CRATER FREQUENCIES ON LAVA-COVERED AREAS RELATED TO THE MOON'S THERMAL HISTORY*

C. S. BEALS and R. W. TANNER
Manotick, Ontario, Canada

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Abstract. Making use of Orbiter and Apollo photographs, frequency counts of craters down to 2 km diam as indicators of the relative ages of lunar features, have been made on 264 areas, including 15 terrae, 27 recognized maria, 174 flat-floored craters and 48 lava-covered areas with indefinite boundaries designated as 'marets'.

Analysis of frequency counts on flat-floored craters on the basis of this data and re-assessment of former results, combined with the relatively restricted age range of lunar samples, make it unlikely that the present observations are able to reach back in time to impacts on an assumed primordial floating crust.

The range of crater frequencies on the marets, together with their wide distribution over the lunar surface, suggest lava migrations to the surface within autonomous domains each with its own chronology, covering an extensive period of lunar history. The close association of marets with flat-floored craters provides a reasonable origin for the floor material of these latter objects. The lava migrations associated with the marets suggest that internal heating may be a more important factor in the origin of lunar surface features than had formerly been supposed.

Kopal's views on the origin of the moon's multiple moments of inertia (1972) are considered to support the concept of autonomous domains.

It is considered that the time sequence of separate lava flows represented by the marets may be a reflection of physical processes within the moon responsible for the successive lava flows associated with the larger maria.

1. Purpose and Initial Assumptions

The purpose of this study is to assemble a representative body of data on flat lava-covered lunar areas, to place them in a time sequence and to attempt to derive from the photographs and the numerical data some information about the origin of the lava and the nature of its migration from the interior to the surface of the Moon. The work is based on two familiar basic assumptions. The first assumption is that a majority of the conspicuously flat areas on the surface of the Moon represent the surfaces of lava pools that have solidified in place.

There are two reservations which should be made in connection with this assumption. The first of these refers to descriptions of flat areas on the Moon's surface by recent geological investigators. This work has been summarized and an extensive reference list prepared in connection with the production of a geological map of the Moon on a scale of 1:5000000. (Wilhelms and McCauley, 1971). In detailed descriptions, flat areas are usually designated as Ip and interpreted as volcanic flows, tuff beds and ash flows from many separate vents (Howard and Masursky, 1968; Offield, 1971). Without dissenting from the general idea that the flat areas may be due to relatively complex volcanic processes it appears that the primary causal agent is the

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flow of liquid lava and we therefore consider it justified to retain the designation 'flat, lava-covered areas' as essentially correct.

In addition to the above considerations which refer largely to the matter of nomenclature, it is now generally conceded that exceptions to the general rule that flat areas on the Moon are due to lava flows, may be found in areas of deposition of fragmental material from major impacts*. This study is based on the assumption that relatively undisturbed lava-covered areas predominate, although, as will be mentioned later there may exist cases where the interpretation of the data is complicated by the presence of fragmental debris.

The second fundamental assumption is that counts of small craters appearing on flat areas of the lunar surface constitute a valid method of placing such areas in a time or age sequence. This method is well known and has been discussed by Baldwin (1964) Hartmann (1970) and Gault (1970) in considerable detail.

In addition, Baldwin (1969, 1970a, 1970b) has devised a method of determining the relative ages of large craters depending on the alteration of the height of rims and depths of floors by isostatic adjustment; while Soderblom and Lebofsky (1972) have used observations of the erosion of craters in the size range 200 to 2000 m to determine the relative ages of the craters themselves and indirectly of the flat (mare) surfaces on which they occur.

The principal difficulty with crater counting methods, involving as they do a cumulative record, is that such a record is being continuously altered and sometimes destroyed by subsequent impact events. Gault (1970) on the basis of elegant laboratory experiments has pointed out that the result of a continuous bombardment by meteorites of all sizes is, at first, a steady increase in the number of craters on the bombarded area. As time goes on a stage is reached where the number of craters destroyed becomes equal to those being formed, a situation which is described as equilibrium. So long as equilibrium is not reached or approached closely, the crater counting method should give a valid indication of relative age for flat lava surfaces. While our crater counts, as will be seen later, range from 8 to slightly over 300 it appears that the great majority of them are confined to values below 150. This suggests that equilibrium values are, in general, not closely approached, so that within the limits of error of the observations, they should give a valid indication of the relative ages of lunar features.

The above discussion refers to a situation where the lunar surface is bombarded by bodies of a limited size range where the smaller craters (<10 km diam) predominate. For craters and lava surfaces which have been blanketed by debris from major impact events such as those which have produced the circular maria (Overbeck *et al.*, 1973; Chao *et al.*, 1973), the surface on which counts are made is clearly different from the original surface. For a very thick deposit of debris the surface may be completely rejuvenated with little trace remaining of the original record. For thinner layers the record may be altered in such a manner as to appear younger if

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* Note some resemblance to suggestions made by Gold (1955).

the method of crater counts is used. It is even possible that it could appear older if the criterion of crater erosion is employed. In any case the possibility of such distortion of the data should be kept in mind in assessing the results.

2. Accumulation and Assessment of Data

2.1. SELECTION OF PHOTOGRAPHS

The studies of this paper are based upon high resolution Orbiter photographs and a small number of Apollo photographs obtained from the Lunar Science Institute of Houston, Texas and the World Data Centre of NASA located at Greenbelt, Maryland. Each of the photographs contains at least one flat-floored crater on which small index craters can be clearly discerned. Careful efforts were made to put together a selection of prints as representative as possible of the entire area covered by the high resolution photographs. Each author made his own list, one based on the best available NASA charts and the other on 35 mm catalogue films from the World Data Centre. The two lists were then combined and reasons for rejecting or accepting doubtful frames discussed in detail. In the first selection, flat-floored craters were emphasized, though a substantial number of recognized maria were incorporated. In addition there were numbers of flat mare-like objects of indefinite outline to be described later in more detail, which are designated by the term *maret*. Some of these objects were noted on lunar maps and others were recognized only on the photographs

TABLE I

Flat-floored craters

Long.	Lat.	Name	Freq. *N*	Area	Photo	Notes
173E	17S	Aitken	70	0.50	II 33M, H3	Central uplift Complex floor
172E	0	Coriolis	97	0.12	II 34H3	
164E	52N	D'Alembert	44	3.00	V 85M	
155E	10S	Anon C	140	1.83	I 115M	
152E	45N	Campbell	98	3.00	V 103M	
149E	20S	Gagarin	136	4.80	I 115M, 116M, AS 15 0095-96-97	Well preserved old crater
141E	6N	Mendeleev	51	5.00	I 115M	Comparable to a mare
129E	21S	Tsiolkovsky	9	0.85	III 121H2, AP 15 SM 003	Large central uplift black floor
122E	20S	Fermi	80	4.30	I 136M, III 121H2	
117E	86N	Anon C	246	0.24	IV 68H3	
108E	18S	Hilbert	159	0.98	II 196M	
105E	12S	Pasteur	131	4.50	II 196M, H2, H3	
104E	54S	Kugler	50	0.28	IV 9H1	
103E	66S	Anon C	57	0.19	IV 5H2	
103E	2S	Saha	94	0.34	II 196H1	
101E	68S	Anon C	111	0.83	IV 5H2	Part of old crater, edge of photo
101E	43S	Lamb	76	0.70	IV 10H2, 11H2	

Table I (Continued)

