X-641-69-369
PREPRINT

NASA TM X- 63672

AN ANALYSIS OF THE DISTRIBUTION OF BOULDERS IN THE VICINITY OF SMALL LUNAR CRATERS

WINIFRED SAWTELL CAMERON
GEORGE J. COYLE

AUGUST 1969

GSFC
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-641-69-369

AN ANALYSIS OF THE DISTRIBUTION OF BOULDERS IN THE VICINITY OF SMALL LUNAR CRATERS

Winifred Sawtell Cameron
George J. Coyle

August 1969

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

AN ANALYSIS OF THE DISTRIBUTION OF BOULDERS IN THE VICINITY OF SMALL LUNAR CRATERS

By

Winifred Sawtell Cameron

and

George J. Coyle*

NASA Goddard Space Flight Center

Laboratory for Theoretical Studies

Theoretical Studies Branch

Greenbelt, Maryland

A survey of boulder distributions inside and around small (0.11-2km) craters was made to investigate statistically a casual impression that there were distinct differences. Several frames from Lunar Orbiter III high resolution (1 meter) photographs in three separate regions of the moon were inspected with a magnifying lens for craters with diameters ≥ 110 meters. Below this limit boulders were difficult to detect. Originally 200 m had been adopted as the lower diameter limit but this yielded too few typical impact craters. The extended survey yielded a total of 603 craters from 9 frames. (Table I.) The three sites were Frame 44 at 27°.0 E, 0°.6 N in Mare Tranquillitatis, (P-4) the region of Ranger VIII and Surveyor V; frame 100 at 0°.9 W, 0°.9 N in Sinus Medii, (P-7) the region

*Now a student at the University of Maryland of Surveyor VI; and frame 181 at 43°.3 W, 1°.6 S in the Flamsteed Ring (P-12) the region of Surveyor I. All coordinates are given in the aeronautical convention adopted by the IAU. (See Fig. 1.) The P-7 and P-12 sites were areas of approximately 60 km^2, while P-4 was approximately 45 km^2. The numbers of craters examined and classified for the three sites were 88 for P-4, 288 for P-7 and 227 for P-12 giving a total of 603.

The boulder distributions around these craters could usually be unambiguously classified according to the following scheme: (α) boulders inside and far outside ($\geq$ 1 crater diameter), (β) boulders within the crater and/or its ramparts, and (γ) no visible boulders. This classification was then correlated with the two-dimensional crater classification scheme of Jaffe (1965) based on similarity of appearance of the lunar craters to his model. His scheme involves crater shape, rim appearance and amount of overlay. In practice, crater shapes were classified as follows: (A) distinct, narrow raised rim, comparatively shallow depth, (B) indistinguishable rim and relatively shallow depth, and (C) broad, distinguishable rim and relatively greater depth. Apparent overlay was judged by closest simulation to the appropriate Jaffe model plus overlay photograph. Jaffe photographed his models with successive steps of overlay varying from step 1 (no covering) to 14 (barely distinguishable from surroundings). Figure 2 reproduces Jaffe's A model craters with their successive steps of overlay from A1 to A14. Figure 3 illustrates examples from lunar photographs of relatively fresh craters (little apparent overlay) of each crater type and each kind of boulder distribution. They illustrate well the apparent differences between the A-type and the others. They also illustrate the dramatic differences between the Aα and Cα (rare) types. In the latter very few boulders are to be found away from the crater and these are usually less than a crater diameter away.

Some ambiguity arose in distinguishing between B and C types of craters, especially when rims were not obvious. In these cases, relative depth was the principle deciding factor. Although the type classification is more subjective, the subjectivity arises in the classifying of the B's and C's, but there was no ambiguity in classifying the A's. In addition to the narrow raised rim, the A's had, almost without exception, inner concentric rings or large mounds in the bottom (or both), superposed on which was a peppering of boulders of nearly equal sizes both inside and outside the crater (see Fig. 3).

There was little or no ambiguity in distinguishing the boulder distributions. There were a few cases of the C-type with the α-distribution. As mentioned above there was a distinct difference in the amount and distance thrown for boulders of Cα and Aα craters, implying very different energy conditions.

Figure 4 shows examples of mantled (judging from appearance) craters of each type and boulder distribution. Boulders also appear to be mantled. Note that the large mounds and distinct rims in the A-type still persist. In the lower left photograph are two "ghost" craters which may be A-type craters filled almost to the brim. It is curious that the narrow, distinct rim can still be easily distinguished. The one near the right edge seems to show the inner ring too. We experimented with clay models of the different types depositing successive steps of fines over them and these experiments showed that the inner ring persists through all stages up to almost complete filling. Another evidence of age in these craters is to be found in the increased number of small craters seen on the rims of these craters in Fig. 4, as compared to those in Fig. 3.

A plot of the number of craters with respect to steps (first numbers or letters were used from Table I in the statistics) of apparent overlay for the data revealed some interesting facts. Figure 5 shows the plots for the boulder distributions for each region and for all the craters (603) combined. For site P-4 the craters seem to be found in all states of apparent mantling. There are no distinct trends in this small sample (88 craters). Discussion of this site is deferred.

The other two sites, P-7 and P-12 and the total number of craters indicate the following: (1) the craters with α-distribution (both inside and far outside) are found exclusively in the lower steps of overlay, possibly peaking at step 3; (2) the β's (boulders only inside) also are concentrated mainly at the lower steps of overlay and have a very similar distribution with a more distinct peak, again at about step 3; (3) the γ's (no boulders) are found to extend to higher steps and their maximum occurs at about step 5 or so. If the distributions represent successive stages of depositional erosion, the α- and γ-distribution results are what we would expect. The γ's apparently represent a stage in which enough deposition (of whatever origin) has been laid down to cover all boulders completely.

The β's, however appear not to be an intermediate step in erosional evolution between the α's and γ's. Reasons for this conclusion are as follows: (1) the apparent amount of overlay for the β's is the same as for the α's and therefore these craters are about the same age, or at least in the same stage of depositional erosion; (2) stages of successive mantling of α-distribution craters can be followed at least to step 6 and exceptionally up to step 9. Above step 6 boulders are seldom found (except in the anomalous M. Tranquillitatis P-4 site); (3) for the β-distribution to be an intermediate step a mechanism of mantling is required that favors deposition on the plains over that inside craters. In fact, the opposite would be expected. Inside the craters the steeper slopes would facilitate talus formation and slumping so that the finer material would accelerate mantling of the inside boulders; (4) the appearance of the boulders often seems to be distinctive between the craters with α-distribution (of A-type) and β-distribution. In the latter, the boulders frequently were larger, elongated, sharper and sometimes seemed to be imbedded in the walls, possibly as outcrops. In the Aα craters the boulders were usually almost uniform in size inside and outside, rounded in shape, superficially deposited, extremely numerous and ejected to great distances, often several diameters away.

For these reasons we think that the results indicate that there are at least two populations of primary craters found here with different origins. There seem to be two regimes of energy involved. In the case of the α-distribution craters there was considerable energy—sufficient to pulverize the lunar terrain into numerous blocks and disperse them to great distances. In the β-distribution craters the energy for lifting was considerably weaker and boulders were thrown only to the confines of the crater. We suggest that the former are most certainly impact craters and that the latter are of internal origin, perhaps maar-type volcanic craters. If this interpretation is correct then an average of 7 percent of the craters examined are impact and 40 percent are internal (see Fig. 7). Little can be said about the γ's for they could represent late stages of both distributions.

Considering the data with respect to crater types we find a similar dichotomy between types. For purpose of comparison, we will generally discuss the A's and C's. Figure 6 shows the plots of the crater types versus the steps of overlay for each of the regions and for the total. The curves seem to be quite similar to those of the boulder distribution curves. Here we find the A's mainly in the lower steps of apparent overlay, perhaps peaking at step 3. The curve is quite similar to that for the α-distribution of boulders. Likewise, the C-type craters are found mainly in the lower steps, also peaking at step 3, with a curve similar to that of the β-distribution for boulders. The B's seem to be distributed quite similarly to the craters with γ-distribution of boulders. In fact, there appear to be genetic relationships between types and distributions, as born out in the numbers in Fig. 7. The craters are probably to be grouped as Aα, Cβ, and Bγ. Again, the implication in Fig. 6 is that the C's are not to be regarded as an intermediate mantled stage between the A's and the B's for the following reasons: (1) the apparent amount of overlay is about the same for the two types, implying similar ages or depositional evolution, (2) the C-type craters are apparently deeper than the A-type, judging from shadow lengths. Approximate calculations of depth for the nearly equal-sized craters in Fig. 3 yield depths of 70 m for A α, 77 m for Cα, 54 m for C β, and 34 m for Bγ. No other measurements of actual depth were made, but all craters are in a small region with almost identical lighting conditions, therefore shadow length is a criterion of depth, (3) because of the greater relative depth of the C's (if regarded as an intermediate type) an erosional process is required which lowers and broadens the rim yet deepens the crater instead of making it shallower by deposition. Such a process is difficult to hypothesize, (4) frequently the C-type craters appear to be funnel-shaped or to have a crater (itself often funnel-shaped) centrally located at its bottom (see the C's and possibly the B-type in Fig. 3). From the above considerations we suggest that the C's are primary craters of different kind and origin than the A's. We think also, that the B's are probably a later evolutionary stage of the C's but not of the A's since the characteristics of the latter type can be seen up to high steps of overlay. From the shapes of the C's (bowl and often funnel-shaped) we suggest that they are of internal origin and that the A's are of impact origin. Figure 7 shows the association of shapes and boulder distribution: (a) percent of boulder distribution with respect to type, (b) percent of type with respect to boulder distribution, (c) same as (a) but in terms of numbers of craters instead of percent, and (d) percent and number of total craters by type and by boulder distribution. Sixty-nine percent of the α-distribution are A-type, and all (statistically) the β-distribution were B or C. Even more striking, eighty-six percent of the A's had α-distribution while fifty-nine percent of the C's had β-distribution. These percentages imply two genetically different types of craters. We do not think that they are both due to impact because it has not been demonstrated that impacts or explosions that produce deep craters (such as the C's here) are not also accompanied by widely dispersed ejecta and more distinct rims (Marcus, [1967]; Walker [1967]; Quaide and Oberbeck [1968]; Maurer and Rinehart [1960] and Moore et al., [1962]). Appeals to arguments for differences in target material within each small region to account for crater morphology and boulder distribution differences are weak. From shapes, (funnel-shaped), central craters, (thought to be the vent) and β-type boulder distribution (boulders confined to crater's ramparts) we conclude the Cβ craters are probably volcanic maars.

