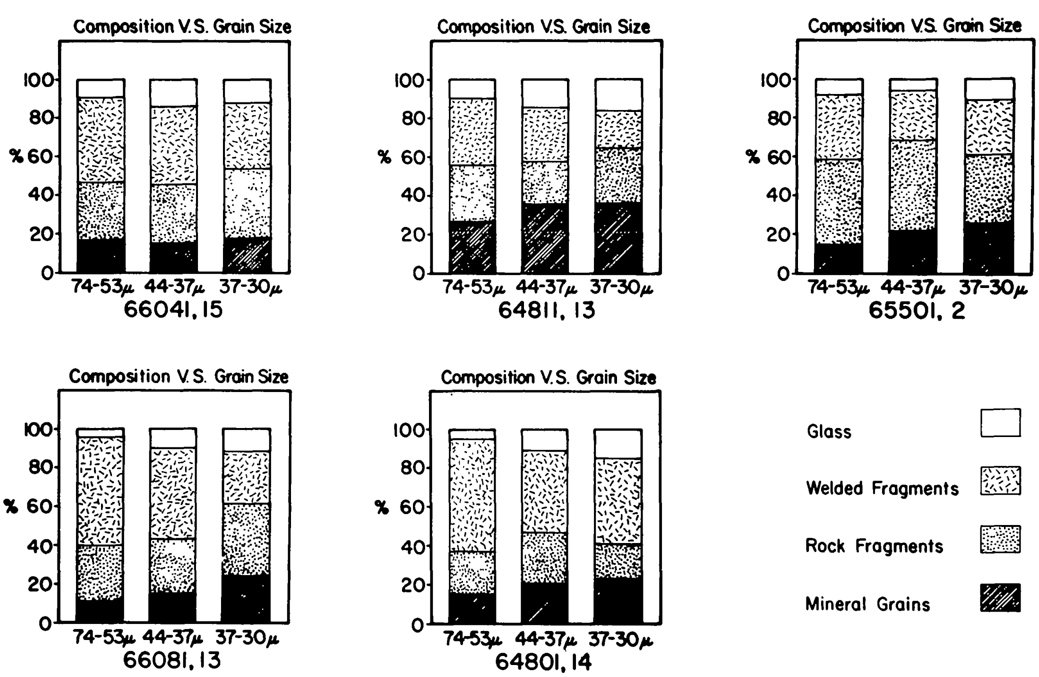

Fig. 4. Modal analyses of Apollo 16 fines from Stone Mountain.

Table 3. Summary of correlation analysis of Apollo 16 modal analyses data.

Variable (I)	Variable (J)	r(I,J)*	p(I,J)†	Significant at 95%?	Line of Organic Correlation
Olivine	— Pyroxene	0.217	0.069	no	
Olivine	— Plagioclase	0.079	0.091	no	
Olivine	— Glass	−0.023	0.131	no	
Olivine	— Welded Frag.	−0.108	−0.108	no	
Olivine	— Rock Frag.	0.104	−0.067	no	
Pyroxene	— Plagioclase	0.370	0.017	no	
Pyroxene	— Glass	0.313	0.054	no	
Pyroxene	— Rock Frag.	0.125	−0.119	no	
Pyroxene	— Welded Frag.	−0.720	−0.154	yes	Welded Frag. = 51.19 − 4.276 × Pyroxene
Plagioclase	— Glass	0.089	0.049	no	
Plagioclase	— Rock Frag.	−0.249	−0.279	no	
Plagioclase	— Welded Frag.	−0.569	−0.346	no	
Glass	— Rock Frag.	−0.467	−0.182	no	
Glass	— Welded Frag.	−0.084	−0.241	no	
Rock Frag.	— Welded Frag.	−0.296	−0.695	yes	Welded Frag. = 68.95 − 1.044 × Rock Frag.

*Computed correlation coefficient.
†Null value computed from Eq. 4.10 (Chayes, 1971).

ments. Results of the correlation analysis of the modal analyses data are presented in Table 3. The significant correlations are described by giving the equation of the line of organic correlation, as we are not able to justify the selection of either variable as the independent variable.

Conclusions

We have previously suggested that the mean grain size of the lunar surface regolith may decrease with increasing exposure to comminution by meteoroids (King *et al.*, 1972, 60–62) and that the mean grain size of the less than 1 mm fraction of samples taken from inter-ray areas could be used to estimate the length of time elapsed since the initiation of regolith development. We have attempted to subdivide all of our analyzed lunar samples into what we have previously described as relatively "undisturbed" and "disturbed" subdivisions (King *et al.*, 1972, 61). There are some samples (for example, samples from Stations 11 and 13 from Apollo 16 and the Cone Crater sample from the Apollo 14 site) that we believe definitely are recent ejecta samples and hence younger than the surface that they overlie; such samples are assigned to the "disturbed" subdivision. If the available information about the sampled locality does not indicate the presence of significant quantities of coarse ejecta, the samples are assigned to the relatively "undisturbed" subdivision. At best, the assignment of many of our samples to either of these categories is somewhat subjective. We are presently re-examining all of our previous analyses in an attempt to recognize groups in an objective numerical fashion. We have previously (Butler *et al.*, 1973) assigned the samples from Station 6 to the Cayley unit and the finer samples from Stations 4 and 5 to an unspecified unit underlying the South Ray ejecta. At the present time we prefer not to assign these samples from Stone Mountain to any unit in particular. We maintain, however, that the finer samples are our best representatives of the regolith underlying the South Ray ejecta at Stone Mountain, although their contamination with some South Ray Crater ejecta is a real possibility.

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