Long.	Lat.	Name	Freq. *N*	Area	Photo	Notes
96E	59S	Chamberlin	9	0.22	IV 6H2	
96E	42S	Jenner	33	0.31	IV 10H2, 11H2	
93E	18N	Al-Biruni	41	0.19	IV 18H2	
93E	26N	Joliot	30	1.20	IV 18H3	Central uplift
91E	56S	Jeans	57	0.19	IV 38H1	
90E	58S	Anon C	26	0.31	IV 6H3	
89E	15N	Goddard	19	0.44	IV 18H2, 165H3	
89E	28N	Rayleigh	67	0.88	IV 18H3	
88E	61S	Petrov	23	0.13	IV 6H3	
87E	55S	Hanno J	62	0.16	IV 38H1	
87E	22N	Hubble	37	0.27	IV 18H3	
86E	64S	Anon C	26	0.31	IV 6H3	
85E	85S	Amundsen	65	0.17	IV 58H1	
85E	51S	Lyot	48	1.29	IV 38H1	
85E	8N	Neper	22	0.83	IV 165H3	
83E	54S	Hanno L	56	0.30	IV 38H1	
79E	36N	Gauss	45	1.39	IV 165H2, 177H2	Complex floor
78E	52S	Lyot H	91	0.26	IV 38H1, 52H2	
76E	44S	Oken	56	0.32	IV 38H2	
73E	53S	Brisbane Z	26	0.23	IV 52H2	
71E	56S	Hanno	319	0.11	IV 64H1	
70E	29S	Legendre	200	0.40	IV 38H3, 39H1	
70E	20S	Balmer	114	1.15	IV 184H1	Oblique photo
68E	32S	Adams	185	0.11	IV 38H3	
68E	75N	Peterman	118	0.21	IV 68H2	
66E	59S	Pontécoulant	80	0.23	IV 64H1	
62E	16S	Vendelinus	129	0.65	IV 184H1	Oblique photo
61E	36S	Furnerius	129	1.00	IV 52H3, 59H2	Only part of crater on each photo
60E	78S	Demonax	124	0.35	IV 58H1, 70H1	
60E	40N	Messala	49	0.86	IV 191H2, 192H1	
60E	50N	Anon C	27	0.70	IV 74H3	
57E	53N	Endymion	16	0.64	IV 67H3, 74H3, 177H3	
56E	28N	Cleomedes	14	0.79	IV 54H3, 62H1	
53E	59N	De La Rue	29	0.78	IV 68H1	
52E	55S	Biela	32	0.18	IV 58H3	Central uplift
49E	17S	Cook	19	0.11	IV 60H2	
48E	30S	Reichenbach	171	0.12	IV 59H3	Small flat floor
47E	60S	Hagecius	62	0.19	IV 58H3	Part of floor obscured
47E	49S	Steinheil	160	0.09	IV 71H2	
47E	37S	Rheita	92	0.18	IV 71H2	
46E	15S	Colombo	12	0.08	IV 60H2	
44E	73S	Boguslawsky	105	0.26	IV 70H2, 82H2	
43E	55S	Rosenberger	111	0.27	IV 58H3, 76H1, 88H1	
43E	41S	Metius	60	0.20	IV 64H2, 71H2	
42E	46S	Janssen	85	0.26	IV 83H2	Most of floor obscured
40E	68N	Arnold A	22	0.19	IV 80H2, 92H2	
39E	54S	Vlacq	106	0.18	IV 76H1, 83H1, 88H1	
39E	47N	Hercules	13	0.12	IV 79H2, IV 86H3	
38E	58S	Nearch	14	0.12	IV 83H1, 88H1	
37E	67N	Arnold	40	0.41	IV 68H2, 80H2, 92H2, 177H1	

Table I (Continued)

Long.	Lat.	Name	Freq. *N*	Area	Photo	Notes
35E	75N	Baillaud	46	0.47	IV 68H2, 80H2, 92H2, 177H1	
33E	21S	Frascatorius	54	0.78	IV 77H1	
31E	51S	Pitiscus	61	0.20	IV 83H1, 88H1, 95H1	
30E	32N	Posidonius	70	0.54	IV 79H1	
31E	77N	Euctemon	104	0.18	IV 92H2	
28E	42N	Plana	46	0.09	IV 86H2	
26E	67S	Manzinus	104	0.21	IV 82H1, 94H2	
26E	11S	Theophilus	0	0.13	IV 84H2, 177H2	Central uplift, annular flat area
26E	63N	Kane	34	0.20	IV 92H1	
25E	28S	Rothmann G	100	0.47	IV 84H1	North half, rest of floor obscured
24E	18S	Catharina	80	0.40	IV 84H2	Includes Cath. P.
24E	68N	Neison	44	0.16	IV 92H2	
23E	35S	Rabbi Levi	84	0.22	IV 83H3	
22E	32S	Zagut	71	0.25	IV 83H3, 88H3	
20E	38S	Busching	105	0.10	IV 88H2, H3, 95H2	
20E	73N	Meton	57	1.68	IV 92H2	includes parts of Meton C, D, E & F
19E	51S	Baco	60	0.10	IV 95H1, 107H3	
18E	48S	Breislak	240	0.08	IV 95H2	
18E	39S	Buch	96	0.11	IV 88H2, H3, 95H2	
18E	50N	Aristoteles	10	0.20	IV 98H3, 104H1	floor small, rather rough
17E	45S	Barocius	100	0.14	IV 95H2	including Barocius B
14E	42S	Maurolycus	41	0.25	IV 95H2	floor partially obscured
14E	34S	Gemma Frisius	46	0.20	IV 95H3	including A. Patches of flat floor
14E	14S	Abulfeda	45	0.13	V 84M, IV 89H2, 96H2	
10E	50S	Cuvier	34	0.12	IV 107H3	
10E	1S	Lade	16	0.18	IV 96H3	
10E	85N	Byrd	157	0.48	IV 140H3, 152H3, 164H3, 190H3	
8E	27S	Apianus	83	0.15	IV 96H1, 100H3, 101H1	
6E	41S	Stofler	46	0.54	IV 107H2	floor partially obscured
6E	24S	Playfair G	80	0.43	IV 101H1	
6E	6S	Hipparchus	20	0.71	IV 96H3, 101H3	
5E	31S	Aliacensis	67	0.16	IV 101H1	
5E	65N	W. Bond	34	2.00	IV 116H2	
4E	12S	Albategnius	23	0.61	IV 101H2	excluding Klein
2E	83N	Gioja	284	0.07	IV 190 H3	
3E	25S	Blanchinus	51	0.18	IV 101H1	
3E	19S	Anon C	29	0.14	IV 101H2	east of Parrot C partially obscured
1	24S	Lacaille	85	0.20	IV 101H1	
0	34S	Walter	76	0.86	IV 107H1	
0	29S	Regiomontanus	94	0.47	IV 107H1	
1W	9S	Ptolemaeus	29	1.40	IV 101H3	
2W	26S	Purbach	86	0.60	IV 107H1, 108H1	
2W	18S	Arzachel	87	0.30	IV 108H2	central uplift
3W	14S	Alphonsus	40	0.75	IV 108H2	central uplift

Table I (Continued)