The three sites appear to differ in some respects. In regard to apparent amounts of overlay, the statistics and appearances imply that site P-12 (Flamsteed Ring) is the youngest, followed by P-7 (S. Medii) then P-4 (M. Tranquillitatis). Figures 8, 9, and 10 show representative areas of each site and include examples of each type of crater and each type of boulder distribution. One can see that P-4 looks generally quite subdued, as if rather heavily mantled. Only 88 craters were found within our selected limits. The area surveyed was only about 3/4 of the other two areas, and if the crater count were extrapolated for larger equivalent area, it would have yielded only about 120 craters, a factor of about two fewer than the other two. There seems to be a real deficiency of craters here. The surprising result was that boulders could be detected in the vast majority of craters, even in one that could not be distinguished from its surroundings except for the patterned ground (rated step 12). Contrastingly, P-7, although most heavily cratered, (288) appears to be a fresher or less-eroded surface. The craters are deeper and better defined and generally rated at lower overlay steps. However, the majority of these craters had no detectable boulders even in some craters of apparently little overlay (rated at steps 2 or 3). Site P-12 was intermediate between these two sites both in numbers of craters (227) and of those with boulders. These observations indicate differences between the three regions, probably in age and condition, but possibly also in composition.

REFERENCES

Jaffe, L. D., Strength of the lunar dust, J. Geophys. Res. 70 (24), 6139, 1965.

Marcus, A. H., Further interpretations of crater depth statistics and lunar history, Icarus 7 (3), 407, 1967.

Maurer, W. C. and J. S. Rinehart, Impact crater formation in rock, J. Appl. Phys. 31, 1247-1253, 1960.

Moore, H. J., R. V. Lugn, and D. E. Gault, Experimental Hypervelocity impact craters in rock, Proc. 5th Symp. Hypervelocity Impact, 625, Denver, Colorado, 1962.

Quaide, W. L. and V. R. Oberbeck, Thickness determinations of the lunar surface layer from lunar impact craters, J. Geophys. Res. 73 (16), 5247. 1968.

Walker, E. H., The structure of the lunar surface as indicated by the geometry of impact craters, Icarus 7 (2), 283, 1967.

ACKNOWLEDGMENTS

We wish to thank J. A. O'Keefe for his support, suggestions and critical reading of this manuscript. We also appreciate the stimulating discussions with N. M. Short, B. P. Glass and T. McGetchin. One of us, (GJC) during part of this project participated through the program for superior high school students sponsored by the National Science Foundation administered by American University.

Table I
Crater, Boulder and Apparent Amount of Overlay Classification

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
Site P-4 (Mare Tranquillitatis)						
1	44 (1) 574	55	605	B 2-3	β	
2		34	374	B 6	β	few boulders
3	577	25	275	B 5	β	
4		11	120	B 12	γ	
5		10	110	C 10	γ	
6	579	13	143	B 12	γ	
7	580-81	25	275	B 3	β	
8		17	187	B 7	β	
9	582	20	220	B 12	γ	dark floor?
10		24	264	B 11	β	few small boulders
11		10	110	B 12	γ	
12		17	187	B 10	β	
13	584	11	121	C 2-3	β	funnel
14		24	264	B 12	γ	
15		34	374	B 5	β	
16		18	198	C 1-2	α	funnel?
17		25	275	B 5	β	
18	587	55	605	C 3-4	β? (α?)	blocks beyond
19	588	23	253	B 12	γ	
20		10	110	B 11	γ	
21		18	198	B 11	γ	
22	589-90	26	286	B 12	γ	
23		28	300	B 2	γ	
24	591	70	770	B 11	γ	
25		25	275	B 13	γ	
26	592	11	120	B 6	γ	
27	593	13	143	B 8	β	
28		20	220	B 12	γ	

Table I (Continued)

No.	Frame and Framelet		Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
29	44 (1)	595	14	154	A 1-2	α	
30			27	297	B 12	β	
31			25	275	B 12	γ (β ?)	bl. in it from A α ?
32			50	550	B 1? (C ?)	β	
33		596	15	165	B 6	β	
34			20	220	B 2-3	β	
35		597	10	110	C 5	γ	
36		598	17	187	A 1	α	
37			10	110	B 10	γ	
38			16	176	B 11	γ	
39		599-600	15	165	B 13	γ	
40			14	154	B 6	β	
41			32	352	B 3	β	
42		601	18	198	B 2-3	β?	1 boulder
43		602	13	143	B 10	γ	
44			23	253	B 5	β?	2 or 3 blocks
45			15	165	B 11	γ	
46		603	20	220	B 3	β	
47			12	132	B 13	γ	? barely detectable
48			25	275	B 6	β	
49		604	20	220	B 6	β	
50	44 (2)	606	10 ?	110	B 11	β	
51			10	110	B 11	β	
52		608-09	13	143	B 9	β	
53		611	11	121	A 1	α	
54		612	13	143	B 6	γ	
55		612	10 ?	110	C 6	β	funnel
56		613	26	286	B 12	β	patterned ground
57		614	12	132	B 5	γ	

Table I (Continued)

No.	Frame and Framelet		Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
58	44 (2)		23	253	B 13	γ ? or β ?	bl. in it fr. A α in it?
59		615	10?	110	B 9	β	
60			17	187	B 6	γ	
61		617	10	110	C 5-6	α	funnel
62			17	187	B 10	β	
63			17	187	B 6	β	irregular
64		621	22	242	C 5	β	
65		623	20	220	C 2-3	β	
66		624	20	220	B 5	β	
67			23	253	B 6	β	
68			15?	165	B 12	γ	
69		629	50 x 1300	550 x 14,300	B 3	β	
70		630	20 x 45	220 x 495	B 5	β	3 ? coalesced craters
71		631	18	198	B 5	γ	
72		632	11	121	A 1-2	α	summit crater on c. p.
73		633	20	220	B 9	β	dome? next it with bl.
74			14	154	C 4	β	funnel
75		634	10	110	B 12	γ	
76			10	110	B 10	γ	
77			17	187	B 9?	β	sharp inner rim-collapse
78			12	132	A? 8 (C?)	γ	
79		635	10	110	B 6	γ	
80		636	18	198	B 5	γ	
81			22	242	B 3	γ?	bl. due to sm. A α in it?
82	44 (3)	638-39	20	240	B 9	β	
83			20?	240	B 12	β	
84		640	10	110	B 12	β	
85			20	240	B 12	β	
86			27	297	B 4	β	

Table I (Continued)

No.	Frame and Framelet		Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
87	44 (3)	642	18	198	A 5	α	3 c.p. with summit crtr.
88		645	15	165	B 6	β?	or are bl. fr. A α in it?
			P-7 (Sinus Medii)				
89	100 (1)	903	32*	352	B 3	γ	
90			14	154	B 12	γ	
91			22*	242	B 6	γ?	bl. from nearby A α ?
92			11 x 15	121 x 165	A 3-4	α	2 overlapping craters?
93		904	34	374	B 5	γ	
94			37*	407	C 4	γ	
95			10	110	B 3	γ	
96			12	132	B 4	β?	funnel, 2 or 3 boulders
97			15	165	B 2	γ	
98			15	165	C 5	β	
99			12	132	C 6	β?	funnel? few boulders
100		905	13	143	C 4	β	bowl or cone
101			25*	275	B 4	β?	few boulders
102		909	16	176	B 6	γ	
103			10	110	B 4	γ	
104			13	143	B 7	γ	
105			15	165	B 7	γ	
106			19	209	B 5	γ	funnel?
107			14	154	C 4	β	
108		910	27	297	C 3	β	
109			10	110	B 4	γ	
110			11	121	B 6	γ	
111		911	12	132	B 7	γ	
112			13	143	B 5-6	γ	
113			17	187	B 5	γ	

*member of a crater chain

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
114	100 (1) 912	17	187	B 5	γ	
115		13	143	B 2	β	
116	913	13	143	B 4	γ	
117		19	209	B 4	γ	
118		14	154	C 5	γ	
119		10	110	B 2	γ	funnel
120	915	10	110	C 3	γ	
121		20	220	C 3	γ	
122	916-17	33	363	C 2	β	eccentric or 2 overlapped
123	918	28	308	C 4	β	
124		28	308	C 3	β	
125		14	154	C 4 (A?)	β	central mound
126		11	121	B 2 (C?)	γ	
127	919	14	154	C 2	γ	
128		16	176	B 6	γ	
129		24	264	B 6-7	γ	elongated N-S
130		13	143	B 3	γ	funnel? deeper than normal
131		15	165	B 4	γ	
132		15	165	B 7	γ	
133	920	20	220	B 3	β?	few boulders?
134		13	143	B 3	γ	
135		30	330	C 3	α	few bl. on plain
136	921	31	341	B 2-3	γ	
137		12 x 17	132 x 187	B 3-4	β	key-hole shaped
138		12	132	B 3-4	β	
139		11	121	B 2	γ	deeper than normal
140		18	198	B 3	β?	
141	922	12	132	B 3	γ	elongated or overlapping
142		23	253	B 3-4	γ	

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
143	100 (1) 922	10	110	B 7	γ	
144		12	132	A 2 (C ?)	α	nar. rim, deep, no in. ring
145		10	110	B 5	γ	
146		19	209	B 5-6	γ	
147		35	385	B 3	γ	
148	923	22	242	C 3	α	few bl. on plain
149		18	198	B 6	γ	
150	924	15	165	B 4	γ	
151		15	165	B 4	γ	
152		15	165	B 4	γ	elongated
153		15	165	B 5	γ	
154		14	154	B 4	γ	
155	925	12	132	B 2-3	γ	
156		10	110	B 2-3	β?	2 or 3 bl. detectable ?
157		10	110	C 3	γ	
158		10	110	C 3	γ	all in a row, all deep (158–160)
159		10	110	B 2-3	γ	
160	926-7	20	220	B 6	γ	
161		34	374	B 3	γ	irregular shape
162		13	143	B 5	β	
163		12	132	B 3-4	γ	
164		11	121	C 3-4	γ	
165		17	187	B 7	γ	
166		21	231	B 3	γ	
167		14	154	B 4-5	γ	
168	928	10	110	A 3-4	γ	secondaries, no blocks
169	928	16	176	B 5	γ	
170		20	220	B 2-3	β	deep, 2 or 3 boulders
171		13	143	B 3-4	γ	

Table I (Continued)

No.	Frame and Framelet		Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
172	100 (1)	928	20	220	B 4-5	β?	2 or 3 boulders
173			21	231	B 4	γ	
174		929	19	209	C 3-4	β	keyhole shape
175			17	187	B 5	γ	composite
176		930	10	110	B 2-3	γ	
177			21	231	C 3-4	γ	
178			28	308	C? 4	γ	irreg., composite?
179			10	110	C 5	γ	
180		931	17	187	C 2	β	
181			11	121	B 4	γ	
182			16	176	C 3	β	central mound
183		932	12	132	B 6	γ	
184			18	198	B? 4	γ	
185			25	275	C 2-3	γ	keyhole shape
186			13	143	C 5	β	
187			11	121	C 2 (A?)	α	sharp rim but deep
188		933	11	121	B 6	γ	
189			12	132	B 6	γ	
190			12	132	B 5	γ	
191			25	275	B 2	β?	
192			12	132	A? 5 (C?)	α	central mound
193	100 (2)	934	16	176	C 5 (B?)	β	
194			25	275	B 3-4	β	
195			30	330	B 6	γ	
196		935-6	23	253	B 4	γ	
197			13	143	B 6	γ	
198			36	396	C 3	β	
199			10	110	C 4	γ	
200		937	12	132	B 5	γ	

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
201	100 (2) 937	12	132	B 7	γ	
202		13	143	B 5	β	
203		12	132	B 6	γ	elongated E-W
204		30	330	B 5	β	
205		12	132	B 7	γ	
206		20	220	C ? 5	β?	boulders detectable ?
207		32	352	B 4	β	
208	938	13	143	B 6	γ	
209		16	176	B 8	γ	
210		10	110	B 4-5	γ	
211		12	132	B 5	γ	
212		15	165	C 4	α	
213	939	12	132	B 8	γ	
214	940	10	110	B 3	γ	
215		10	110	A ? 3 (C ?)	α	central mound, deep
216		13	143	C 5	γ	
217	941	16	176	B 4	γ	
218		12	132	B 6	γ	
219		11	121	B 3	γ	
220		11	121	B 2-3	β	
221		14 x 26	154 x 286	B 4	γ	
222		25	275	B 3	γ	
223		17	187	B 2	β	
224		13	143	B 2	β	
225		13	143	B 6	γ	
226	942	23	253	B 8	γ	square
227		21	231	C 5	β(α ?)	some bl. on plain?
228		12	132	A 1	α	
229	943	17	187	B 4	γ?	bl. in it due nearby A α ?

Table I (Continued)

No.	Frame and Framelet		Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
230	100 (2)	943	11	121	B 6	γ	elongated
231			11	121	B 3	γ	
232		944	12	132	A 3	α	somewhat deep
233			10	110	C 6	β	
234			25	275	B 3-4	γ	
235			60	660	C 4	β	funnel?
236		945-6	19	209	C 2	α	
237			12	132	B 4-5	γ	
238			16	176	B 4	γ	
239			16	176	B 3	γ	
240			10	110	C 5	γ	
241		947	17	187	B 5	γ }	central mound? overlap
242			20	220	C 4	γ }	some mounds but not old A
243			23	253	B 4	γ }	
244			15	165	B 5	γ	
245			14	154	B 3	γ	
246			15	165	B 6	γ	
247		948	17 x 22	187 x 242	B 4	γ	
248			10 x 17	110 x 187	A 3-4	α	2 appendages, few boulders
249			15	165	A? 8 (C7?)	γ? (α ?)	few bl. due to near sm. A α ? on edge, rather deep only lg., part covered
250		949	21	231	B 2	β	
251			26	286	B 2-3	β?	
252			16	176	B 4-5	γ	
253			26	286	C 4-5	β	funnel-looks out-of-focus
254			21 x 30	231 x 330	B 5	γ	
255		950	11	121	C 5	β	funnel?
256			19	209	B 5	γ	
257			11	121	C 5	γ	
258			33	363	C 5-6	β	few boulders seen

Table I (Continued)

No.	Frame and Framelet		Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
259	100 (2)	951	18	198	B 3-4	γ	
260			11	121	C 6	γ	
261		952	11	121	B 6-7	γ	
262			15	165	B 3	β?	
263			14	154	B 4	γ	
264		953	20	220	B 4-5	γ	
265			11	121	B 5-6	γ	
266		954-5	11	121	B 6	γ	old funnel?
267			15	165	B 5	γ	
268			12	132	C 7	γ	old funnel?
269			11	121	B 6	γ	
270		956	16	176	B 3-4	γ	
271			14	154	B 3	γ	
272			11	121	B 2-3	γ	
273		957	10	110	B 4	γ?	bi. in it due to nearby A α ?
274			16	176	C 6	γ	
275			33	330	B 5-6	γ	composite
276		958	11	121	A 2 (C4?)	α	2 or 3 bl. summit crater on c. p.
277		959	11	121	B 4	γ	
278			13	143	B 6-7	γ	
279			11	121	B 4	γ	
280		960	15	165	B 6	γ	
281			17	187	B 6	γ	
282			12	132	C 7	γ	
283		960	·17	187	B 6	γ	
284		961	13	143	C 6	γ	
285			11	121	B 4	γ	
286		962	37	407	B 7	γ	
287			12	132	B 5	γ	

Table I (Continued)

No.	Frame and Framelet		Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
288	100 (2)	962	17	187	B 4	γ	
289			25	275	B 3	β	
290		963	45	495	C 4-5	β	
291			14	154	B 4-5	γ	
292			13	143	B 3-4	β	
293		964-5	35	385	B 3	β? (γ)?	edge of photo
294			17	187	B 4	γ	
295		966	13	143	B 5	γ	
296			15	165	B 4	γ	
297	100 (3)	967	13	143	B 2-3	β	
298			26	286	C 4	α	few in, 2 or 3 on plain
299			16	176	B 3	γ	
300			10	110	B 4	β	
301		968	35	385	B 3	β?	a few boulders?
302			17	187	B 5	γ	
303		969	31	341	C 3	β	
304			17	187	B 3-4	β	
305			10	110	C 3	γ	funnel
306		970	10	110	C 2-3	β?	funnel, 2 or 3 boulders?
307			10	110	C 3	γ?	funnel
308			13	143	B 6	γ	
309			14	154	B 4	γ	
310		971	13	143	B 3	β	
311			43	473	C 4	β	
312		972	30?	330	B 6	γ	
313			15 x 24	165 x 264	C 3-4	β	boulders almost buried
314		973-4	12	132	C 3	β?	funnel, few boulders?
315			12	132	B 7	γ	
316			16	176	B 11	γ	

Table I (Continued)

No.	Frame and Framelet		Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
317	100 (3)	973-4	17	187	B 6	γ	
318		975	26	286	B 9	γ	
319		976	10	110	B 5	γ	
320			13	143	A 2	α	
321		977	22	242	A 1-2	α	
322			10	110	C 4	γ	funnel
323			16	176	B 4	γ	
324		978	20	220	B 9-10	γ	
325			23	253	B 6	γ	
326			10	110	C 2	β	inno. 325, funnel?
327		979	14	154	B 2-3	β	
328			18	198	B 5	γ	
329			16	176	C 2	β	
330		980	14	154	B 4	γ	
331			15	165	C 4	β	funnel?
332			21	231	B 10-11	γ	
333			24	264	B 8	γ? (β)?	some buried boulders?
334			12	132	C 3	β	funnel
335		981	20	220	C 3	β	
336			15	165	A 4-5	α	
337			10	110	A 5	β? (α)?	one boulder outside?
338		983-4	12	132	B 5	β?	
339			22	242	C 2-3	β	
340		984	22	242	C 4	β	funnel
341		985	23	253	C 2-3	β	funnel?
342			10	110	C 5	β	
343			10	110	C 2	γ	funnel
344			11	121	B 6	γ	
345			21	231	B 3	β	

Table I (Continued)

No.	Frame and Framelet		Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
346	100 (3)	985	14	154	B 2	β	from here through
347		986	10	110	A 4	γ	no. 376, craters
348			21	231	B 12	γ	are on a ridge or
349			14	154	B 10	γ	highland terrain
350			12	132	C 4-5	γ	
351			11	121	B 5	γ	
352		987	10	110	B 10-11	γ	
353			11	121	C 7	γ	
354			15	165	B 7	γ	
355		988	18	198	B 4-5	β?	covered lg. bl. or mounds
356			30 x 41	330 x 451	C 3 (B)?	α	deep but rim undetectable
357		992-3	12	132	B 4	γ	
358			11	121	B 5	γ	
359			18	198	B 4-5	γ	irregular
360			10	110	B 4-5	γ	deep, funnel?
361			23	253	C 3	γ	
362			12	132	B 3	γ	
363			11	121	B 6	γ	
364		994	18	198	B 4-5	β?	2 or 3 boulders in it?
365			15	165	B 3	β	
366			25	275	B 4	γ	
367		995	21	231	C 3-4	γ	
368		996	13	143	B 6	γ	
369			12	132	B 7	γ	
370		997	11	121	C 4	γ	
371			18	198	B 5	γ	
372			10	110	C 2	β?	funnel? few lg. bl. buried
373		998	15	165	B 6	γ	
374			10	110	C 5	γ (β)?	couple buried boulders?