Long.	Lat.	Name	Freq. *N*	Area	Photo	Notes
3W	73N	Goldschmidt	61	1.06	IV 116H2	
4W	30N	Archimedes	12	0.51	IV 115H1	
6W	33S	Deslandres	99	3.50	IV 107H1, 112H3	ancient crater much altered by subsequent events
6W	50S	Maginus	50	0.65	IV 124H1, 131H1	
9W	52N	Plato	9	0.57	IV 127H3	
13W	34S	Gauricus	42	0.19	IV 119H3	
13W	30S	Pitatus	4	0.49	IV 119H3	
14W	58S	Clavius	48	2.87	IV 130H3, 131H3, 136H1	
21W	51S	Longomontanus	24	0.54	IV 130H3, 131H1, 136H1, IV 142H1	
21W	43S	Wilhelm	86	0.41	IV 131H2	
22W	64S	Blancanus	60	0.37	IV 130H3	
25W	78N	Mouchez	120	0.54	IV 140H3, 152H3, 164H3	
27W	70S	Klaproth	71	0.52	IV 154H2	
27W	34S	Capuanus	16	0.18	IV 131H3	
30W	73S	Casatus	73	0.34	IV 154H2	
30W	81N	Mouchez A	157	0.14	IV 190H3	
31W	20S	Agatharchides H	25	0.20	IV 132H1	
39W	52S	Schiller	31	0.34	IV 154H1, 155H1, 160H1	
42W	62N	J. Herschel	84	1.35	IV 164H1	only S two thirds on photo
43W	42N	Mairan	17	0.12	IV 151H2	
45W	72N	Anaximenes	130	0.40	IV 164H2, 176H2	
50W	14S	Billy	10	0.16	IV 149H2	
51W	38S	Drebbel E	24	0.12	IV 135H2	
51W	12N	Marius	29	0.13	IV 150H2	
51W	58N	South	91	1.20	IV 164H1	
53W	34S	Anon C	40	0.32	IV 155H3	pair of craters south of Fourier
55W	44S	Schickard	30	2.30	IV 160H2, 167H2	
55W	76N	Poncelet	258	0.27	IV 164H2, 176H2	
56W	50S	Nasmyth	52	0.27	IV 167H1, 172H1	
56W	29S	Vieta	41	0.24	IV 155H3	
57W	53S	Phocylides	81	0.61	IV 167H1, 172H1, 180H1	
60W	50S	Wargentin	45	0.59	IV 167H1, 172H1, 180H1	
60W	68N	Anaximander B	49	0.75	IV 190H2	
63W	64N	Pythagoras	10	0.56	IV 190H1, 190H2	
64W	57N	Oenopides	168	0.29	IV 190H1	
65W	25S	Byrgius	31	0.32	IV 161H1	
67W	17S	Cruger	12	0.16	IV 168H2	
67W	10S	Rocca W	18	0.54	IV 168H2	
68W	5S	Grimaldi	8	1.91	IV 168H3	
69W	66S	Bailly	124	7.40	IV 166H2, 179H2, H3	old complex area

Table I (Continued)

Long.	Lat.	Name	Freq. N	Area	Photo	Notes
70W	74N	Pascal	165	0.30	IV 190H2	
72W	21N	Eddington	14	1.11	IV 174H3	
74W	59S	Pingré	130	0.29	IV 179H3	
75W	74S	Le Gentil	164	0.49	IV 193H1	
75W	3S	Riccioli	32	1.2	IV 173H3	complex floor affected by M. Orientale deposition; contains recent lava flow
75W	27N	Russell	26	0.50	IV 174H3	
75W	49N	Repsold C	26	1.18	IV 189H3	a bay of Oc. Proc.; eastern boundary arbitrary
76W	23N	Struve	52	1.94	IV 174H3	many secondaries
78W	52N	Repsold	51	0.41	IV 189H3	
78W	60N	Cleostratus	155	0.12	IV 190H1	
80W	34N	Ulugh Beigh A	9	0.11	IV 189H1	
82W	33N	Ulugh Beigh	83	0.24	IV 183H1, 189H2	
86W	12N	Bohr	96	0.20	IV 188H2	
88W	16N	Einstein	41	1.65	IV 188H2	including Einstein A. Relation between the two craters not clear
88W	28N	Voskresensky	0	0.07	IV 188H3	
88W	32N	Aston	64	0.06	IV 189H1	
90W	21N	Moseley	32	0.23	IV 188H3, 196H3	
90W	24N	Bartels	0	0.07	IV 188H3, 196H3	
96W	22N	Bell	142	0.30	IV 196H3	contains central peak and complex small crater.
109W	46N	Stefan	35	0.65	V 12H1	part only. very low illumination.
113W	46N	Wegener	55	0.45	V 12H1	
145W	58N	Birkhoff	93	4.37	V 29H2	
166W	36S	Oppenheimer	68	2.95	V 43M	many secondaries

TABLE II

Recognized Maria

Long.	Lat.	Name	Freq. N	Area	Photo	Notes
147E	27N	M. Moscoviense[a]	70	14.00	V 103M	Central floor 3.70 $N=35$, mid-annulus 4.60$N=71$
100E	50S	M. Australe[a]	40	20.00	IV 5H3, 9H3, 10H2	Probably a maret boundaries indefinite
90E	12N	M. Marginis	36	3 80	IV 18H2	Possibly a maret
86E	2S	M. Smythii	15	6.00	IV 18H1	
80E	55N	M. Humboldtianum	13	2.50	IV 165H1	oblique photo
66E	2N	M. Spumans	20	1.00	IV 184H1	oblique photo
59E	17N	M. Crisium	6	14.00	IV 54H2, H3	
52E	10S	M. Fecunditatis	21	22.00	IV 60H2, 65H2, 65H3	
33E	15S	M. Nectaris	27	11.00	IV 77H2	
30E	10N	M. Tranquillitatis	10	40.00	IV 78H2, 85H1	

Table II (Continued)

Long.	Lat.	Name	Freq. *N*	Area	Photo	Notes
30E	35N	Lacus Somniorum	20	8.00	IV 86H2, 91H2	
28E	45N	L. Mortis	19	3.60	IV 91H2	
19E	27N	M. Serenitatis	6	31.00	IV 78H3, 90H3, 91H1, 97H3	
5E	55N	M. Frigoris	12	50.00	IV 86H3, 92H1, 98H3, 128H1, 134H3	
3E	15N	M. Vaporum	5	4.50	IV 97H2, 102H2	
0	1N	Sinus Medii	20	3.50	IV 97H1, 101H3, 109H1	
0	27N	Palus Putredinis	30	2.20	V 106M	
8W	12N	S. Aestuum	14	4.60	IV 109H2	
17W	23S	M. Nubium	10	18.00	IV 113H2, 119H3, 131H3	
20W	35N	M. Imbrium	10	87.00	IV 115H1, 121H3, 127H1, 134H3	
25W	10S	M. Cognitum	7	28.00	IV 125H2, 132H2	
26W	32S	P. Epidemiarum	12	1.30	IV 131H3, 136H3	
31W	45N	S. Iridum	9	4.00	IV 145 H2	Often designated as a crater
37W	24S	M. Humorum	10	11.00	IV 136H3, 142H3, 143H1	
50W	50N	S. Roris	11	4.00	IV 164H1, 176H1	
60W	30N	Oceanus Procellarum	10	160.00	IV 144H2, 149H3, 150H1, 150H2, H3, 182H3, 183H1, 183H3, 189H2, H3	
95W	20S	M. Orientale	14	3.50	IV 195H1, H2	

[a] *N* value not used for mean.