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
375	100 (3) 998	20	220	B 3	γ	
376		11	121	C 2 (A)?	β	
		P-12 (Flamsteed Ring)				
377	181 (1) 1523	19	209	B 9	γ	
378		12	132	B 11	γ	
379	1524	10	110	B 4	γ	
380		10	110	B 5	β	
381		12	132	B 5	γ	
382		14	154	B 7	γ	
383		15	165	B 11	γ	
384		10	110	C 4	β	
385	1525	14	154	B 3	β	funnel (dimple)
386		10	110	B 2	β	
387	1526	12	132	A 4	α	
388		25	275	C 4	β	
389		13	143	A 8 (C4)?	α	deep, few bl. ~ 1/2 diam. away
390	1527	11	121	A 1	α	
391		10	110	B4	γ	
392		14	154	B 12	γ	
393	1528	12	132	C 6	γ	
394		12	132	B 9	γ	
395	1528	14	154	B 4	γ	
396	1529	31	341	C 4	β	funnel?
397		20	220	B 4	β	
398		10	110	C 7	γ	
399		12	132	B 6	γ	
400		10	110	C 5	γ	
401	1530	10	110	C 3 (A4)?	β	deep, bulbous interior
402		10	110	C 5	γ	

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
403	181 (1) 1530	12	132	B 6	γ	
404	1531-2	16	176	B 7	β	
405		10	110	C 5-6	γ	
406	1533	12	132	C 4	β	funnel (dimple)
407		12	132	B 5	γ	
408		11	121	B 6	γ	
409		20	220	B 3	β	bl. due to another?
410	1534	12	132	A 1-2	α	
411		12	132	B 6	γ	
412		11	121	B 7	γ	
413		11	121	C 7	γ	
414	1535	25	275	C 3-4	β	
415		12	132	B 4	γ	
416		11	121	C 9	γ	
417		16	176	B 2 (C4)?	β	somewhat deep
418	1536	12	132	B 4-5	β	few boulders in it
419	1537	15	165	A 1-2	α	
420		11	121	B 4	γ	
421		19	209	B 2	β	
422		20	220	B 1 (C3)?	γ	no rim but deep
423		10	110	C 3	γ	
424	1538-9	14	154	B 2	γ	
425		10	110	B 4	γ	
426		13	143	A 3	α	
427	1540	11	121	B 6	γ	
428		10	110	A 5	α	
429	1542	16	176	A 2	α	
430	1543	18 x 26	198 x 286	C 5	β	bl. barely detectable
431	1544	11	121	B 11	γ	bl. in it from rim A α

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
432	181 (1) 1545	11	121	B 9	γ	
433		12	132	B 9	γ	
434	1546	14	154	B 5	β	irregular shape
435	1548-9	35	385	C 4	β	
436		10	110	C 6	γ	not evolutionary A's
437		13	143	C 5	β	not evolutionary A's
438		14	154	C 5 (B3)?	β	not evolutionary A's
439		10	110	C 4	γ	
440	1550	12	132	C 4	γ	
441	1551	21	231	B 3	β	
442		10	110	B 3	β	
443	1552	13	143	C 3	β	mound in bottom
444		10	110	B 4	γ	
445		15	165	B 4	γ	
446		10	110	C 3	α	funnel? in an old crater?
447		40	440	C 2	β	
448	1553	13	143	B 4	γ	
449		10	110	A 4	α	
450		14	154	B 4	γ	
451	181 (2) 1554	12	132	B 3	γ	
452		13	143	C 6	γ	
453	1555	11	121	B 10	γ	
454		12	132	B 9	γ	
455	1556	15	165	C 7	γ	
456		13	143	C 6	γ	
457		11	121	B 6	γ	irregular
458	1557-8	10	110	B 4?	γ	
459		10	110	B 7	β	2 or 3 bl. can be seen
460		10	110	A 4	α	

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
461	181 (2) 1559	10	110	B 4	β	few bl. can be detected
462	1560	12	132	C 3	β	bl. barely detectable
463	1561	22	220	C 2	β	
464		10	110	B 3	β	
465		10	110	B 4	β	
466	1562	13	143	C 3	β	boulders small
467		10	110	B 4	β	boulders barely detectable
468		14	154	C 3	β	
469		12	132	B 4	γ	
470	1563	10	110	B 5	β	2 or 3 boulders
471	1564	10	110	A 5	α	
472		11	121	C 6 (B3)?	γ	
473	1565	22	220	C 3	β	small boulders
474		16	176	A 1	α	
475	1566	14	154	C 3	β	funnel?
476		10	110	C 4	β?	its own or fr. the A 1?
477	1567-8	11	121	B 2	β	eccentric funnel?
478		10	110	B 4	β?	bl. in it from the A 1?
479		13	143	C 4	β	
480	1569	17 x 22	187 x 242	C 2-3	β	spoon-shaped
481		21	231	B 3	β?	bl. due to others?
482	1570	10	110	C 4-5	β	
483		16	176	B 2	β	deeper than normal
484		26	286	C 1-2	β	
485		16	176	B 3	β	few bl., triangular
486		17	187	B 3	β	
487	1571	11	121	B 5	β?	boulders detectable?
488		12?*	132	C 3	β	
489	1572	12	132	C 4 (A5)?	β? (α)?	poss. some bl. around

*member of a crater chain

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
490	181 (2) 1572	11	121	B 3	β	
491		26	286	C 4	β	
492		14	154	C 5	β	
493	1573	55 x 85	550 x 935	C 1	β	spoon or keyhole shape
494	1574	18	198	B 3	β	
495	1575	15	165	B 4	β?	on big one, bl. its own?
496		18	198	B 5	γ	
497	1578	12	132	B 1	β	funnel? overlaps another
498		13	143	B 4	γ	
499		23	253	C 3	β? (α)?	some bl. out little way
500	1579	25	275	C 3	β	
501		12	132	C 2	β	
502		16	176	C 2	β	
503	1580	10	110	B 6	γ	
504		12	132	C 3	β	
505		21	231	C 2	β	
506		15 x 10	165 x 110	C 5	β	elongated E-W
507	1581	12	132	C 4	β	irregular shape
508		14	154	B 9	γ	elongated E-W
509	1581	11	121	B 4	β?	bl. detectable?
510		17	187	B 5	β?	bl. detectable?
511	1582	17	187	B? 3	β	deeper than normal
512	1583	21	231	C 3	β	
513		13	143	B 6	γ	
514		27	297	B 2	β	deeper than normal
515	1584	23	253	C 2	β	
516		18	198	C 2-1	β	
517	1585	10	110	C 1	β	
518		13	143	B 6	γ	

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
519	181 (2) 1585	12	132	B 4	β?	bl. detectable?
520		30	330	C 1	β	
521	181 (3) 1588	32	352	C 1	β (α) ?	few bl. on outer apron
522		14	154	B 4	β	
523		15	165	B 3	β	
524	1589	18	198	C 3	β	
525		13	143	B 4-5	β	2 or 3 bl. seen
526		10	110	A 3	α	
527	1590	11	121	B 5	β?	bl. detectable?
528		10	110	B 8	γ	
529		11	121	B 10	γ	
530		13	143	B 6	γ	
531	1591	12	132	A 1-2	α	elongated E-W
532		11	121	B 3-4	β?	bl. detectable?
533		12	132	B 6	γ	
534		26	286	C 2	β	
535		10	110	C 4 (A5)?	β	
536		12	132	B 4	β?	bl. detectable?
537	1592	13	143	C 3-4	β	
538		12	132	B 4	γ	
539		12	132	C 4	β	
540		11	121	B 11	γ	
541	1593	10	110	B 5	γ	
542		13	143	C 5	β?	few bl. detectable?
543		15	165	B 9	γ	
544		10	110	B 11	γ	
545		14	154	B 4	γ	
546	1594	10	110	B 5	γ	
547		11	121	B 4	γ	

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
548	181 (3) 1595	12	132	C 2	α	central mound
549		16	176	B 3	β	
550		11	121	B 3-4	β?	elong. E-W, bl. on rim?
551		11	121	B 3-4	β?	few tiny boulders?
552	1596-7	11	121	B 10	γ	
553		13	143	B 6	γ	
554		10	110	B 5	γ	
555		10	110	B 9	γ	
556	1598	11	121	C 7	γ	
557		10	110	B 7	γ	
558		11	121	C 4	β?	2 or 3 boulders?
559	1599	15	165	B 4	β?	2 or 3 boulders?
560	1600	10	110	C 3-4	γ	funnel?
561		15	165	C 4	β?	few boulders?
562		15	165	C 4	β	
563		10	110	B 3-4	β	
564	1601	13	143	B 3-4	β	
565		11	121	B 3-4	β?	few boulders?
566		10	110	B 4	γ	
567	1602	10	110	C 4	γ	
568		14	154	B 8	γ	
569		16	176	B 6	γ	
570		14	154	B 6	γ	
571	1603	13	143	C 4	β?	bl. barely detectable?
572		10	110	B 3	γ	
573		10	110	C 3-4	β	
574	1605	20	220	C 2	α	
575		18	198	B 5?	β	
576	1608	15	165	B 5	γ	

Table I (Continued)

No.	Frame and Framelet	Diameter (mm)	Diameter (m)	Crater Type and Overlay	Boulder Type Distribution	Remarks
577	181 (3) 1609	15	165	B 2	γ	
578		16	176	B 2	β	
579		16	176	B 4	γ	
580		14	154	B 3-4	γ	
581	1610	10	110	B 5	γ	
582		12	132	B 2	γ	funnel ?
583		22	242	B 3-4	β	
584		12	132	B 3	β	
585	1612	18	198	C 2	α	
586		22	242	B 4	β	irregular shape
587		11	121	B 3	γ	
588	1613	12	132	B 2	β	
589		14	154	B 5	γ	
590		10	110	B 6	γ	
591	1614	15	165	B 3	β?	few bl. just detectable
592		10	110	A 3-4	α	
593		12	132	B 10	γ	
594		12	132	B 9	γ	
595		12	132	C 5	γ	
596		12	132	C 4	β	elongated E-W
597	1616	12	132	B 4-5	γ	
598		10	110	B 7	γ	
599	1617	12 ?	132	B 10	γ	
600		16	176	C 7	γ	
601	1618	10	110	B 4	γ	
602		10	110	C 6	α	bl. just detectable ?
603		19	209	B 3	β	muted boulders

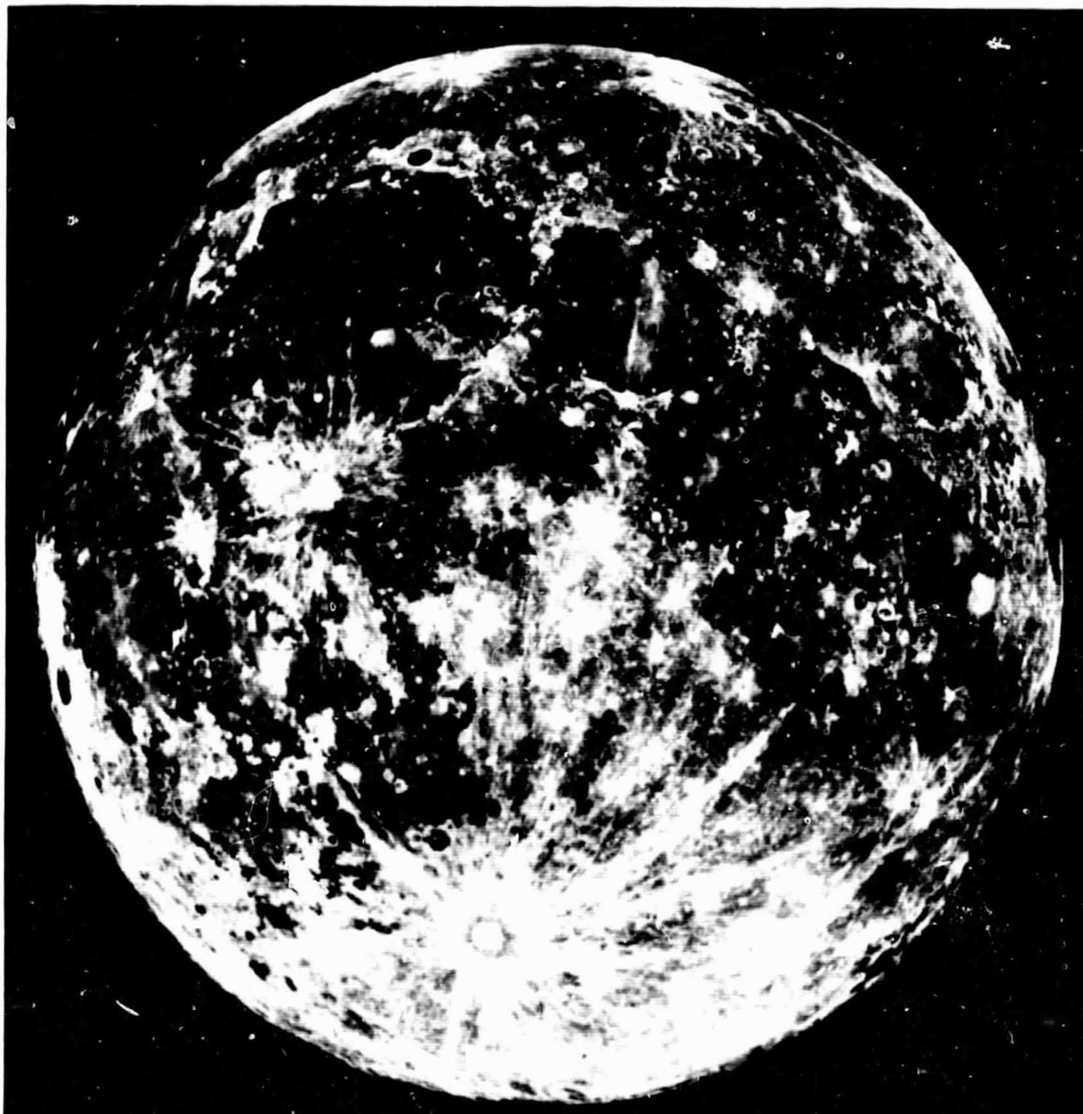

Figure 1. Mount Wilson full moon photograph showing locations of three sites examined on the Lunar Orbiter III high resolution photographs. T = Tranquillitatis, site P-4; S = Sinus Medii, site P-7; and F = Flamsteed Ring, site P-12.

PRECEDING PAGE BLANK NOT FILMED.

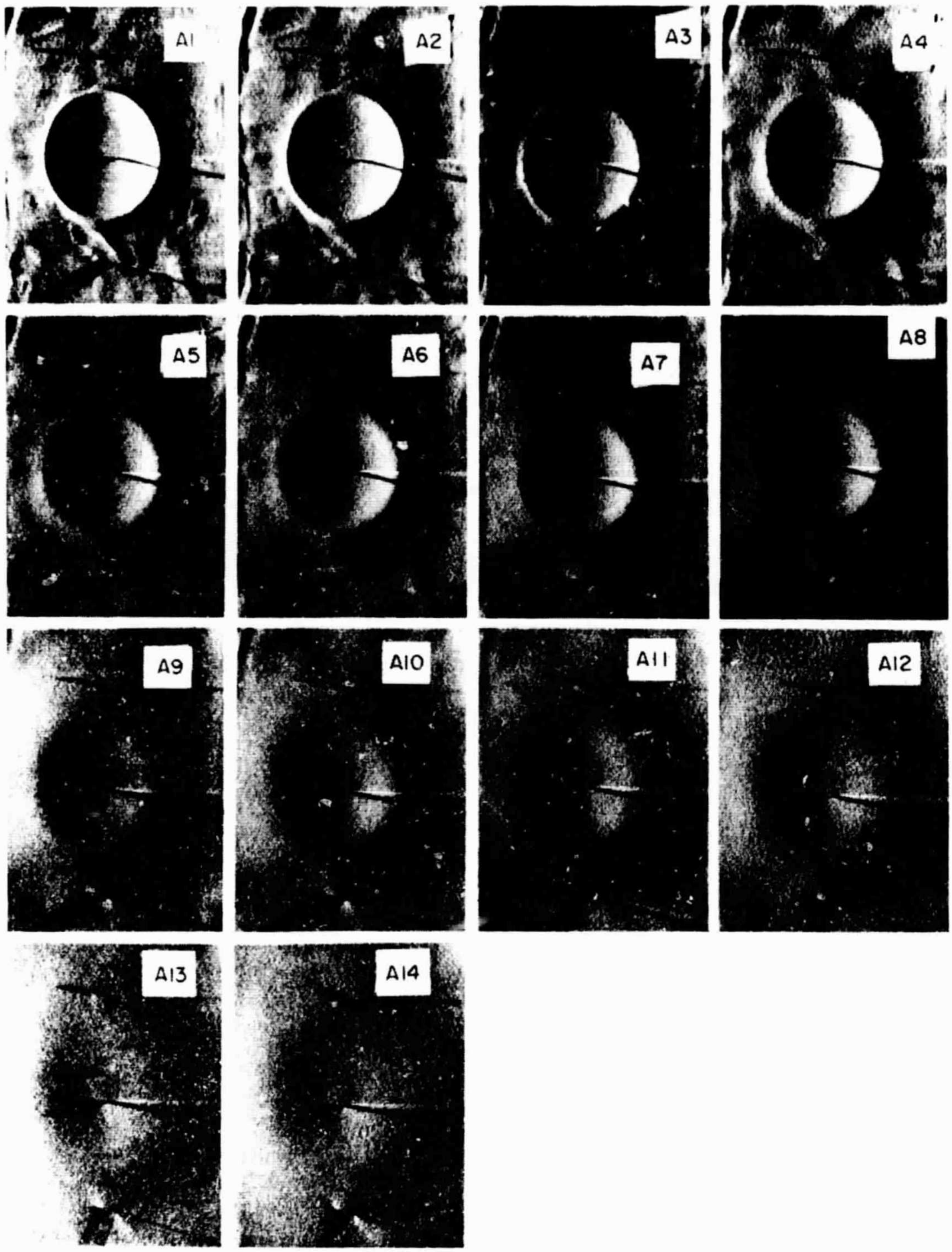

Figure 2. Reproduction of Jaffe's A-type model crater (sharp, narrow raised rim and relatively shallow) showing it with steps of increasing overlay from step 1 (no overlay) to step 14 (barely distinguishable).