TABLE III

Marets

Long.	Lat.	Name	Freq. *N*	Area	Photo	Notes
91E	33S	Anon. M	64	5.24	IV 9H3	Part of Mare Australe
75E	47S	,, ,,	54	0.75	IV 38H2	Near or part of M. Australe
70E	51S	,, ,,	52	4.09	IV 52H2	Near or part of M. Australe (Figure 2)
64E	61N	,, ,,	22	0.45	IV 177H1	Elongated area W of Endymion B
62E	33N	,, ,,	42	1.90	IV 192H2	SE of Bernoulli
56E	46N	,, ,,	27	1.48	IV 67H2, 191H2, 192H2	Between Messala & Endymion
53E	58S	,, ,,	55	4.62	IV 76H1, 58H3	E of Hagecius
51E	52S	,, ,,	59	4.71	IV 58H3	N of Biela
46E	28N	,, ,,	28	0.54	IV 66H3	NW of Tralles A
43E	22N	,, ,,	21	0.24	IV 66H3	NW of Macrobius
42E	61S	,, ,,	47	4.98	IV 70H3	SW of Hagecius
38E	24S	,, ,,	47	3.63	IV 72H1	S of Frascatorius B
32E	59S	,, ,,	54	5.27	IV 82H3	Mutus to Nearch
31E	42S	,, ,,	72	3.56	IV 83H2	E of Nicolai
27E	67N	,, ,,	29	4.52	IV 92H2	Arnold to Niesen. Part of Figure 3

Table III (Continued)

Long.	Lat.	Name	Freq. *N*	Area	Photo	Notes
25E	45S	Anon. M	119	3.29	IV 88H2	SW of Nicolai
20E	47S	,, ,,	90	3.70	IV 95H2	SE of Barocius
20E	73N	,, ,,	38	6.52	IV 104H2	Includes Meton (Figure 3)
20E	83N	,, ,	66	8.39	IV 104H3	NW of de Sitter (Figure 5)
16E	53S	,, ,,	111	3.97	IV 107H1	W of Baco
12E	14N	,, ,,	12	0.32	IV 97H2	Manilius M
10E	55S	,, ,,	100	3.65	IV 112H1	S. of Cuvier
10E	34S	,, ,,	46	5.14	IV 100H3	S. of Aliacensis
0	70N	,, ,,	29	4.35	IV 116H2	SW and S of Barrow, E of W. Bond
3W	58S	,, ,,	72	3.84	IV 124H1	E of Clavius
12W	81N	,, ,,	57	5.7	IV 140H3, 152H3	W of Scoresby
20W	54S	,, ,,	38	5.82	IV 130H3	N and NW of Clavius
28W	39S	,, ,,	41	0.22	IV 131H2	NW of Wilhelm
26W	49S	,, ,,	54	3.69	IV 142H1	W of Longomontanus
33W	57S	,, ,,	47	4.03	IV 155H1	S of Schiller
35W	80N	,, ,,	72	4.06	IV 164H3	Contains Mouchez
40W	67N	,, ,,	74	2.23	IV 152H2, 164H2	Anaximander
42W	36S	,, ,,	52	0.73	IV 148H	N of Clausius
43W	36S	,, ,	52	0.75	IV 142H3	SW of Vitello Part terra
44W	40S	,, ,,	47	3.52	IV 148H2	N of Drebble C Part terra
45W	46S	,, ,,	50	3.49	IV 155H2	SE of Schickard
46W	56S	,, ,,	71	3.84	IV 167H1	SE of Phocylides
47W	53S	,, ,,	34	3.33	IV 154H3	W of Schiller (Figure 4)
50W	80N	,, ,,	84	5.08	IV 190H3	E of Sylvester
52W	35S	,, ,,	38	3.57	IV 155H3	S of Fourier
54W	26S	,, ,,	34	3.24	IV 156H1	N of Vieta
57W	75N	,, ,,	67	4.39	IV 176H2	W of Anaximenes
63W	18S	,, ,,	45	5.00	IV 161H2	Contains de Vico T
65W	48S	,, ,,	28	1.08	IV 167H2, 172H2, 180H1	NW of Wargentin, Baldwin's marshy area
65W	70N	,, ,,	64	4.35	IV 190H2	SE of Pascal
72W	57S	,, ,,	49	6.37	IV 179H3	N of Pingré. Some terrae included
87W	25N	,, ,,	42	2.77	IV 188H3	E of Bartels
89W	15N	,, ,,	37	2.59	IV 188H	W of Bohr

TABLE IV

Terra areas

Long.	Lat.	Name	Freq. *N*	Area	Photo	Notes
146E	7S	Terra	170	0.80	I 115H2	
130E	8S	,,	136	1.23	I 136H1, H2, H3	
92E	26S	,,	106	1.58	IV 9H3	
91E	30N	,,	38	3.01	IV 18H3	
90E	22N	,,	40	3.01	IV 18H3	
78E	28N	,,	33	3.80	IV 177H2	
55E	40S	,,	66	2.03	IV 59H2	

Table III (Continued)

Long.	Lat.	Name	Freq. N	Area	Photo	Notes
46E	45S	Terra	35	10 20	IV 71H2	
10E	53S	„	114	1.57	IV 112H3	
7E	29S	„	78	1.04	IV 101H1	
4E	15S	„	71	1.68	IV 101H2	
2E	46S	„	73	1.02	IV 107H2	
40W	74S	„	49	5.12	IV 154H2	
55W	70S	„	93	2.72	IV 166H2	
95W	22N	„	55	3.24	IV 196H1	

and were included in the lists as the work proceeded. The total number of these marets in the initial lists came to 25. Since these objects made up a more important fraction of the data than had been anticipated, it was decided to go through the collection of photographs again and see whether others could be found. What we regard as marets were found on over one third of the photographs and in many cases the flat areas comprised more than 50% of the frame area. It was accordingly decided to incorporate most of them in the list of objects to be investigated. The resulting compilation contains 174 flat-floored craters, 26 well known maria and 48 of the marets discussed above.

All of the assumed lava-covered areas are listed in Tables I, II and III described later in more detail. In addition 15 photographs were selected which were considered to contain representatives of the terrae or highland areas of the Moon and these are listed in Table IV.

2.2. CRATER COUNTING TECHNIQUES

Two methods of crater counting were tried. At first an attempt was made to utilize 35 mm transparencies of lunar photographs projected on a screen, on which also was projected two parallel lines with a separation corresponding to 2 km, the lower limit of crater size. This method proved to be entirely practical and was pleasant to use but experience showed that direct use of the large Orbiter paper prints (55 × 47 cm) without further magnification, with a transparent movable template to indicate the lower limit of crater size, was faster and capable of somewhat greater accuracy. This method was accordingly adopted and practically all of the crater counts were made in this way. The following definitions indicate the numerical terms in which the crater counts are expressed.

Index Craters = circular features of diameter equal to or greater than 2 km considered to be due to impact on solidified lava surfaces or elsewhere on the lunar surface.

A = area of surface in terms of standard unit, 10^4 km^2.

Frequency N = no. of index craters per unit area.

$\sum A_{N1}^{N2}$ = total area showing frequencies between N_1 and N_2.

Measuring sheets on a standard form provided for the records and calculations required to derive values of *A* and *N* for each feature measured. A micrometer caliper with parallel jaws mounted on a flat surface made it possible to scribe accurately spaced parallel lines on a sheet of transparent plastic for the necessary template. All nearly circular depressions equal to or greater than the standard 2 km diam were counted, with no attempt to exclude secondaries or drowned craters. Whenever possible, oblique photographs were avoided as were frames of poor definition or illumination.