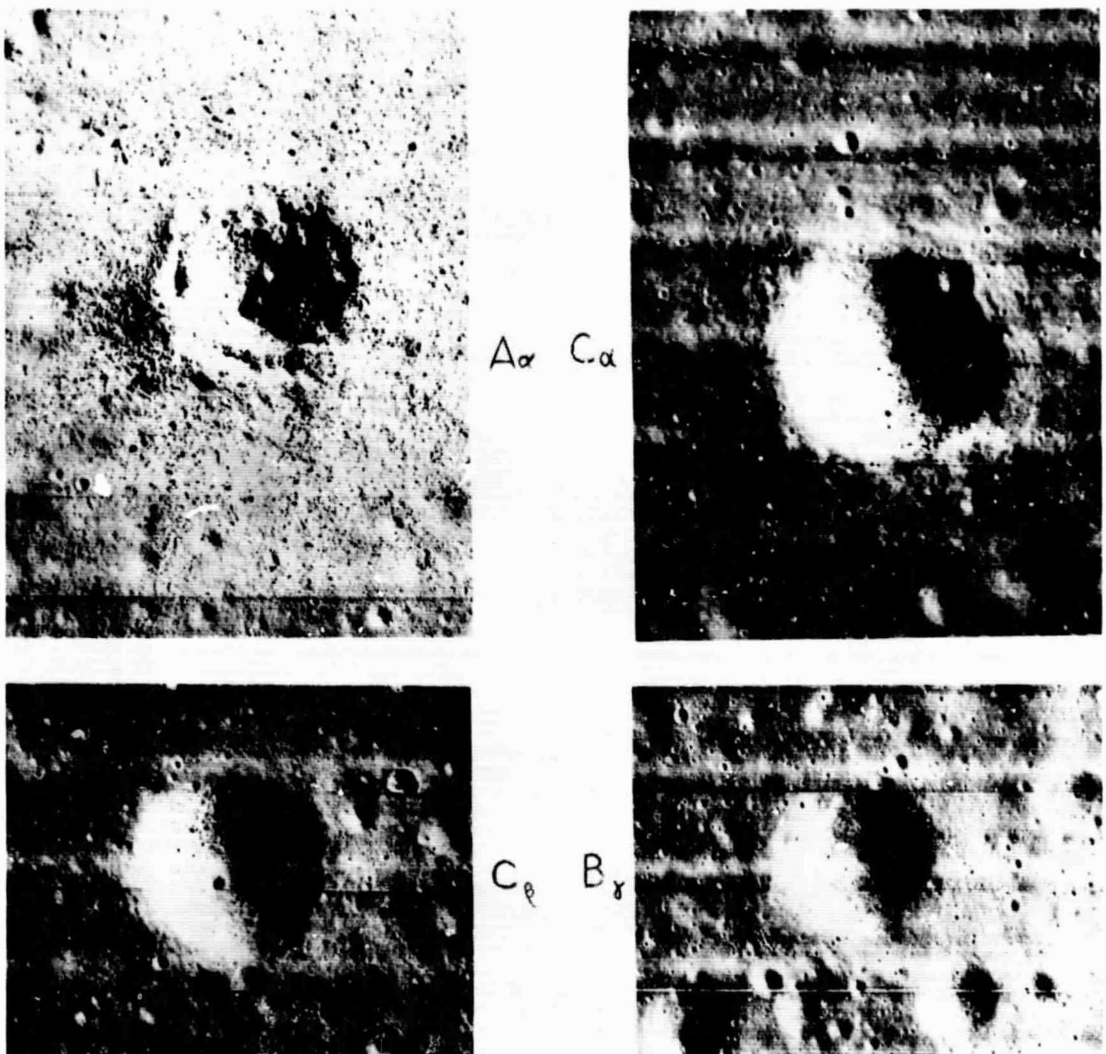

Figure 3. Examples of relatively fresh craters (each about 400 m in diameter) illustrating each type and each kind of boulder distribution considered. Note the numerous and almost uniform size of boulders peppering the inside of the A α crater (superposed on the large mounds) and the surrounding plain. Boulders were distributed far beyond the limits of this photograph. In contrast, the C α crater has only a few boulders outside, detectable at about 2, 8, and 10 o'clock directions. Note also the possible central crater in its bottom, and its entirely different appearance from that of the A α crater. In the C β crater there is definitely a central crater, apparently funnel-shaped. No blocks can be found around this crater, only inside it, while none at all can be detected in or around the B γ crater.

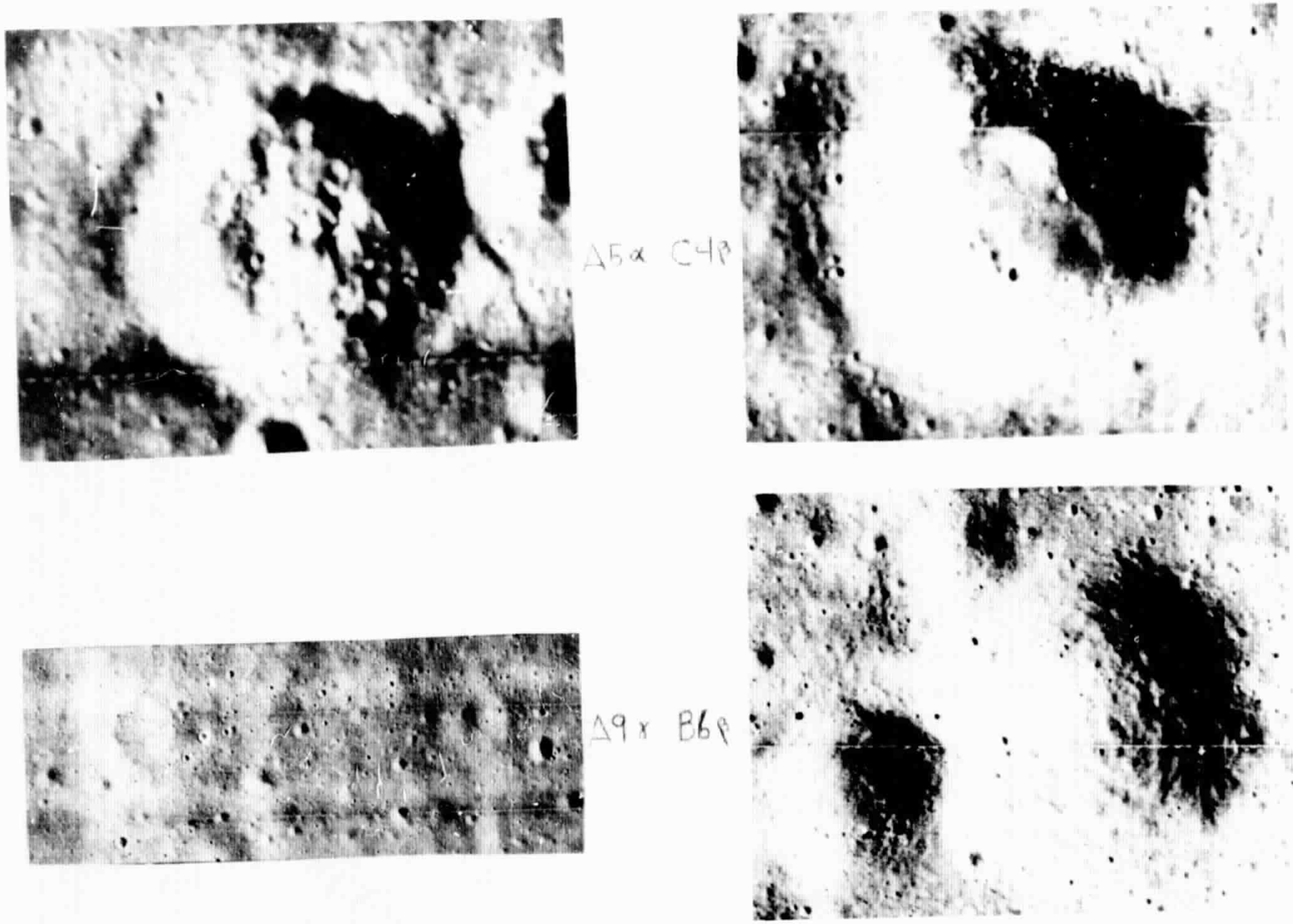

Figure 4. Examples of apparently more mantled craters of each type and boulder distribution. Note the persistence of the large mounds (not boulders). Boulders are still visible on the plain also. Note two ghost craters (to which the indicated classification belongs) in the A 9 γ photograph, the larger one near the left edge and the other near the right edge. Their narrow rims are still detectable even though the craters are nearly completely filled.