For over 90% of the measurements only high resolution Orbiter photographs with favourable angles of illumination were used. It is considered that such differences of scale as exist among these photographs is not sufficient to cause serious errors. In some cases where photographs of widely different scales were used e.g. Orbiter M and Apollo which differed by a factor of 7, means were used which aimed at producing values of N corresponding to those derived from Orbiter high resolution photographs. The correlation of such values with the main body of the data is open to some doubt but their numbers are too small to seriously affect our overall results. Repeated measures of one object on the same high resolution photograph suggest an accuracy of the order of 10 to 15% and it is considered that differences in illumination and photographic quality could result in considerably larger errors as between one photograph and another. Unfortunately there are other important sources of error that are largely beyond the control of the observer. These include the contamination of the data by secondary craters that tend to occur in clusters, a lack of uniformity of distribution of primary index craters, and the obscuration of index craters by debris from neighboring impact events. While these effects could lead to substantial errors in comparing a single lava covered area with another, it is reasonable to suppose that where a considerable number of such areas are involved or where differences in age are quite large, the results would still be statistically valid. There does not seem to be any certain method of evaluating the numerical effect of secondary craters on attempts to place a group of flat lava-covered areas in a time sequence. In a recent paper Hartmann (1972) suggests that for craters above 2 km diam, secondaries are too rare to be significant. While our counts have not attempted to isolate the secondaries we feel that in some cases their distortion of the data is appreciable. It even seems possible that for certain abnormally high counts (of the order of 300) the secondaries may be a substantial fraction of the whole.

The method used here, as compared with more elaborate applications of crater counting technique, has the advantage of simplicity, while the lower limit of crater diameter (2 km) is large enough to be applicable over a considerable range of index crater frequencies. Apart from personal equations, most of the errors of crater counting techniques are inherent in the physical process of crater accumulation due to impacts large and small and to vagaries of illumination and recording methods, most of which are independent of the observer. Where comparisons are possible our results are in reasonable accord with those of other observers and the diagrams of Figure 1 and Figure 6 suggest a statistical validity adequate for the purposes of the present investigation.

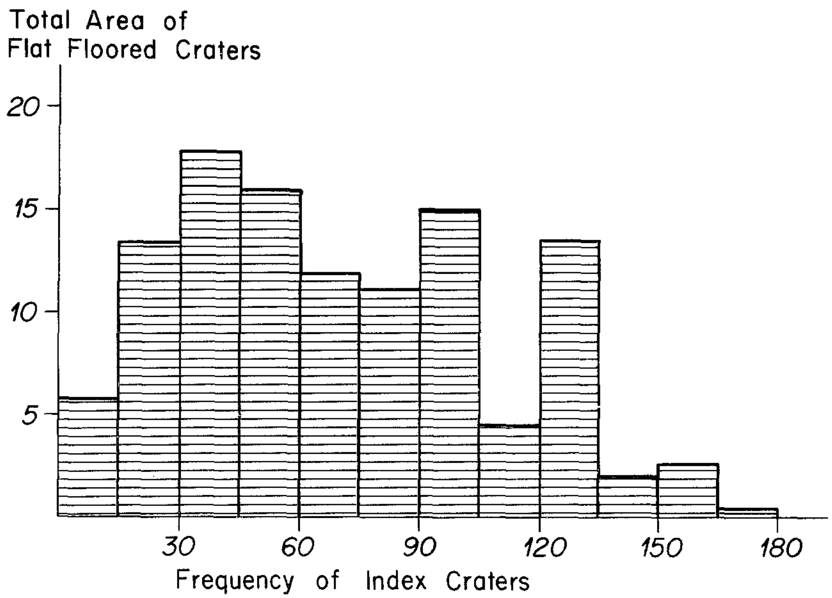

Fig. 1. The integrated lava areas of flat-floored craters (ΣA) over successive frequency intervals of 15 are plotted against index crater frequencies. From this figure it is apparent that the minimum in the value of ΣA at $N = 45$ predicted by Beals (1972) is not observed, leading to the conclusion either that it does not exist or that it is too far in the past to be detected by present observations. The scatter of the points in the diagram illustrates the marked irregularity of distribution in diameter and age of the flat-floored craters of Table I.

The circular maria represent a special problem since these surfaces are apparently due to a succession of lava flows that are not uniformly distributed over the mare area. The number of areas sampled within any one large mare which shows a variety of ages (Ronca, 1971) may not always suffice to represent it as a whole but we consider that the maria collectively are well represented by the average frequency value of 15 derived from Table II.

2.3. TABULATION OF RESULTS

The results of index crater counts are contained in Tables I, II, III and IV arranged in order of longitude. For each Table, columns 1 and 2 contain longitudes and latitudes; column 3 gives names when available e.g. Plato, Mare Imbrium etc.; where a feature has no recognized name it is designated as 'anon C' if it is a crater and 'anon M' if it is a maret. The numerical value of N (frequency) and A (area) are found in columns 4 and 5. Column 6 indicates the number of the photograph or photographs on which the counts were made while column 7 is reserved for notes. For flat-floored craters (Table I) the values of A are in general, direct measurements on the photographs of the total lava covered area of the crater floor. For the recognized maria, (Table II), the areas are derived from maps and published values. For the marets and the terrae, (Tables III and IV), objects of indeterminate boundaries, the values of A have a less definite significance and simply indicate the area used for the determination of the frequency N.

Most of the photographs are in the Orbiter series. This is partly because Orbiter was the only series available with reasonably comprehensive coverage when this investigation was begun, but mainly because it covers a much larger area of the lunar surface than the later Apollo 15 photographs.

3. Discussion of Results and Tentative Interpretation

3.1. RELATIVE VALUES OF N FOR TERRAE AND FLAT-FLOORED CRATERS

What at first sight appears to be an anomaly has been observed in connection with values of N for the terrae or upland areas, generally conceded to be the oldest exposed surfaces of the Moon. Counts were made for 15 terra areas selected at random and the results are presented in Table IV. It will be seen that their mean N value of 77 is considerably less than the value of 150, considered to be a well authenticated part of the curve of Figure 1 for flat-floored craters. Since modern interpreters (Baldwin, 1963; Fielder, 1963; Hartmann, 1965) of the lunar surface agree that the terrae are the oldest parts of the lunar surface, this anomaly appears to conflict with our general assumption that index crater frequency is a reliable indication of relative age. Some suggestions from Gault's paper (1970) may help in understanding the reasons for this anomaly. He shows that equilibrium is more rapidly reached for the smaller craters and that as equilibrium continues, the proportion of degraded and modified craters rises. Since nearly 90% of our counts are of index craters under 5 km diam it is plausible that counts in the terrae, rough, with random slopes of several degrees everywhere, should miss many craters visible on flat floors where conditions are more favourable for observation. It is therefore assumed that the apparent anomaly in no way invalidates the use of N values as indicators of relative age for lava covered areas, nor does it alter the generally accepted conclusion that the terrae are the oldest areas of the Moon's surface.

3.2. CORRELATION WITH RADIOACTIVE AGES

The only part of the data which can definitely be associated with radioactive ages of lunar materials is the average of $N = 15$ corresponding to the 'recent' large maria (Table II). The discussion of maria ages by Ronca (1972), the Lunar Sample Analysis Planning Team (LSAPT, 1973), Papanastassiou and Wasserburg (1970), and Schaeffer and Husain (1974) indicates a mean age for the mare basalts of about 3.5 b.y.

The values of N for the flat-floored craters are in general considerably higher (Table I) and show a considerably greater range than those for the larger maria and this may be seen very clearly from the curve of Figure 1, where values of $\sum A_{N1}^{N2}$ are plotted at frequency intervals of 15. It will be seen that for values of N from 7 to about 150, the course of the curve is relatively well defined. Beyond this point the curve is not well enough defined to make possible any clear relationship between $\sum A_{N1}^{N2}$ and N.

Modern ideas concerning the maximum ages of observable lunar features depend greatly on the radioactive ages of lunar samples. The Lunar Sample Analysis Planning Team (LSAPT, 1973) has stated that the greatest age found so far for any lunar specimen is 4.2×10^9 yr for terra material while a slightly smaller age is given for the oldest crystalline rock by Papanastassiou and Wasserburg (1972). It seems unlikely that any of the large craters of Table I would be older than this. If therefore we arbitrarily assign an age of 4.0×10^9 yr to that point of the curve of Figure 1 where $N = 150$, it becomes apparent that for an increase in age of 0.5×10^9 yr the value of N goes from 15 (the average for the maria) to 150 for the older flat-floored craters. This indicates a very rapid increase of N for earlier ages, a conclusion already reached by Baldwin (1970), Hartmann (1970), and Baedeker (1972). Baedeker suggests that a dramatic upturn of the flux of meteorites takes place at 3.8×10^9 yr with a doubling time of 4.5×10^7 yr. While the larger values of N recorded by us are not closely tied to specific ages their general indication of a rapid increase of N with earlier ages is in excellent agreement with that of others and would remain so, even if we made the improbable assumption that our high crater counts corresponded to an age of 4.6×10^9 yr usually associated with the age of the Moon.

In attempting to relate the data of Table I to the physical processes going on at and immediately below the surface of the Moon during the period covered by these observations we consider the following two processes which are not necessarily mutually exclusive.

(a) As a result of cooling of an assumed molten surface, a solid crust formed and gradually thickened as cooling proceeded. The flat-floored craters and other lava surfaces were formed as a direct or indirect result of meteorite bombardment during the cooling process.

(b) The Moon contained within itself various heat-generating sources of unspecified nature which resulted in a build-up of internal pressure and the production of lava which forced its way to the surface in different locations giving rise either directly or indirectly to the flat floors of the craters and other lava surfaces observed in the Moon.

3.3. THE COOLED CRUST

Beginning with (a) above we designate as the 'cooled crust' (Beals, 1971, 1972) that part of the solid outer layer of the lunar surface, extending to a depth Z_0 at which the temperature T_0 corresponds to the zero-pressure melting point of the material. The physical state of the material below Z_0 will depend on the thermal gradient $\mathrm{d}T/\mathrm{d}Z$ and the elevation with depth of the melting point $\mathrm{d}M/\mathrm{d}Z$.

If the temperature gradient in the vicinity of Z_0 is appreciably greater than the rate of elevation of the melting point due to increasing depth – i.e.,

$$\mathrm{d}T/\mathrm{d}Z > \mathrm{d}M/\mathrm{d}Z,$$

then a layer of melted material will result at depth Z_1 whose distance below Z_0 will depend on the steepness of the temperature gradient in the range $Z_1 - Z_0$. If the meteorite is of sufficient energy to excavate a crater deeper than Z_1 then the already liquid lava will rise to fill the depression caused by the impact, to the point where hydrostatic equilibrium is reached. This case, designated as hypothesis I, (Beals, 1971) corresponds to the lunar model suggested by Wood *et al.* (1970) and Wood (1970)* where a crust of solid anorthosite floats on a magma of dense basalt.

In the second case (hypothesis II) the material below Z_0 and to depths greater than those of even large impact craters is subject to a temperature gradient less than the rate of elevation of the melting point – i.e.,

$$\mathrm{d}T/\mathrm{d}Z < \mathrm{d}M/\mathrm{d}Z.$$

In this case there is no 'free' lava involved and such melting as occurs will be due to the removal of load from the high temperature material below Z_0. The case of hypothesis II is complicated by the fact that the change from the solid to the liquid state is not a sharply defined process and may require a temperature range of the order of 200° to be complete.

While there is good reason to suppose that the processes of hypotheses I and II could be applicable to any differentiated cooling body of lava, regardless of age, the assumption was made that the great majority of flat-floored craters were associated with impacts on an assumed primordial crust. On the basis of this assumption and making use of a small number of excellent Apollo photographs Beals (1972) suggested a cycle of cooling followed by reheating of the lunar interior, resulting in first a thickening followed by a thinning of the primordial crust. Such a cycle called for a minimum in the curve of Figure 1 between frequency values of $N=15$ and $N=91$, a minimum which is certainly not shown by these observations. Since Table I and Figure 1 are derived from a volume of data greater by a factor of 20 over that of Beals, it must be concluded either that the above mentioned cycle of cooling and reheating did not exist or that the earlier part of the cycle is too far in the past to be accessible to observation. While it is still possible that some of the very large ancient craters such as Deslandres, Bailly and Gagarin may have been due to large meteorites piercing a floating crust** it appears that the great majority of flat-floored craters now observable must be due to some other cause. This conclusion is re-inforced by the restricted age range of lunar samples already mentioned. We are therefore forced by the data to consider the second process, (b) where heat-generating sources within the Moon have resulted in lava which forced its way to the surface and provided the molten material of the flat floors of craters and other lava surfaces observed on the surface of the Moon.

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* As a result of the evolution of the subject there has been a rather general change in ideas, shared by these authors, regarding the nature of the maria and the extent to which present day observations can penetrate into the past history of the Moon.

** While Kopal (1972) q.v. discounts a continuous floating crust over the whole Moon, that does not preclude the existence of large pools of lava of sufficient depth and extent to support a local floating crust. Baldwin in a private communication has suggested that the flat floors for these large craters may be due to isostatic compensation.

3.4. LUNAR VOLCANISM AS REVEALED BY THE FAMILIAR MARIA AND OTHER RELATIVELY RECENT FEATURES OF THE LUNAR SURFACE

Lunar volcanism differs from the processes already discussed in connection with the assumed primordial floating crust which describe the movement of lunar magma near the surface under the action of gravity combined with the principles of hydrostatic equilibrium. Lunar volcanism, like earthly volcanism, must have its origin in internal pressure which forces lava upward and on to the surface against gravity. Evidence for this is found in the appearance of lava mounds or flat areas on the lunar surface where impact appears not to have been an important process in breaching the crust. It is possible that the Marius Hills, an assemblage of elongated elevations on the lunar surface in the general area 12° N, 54° W, may have been formed by lava extrusions finding their way to the surface through cracks or fissures in the crust. The appearance in the crater Wargentin of a flat floor elevated above the neighboring lunar surface (Baldwin, 1963) is probably due to subsurface lava under sufficient pressure to force it not only through crater floor but also to a height of the order of hundreds to thousands of metres above the initial floor to a level close to the top of the crater rim. Another crater which may have been the site of volcanic activity is Tsiolkovsky, 175 km in diam with a well marked central uplift, surrounded by a level floor very dark in colour with a very low frequency of index craters (Beals, 1972). Since a conspicuous central uplift in general is not expected in craters of hypothesis I or II origin it may be that the present lava surface in Tsiolkovsky is due to a lava flow of more recent age than the impact that formed the crater.

At first sight a very attractive explanation of the large maria would appear to be that they represent examples of hypothesis I where an exceptionally large meteorite pierces a floating crust, releasing liquid magma which would results in a flat lava floor. While the last word may still remain to be said on this subject, Baldwin (1970) rejects this explanation and suggests that the present large maria are due to a succession of lava flows of considerably later date than the impacts producing the basins. The evidence, which depends both on the appearance of drowned craters and on flow marks suggesting a succession of lava extrusions, is rather convincing and is reinforced by the existence of features like Oceanus Procellarum and Mare Frigoris which show no immediate evidence of association with impacts. The magnitude of the phenomena involving the maria is very great and some very definite physical process must have been at work in the Moon's interior to generate the pressure which causes such a large amount of lava to break through to the surface. Baldwin attributes it to an increase in temperature of material within the body of the Moon, causing melting, increase of volume and the forcing of large quantities of lava upward to the lunar surface. Since this essentially volcanic explanation seems to have received general acceptance, its validity is assumed here and in subsequent discussions.