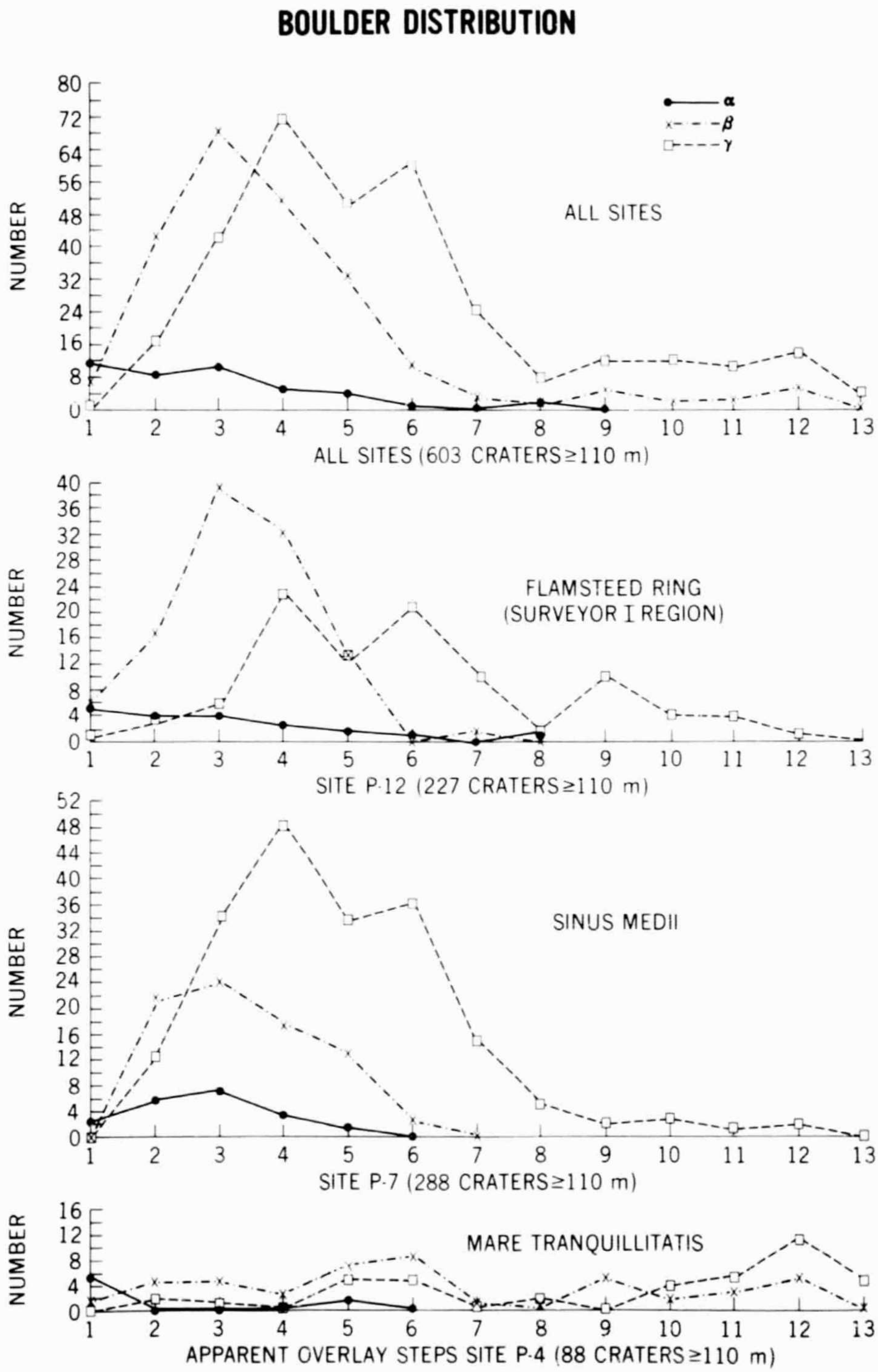

Figure 5. Plots of the number of craters for each of the boulder distributions versus the steps of apparent overlay for each of the three sites investigated and the combined number of craters (top graph).

CRATER TYPES DISTRIBUTION

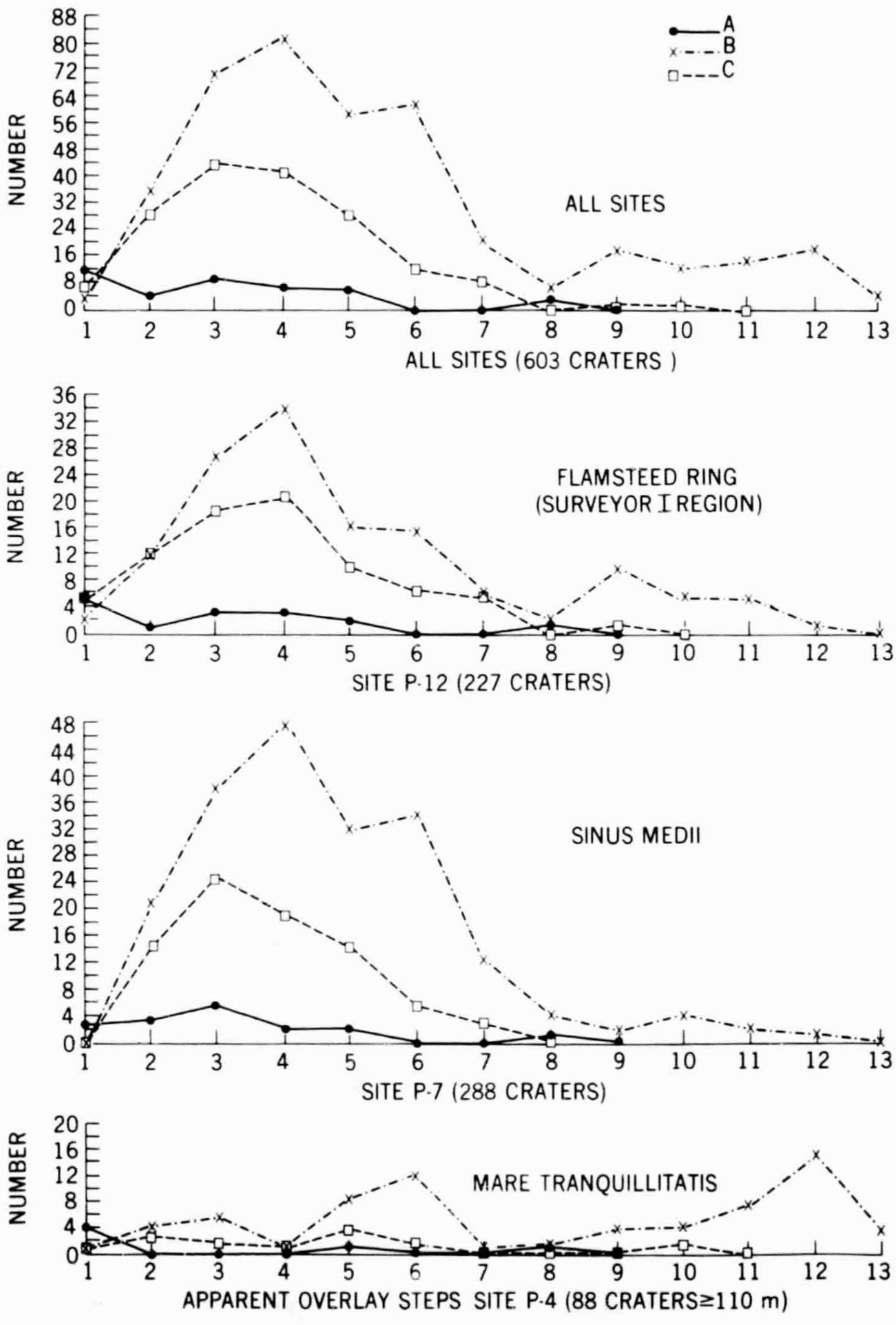

Figure 6. Plots of the number of craters for each crater type versus the steps of apparent overlay for each of the three sites and the combined number of craters

PERCENT of BOULDER DISTRIBUTION

BOULDER DIST. / CRATER TYPE	A	B	C
α	69	0	31
β	0	57	43
γ	1	82	17

(a)

PERCENT of CRATER TYPE

CRATER TYPE / BOULDER DIST.	α	β	γ
A	86	3	11
B	0	33	67
C	8	59	32

(b)

NUMBER of BOULDER DISTRIBUTION ·VERSUS CRATER TYPES

BOULDER DIST. / CRATER TYPE	A	B	C
α	31	0	14
β	1	132	99
γ	4	268	54

(c)

PERCENT and NUMBER of TOTAL

CRATER TYPE	A		B		C	
	%	NO.	%	NO.	%	NO.
	6	36	66	400	28	167
BOULDER DISTRIBUTION	α		β		γ	
	%	NO.	%	NO.	%	NO.
	7	45	38	232	54	326

(d)

Figure 7. (a) percent of boulder distribution (ordinate) with respect to crater type (abscissa), (b) percent of crater type (ordinate) with respect to boulder distribution (abscissa), (c) same as (a) giving numbers of craters involved, (d) percent and number of craters of each crater type and each boulder distribution.