3.5. THE NATURE OF THE MARETS AND SUGGESTIONS AS TO THEIR ORIGIN

In connection with the selection of lunar photographs, mention has already been made of numerous flat areas of various sizes, with some similarity to maria, which we designate by the term maret. The following characteristics are associated with marets,

(1) They have flat lava surfaces often broken by other features.

(2) They appear in a great variety of sizes. For example Mare Australe covering an area of the order of 200000 km^2 is considered to be a maret. Others may be a tenth or less this size.

(3) Marets are usually of irregular shape with rather indefinite boundaries.

(4) They are not circular like the recognized large maria. We are inclined to regard objects like Mare Marginis and Sinus Medii as marets.

(5) In practically all cases marets are associated with numerous flat-floored craters. Crater counts in marets include the crater floors and are not necessarily uniform over the area.

(6) The marets are widely distributed over the lunar surface, although they do not appear within the large mare boundaries. Complete data is lacking for the far side of the Moon but from lunar maps it appears that the areas in the vicinity of Apollo, Coulomb, Birkhoff, and Mare Australe partake of the nature of marets and it seems likely that high resolution photographs would reveal numerous others.

In suggesting interpretations of the marets it should be indicated that although the tendency of this discussion is to emphasize the importance of lava flows in explaining flat areas on the Moon it is necessary to recognize the existence of alternatives in the so-called Cayley plains and other similar features attributed to the settling of fragmental material from major impacts. (Overbeck *et al.*, 1973; Chao *et al.*, 1973; Eggleton and Schaber, 1972). It has in fact been suggested that some or all of the marets of Table III may be Cayley plains and indeed the general appearance of some of the marets is such as to lend some credence to this possibility. With this in mind searches have been made of the U.S. Air Force Lunar Reference Mosaic of 1962 as well as the more recent map of the near side of the Moon already mentioned (McCauley, 1971) and numerous maps of limited area on the lunar surface published by the U.S. Geological Survey. Some general conclusions from the searches are as follows. (1) Up to the present we have not been able definitely to identify any of the marets with Cayley plains on maps available to us. This result is not conclusive since the detailed maps cover only a small proportion of the features of Table III. In addition, many of the maps do not make a clear distinction between volcanic features and Cayley plains which may have a generally similar appearance. (2) Several large flat-floored craters including Ptolemaeus, Alphonsus, Albategnius and Hipparchus have been described by Masursky (1968) and Howard and Masursky (1968) as having their floors covered by Cayley plains material. Here the symmetry of the ghost crater Ptolemaeus B, 18 km in diam on the north east sector of the crater floor suggests that it was due to an impact on a flat (lava?) surface. Its near-obliteration by a relatively thick layer of debris fits in with its identification as a Cayley plain as does its crater count of $N=29$ which is similar to that of the Apollo 16 landing site which is considered to be blanketed by the Cayley formation. The value of $N=29$ was derived from counts on Orbiter IV 89 H3 and centred on a flat area at 15.3°E, 7.4°S, slightly north of the actual landing site.

It thus seems a reasonable presumption that these craters were originally lava-filled and that the fragmental material is a superficial addition to what was originally a flat lava surface. If this is so for the craters it could hold also for some of the other lunar features whose flatness had hitherto been attributed to layers of fragmental debris. Unless such layers were very thick they would tend to reproduce in modified form the original topography which could well have consisted of flat lava areas. In addition most of the values of N for the marets of Table III are greater than the value of 29 associated with Cayley plains, suggesting that they are associated with earlier stages of lunar history then the emplacement of the Cayley formation. (3) Half the marets of Table III are located at latitudes higher than 50°, most of them in areas rather far removed from the circular maria, regarded as the major sources of impact debris. A

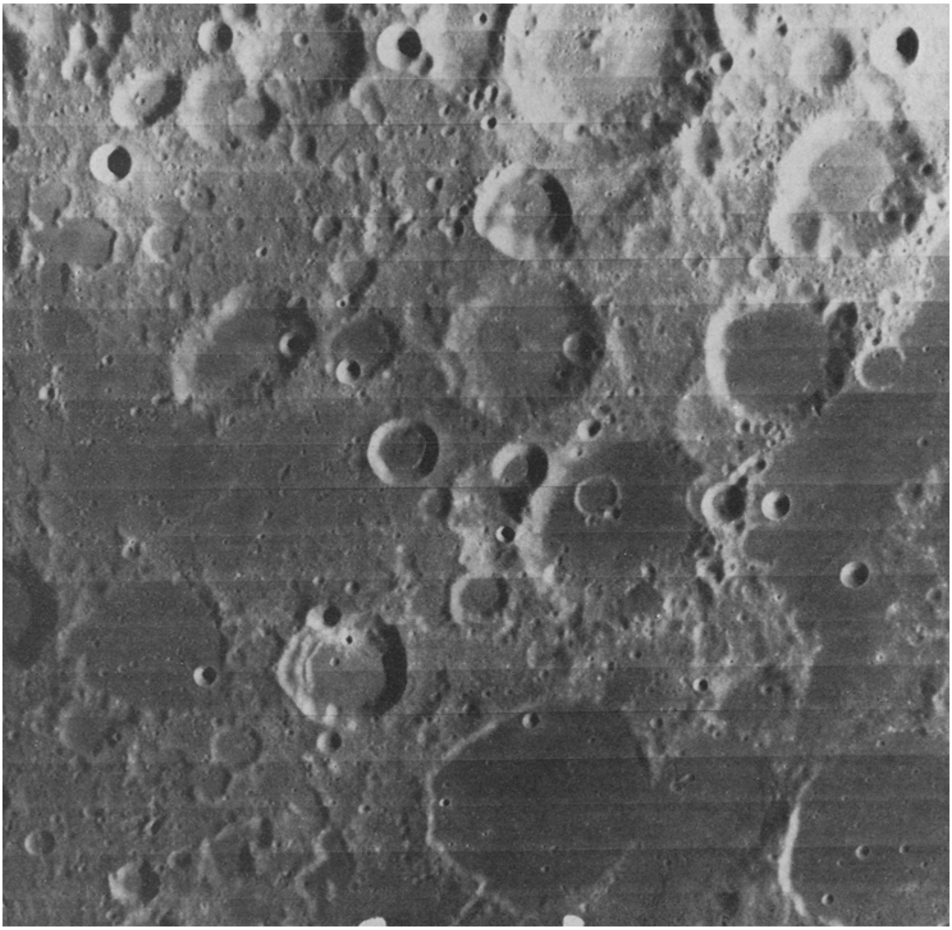

Fig. 2. IV 52H2; 67° N, 51° S: Near or part of Mare Australe. This maret shows marked similarities to the edges of some of the large maria, suggesting that the lava of the marets, like that of the large maria, is due to a form of lunar volcanism. The numerous flat-floored craters associated with this feature are characteristic of all objects of this type.