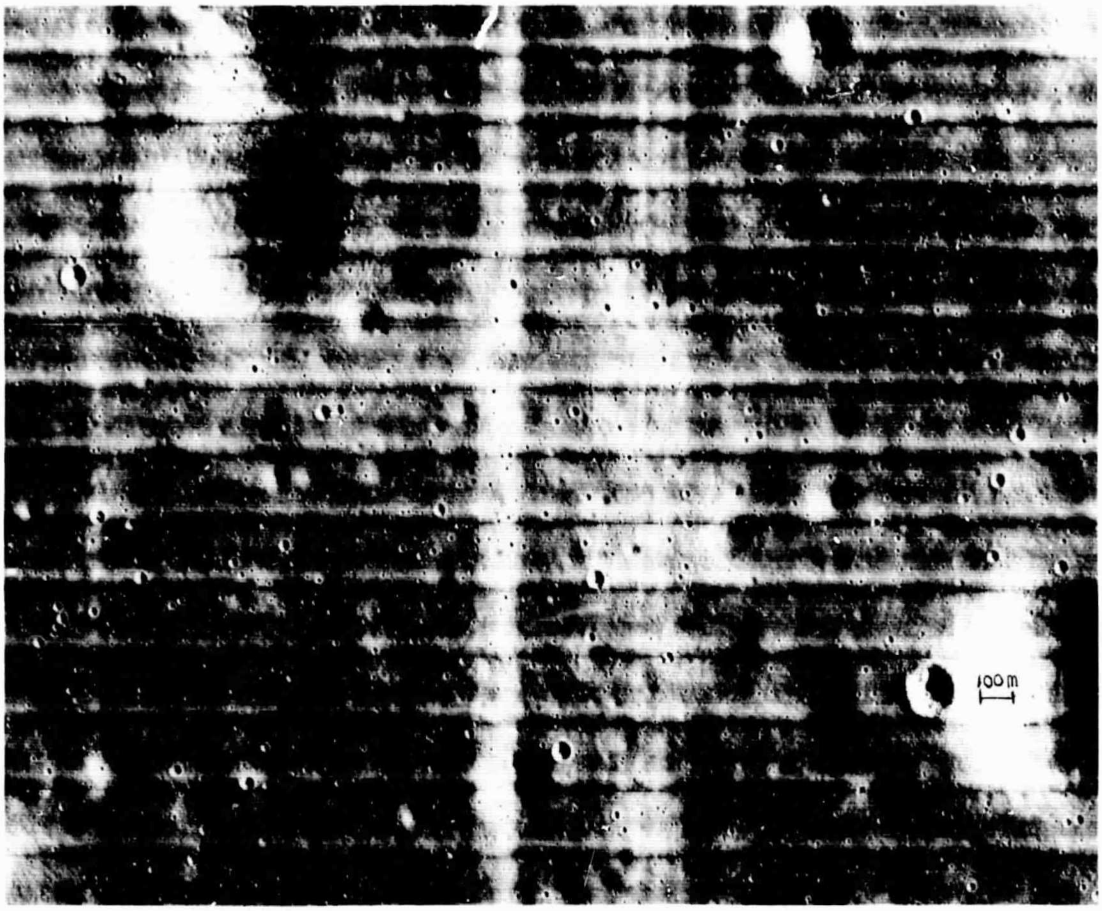

Figure 8. A representative section of the P-4 site in M. Tranquillitatis showing the general appearance of the terrain and each type of crater and boulder distribution. At lower left corner is e.g., an A α, at upper right is a C α, (with vent?) the larger crater in the upper left is a C β and at the lower middle is a B β. Note the subdued character of most craters, yet boulders are visible in most of them, e.g., the barely detectable crater in the center.

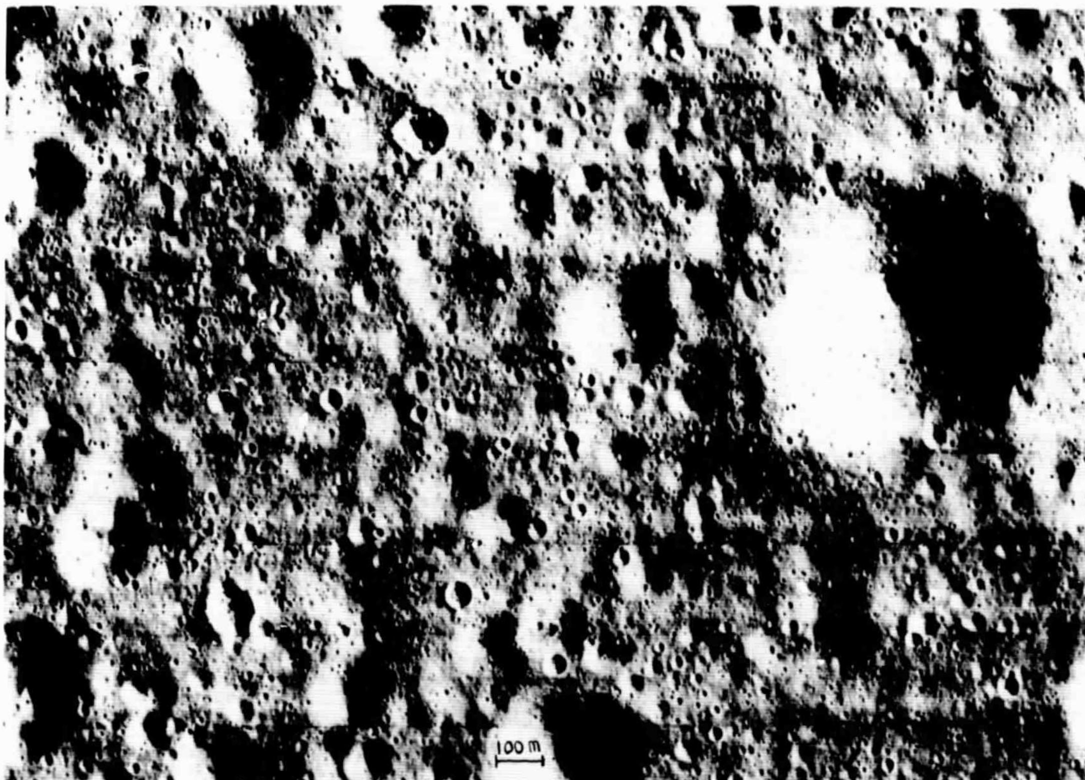

Figure 9. A representative section of the P-7 site in S. Medii showing its general appearance and each crater type and boulder distribution. Note the high density of craters, but general apparently greater freshness than those in Figure 7. Examples of types and distribution are: A α in the upper center, B γ just to the right and below the A α, and a C β with a central crater (vent?) in its bottom - the large crater at right. Successive mantled stages of the A type can be seen in this photograph. The majority of craters in this region have no visible boulders, usually only the sharper-looking craters do and then relatively few.

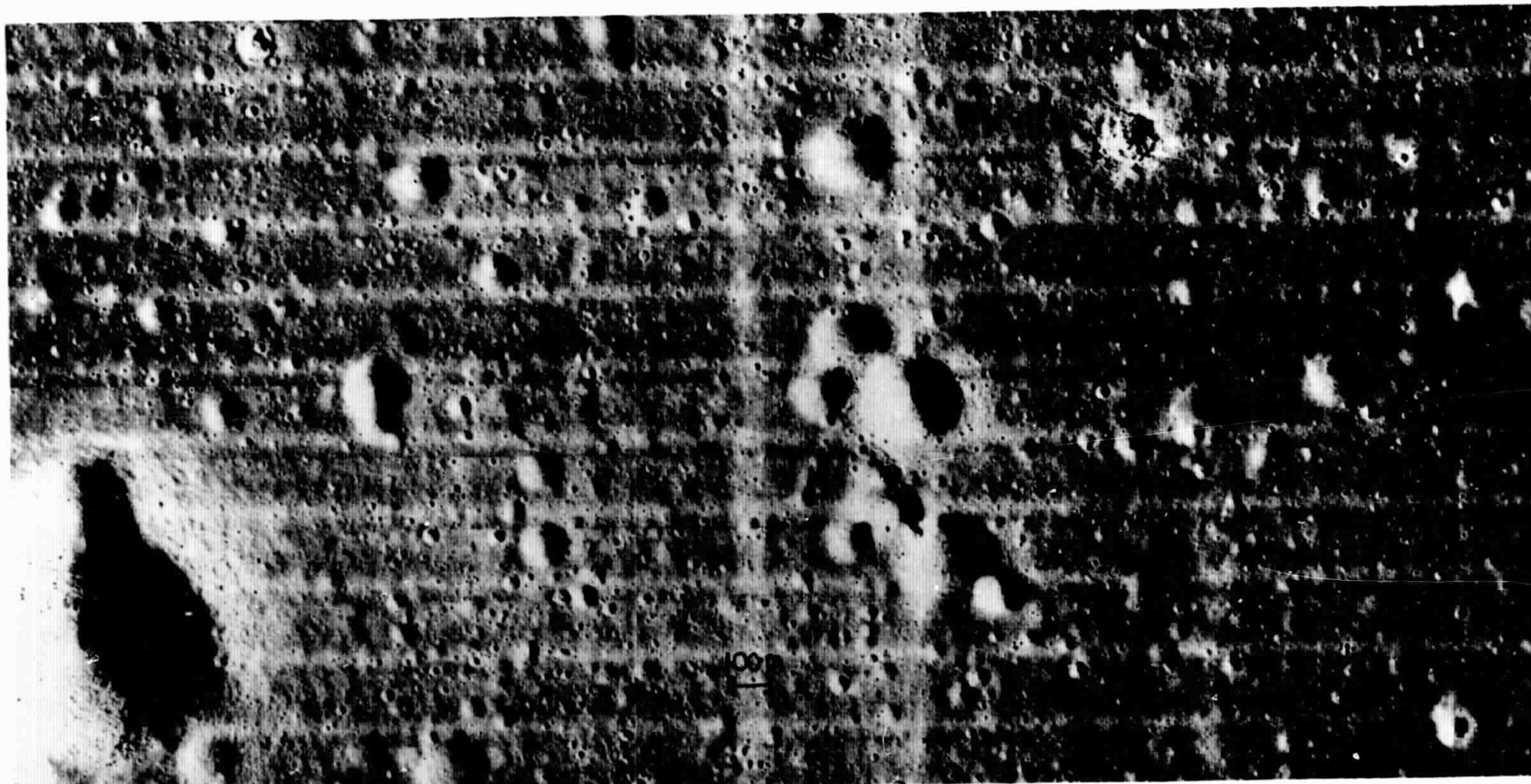

Figure 10. A representative section of P-12 in the Flamsteed Ring is shown here. Note the intermediate character in appearance for this site compared to those of P-4 and P-7. It is intermediate both in number of craters and number of craters with detectable boulders. Again, successive evolutionary stages of the A's can be seen, such as in the upper right and upper left respectively. Near the center and upper right are examples of relatively fresh craters of the same size and freshness: C β, B β ? and A α respectively. The question for the B β pertains to the origin of the blocks, whether to it or craters in and around it. The B-type here does not seem to be an evolutionary mantled stage of the A-type, but may be of the C-type. Note that despite the large size of the fresh crater in the lower left corner, boulders are found only in it and are quite fresh and sharp in appearance.