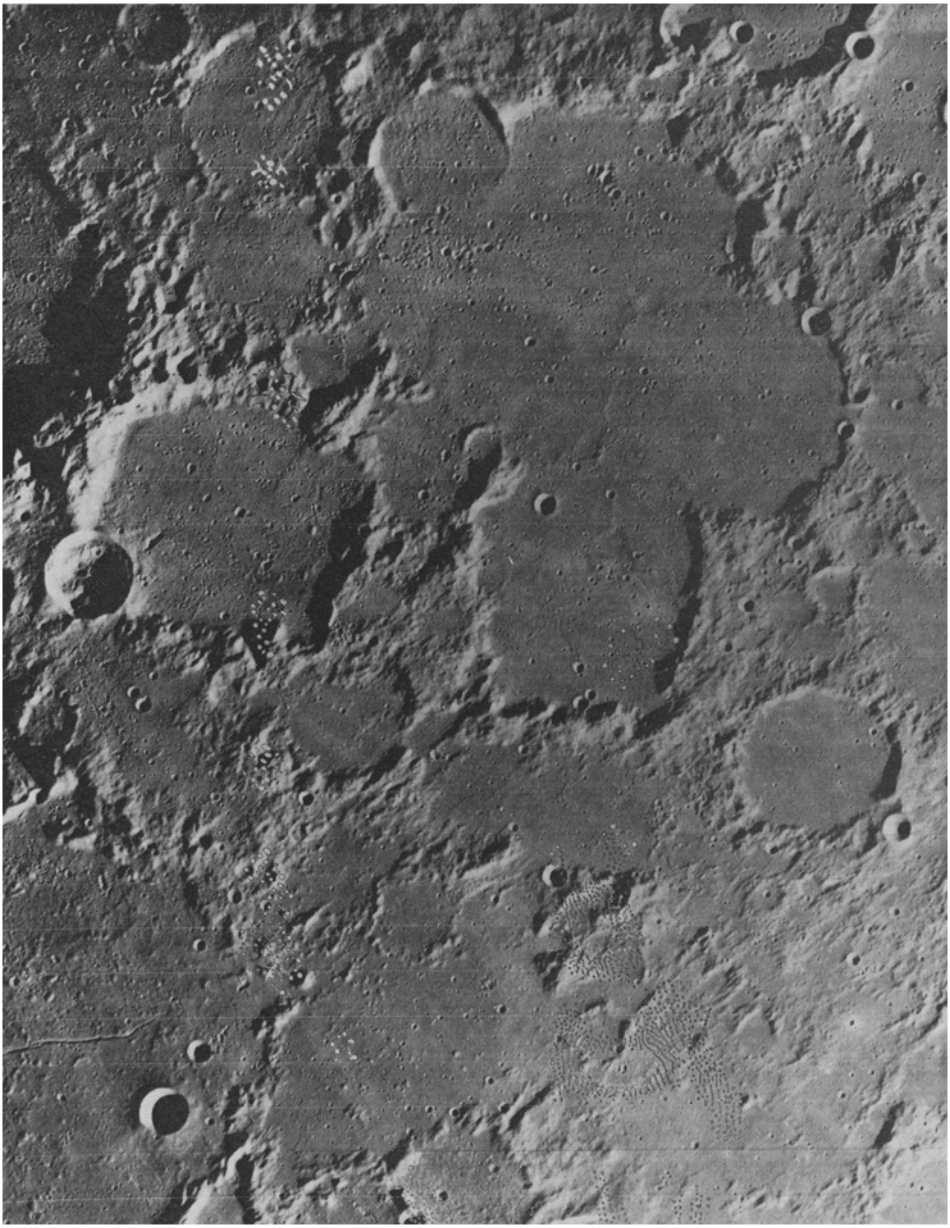

Fig. 3. IV 104, H2; 20° E, 70° N; includes Meton. This maret in its central area appears to have been bombarded by a cluster of large meteorites, resulting in an irregularly shaped continuous flat area of considerable size bounded on the outside by parts of the walls of the craters caused by the impacts. If there had been, in this area, a single impact of sufficient energy, it is possible that a large mare of the order of size of Mare Crisium or Mare Imbrium could have been produced.

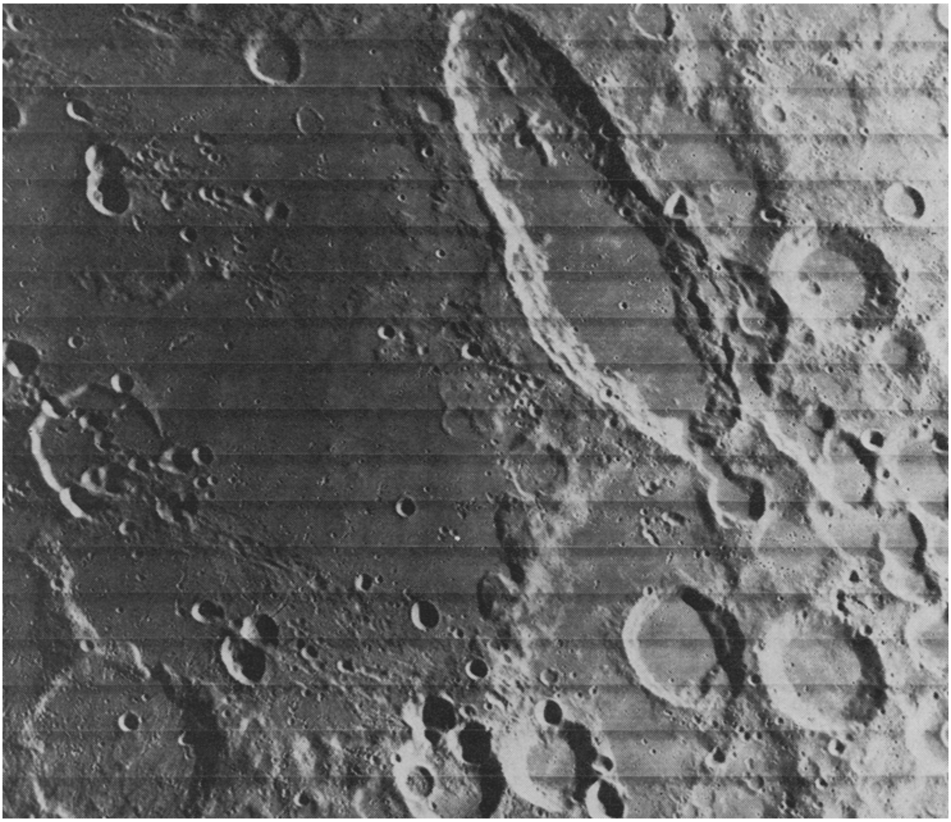

Fig. 4. IV 154H3; 47°W, 53°S: region of Schiller. The value of *N* for this maret has the relatively low value of 34, suggesting that it is of relatively recent origin.

good example of one of them is Figure 3. Here the sharpness of the non-inundated topography gives little indication of modification by mantling debris and it seems a reasonable assumption that the flat areas are due to solidified lava. On the whole the evidence seems in accord with the conclusion that a majority of the marets have a lava origin and, without minimizing the uncertainties, we adopt this assumption in subsequent discussions.

Specimens of features identified as marets in Table I are shown in Figures 2, 3, 4 and 5. Of these examples Figure 2 shows a marked similarity to the edges of large maria where drowned craters are conspicuous. The generally accepted idea of the large maria as due to lunar volcanism would appear to apply equally to the marets. Baldwin (1963) apparently recognized the general character of the marets on the basis of pre-Apollo observations of Mare Australe and a marshy area near Schickard and Wargentin, while Fielder (1963) also found that terra areas are often invaded by mare material. While the marets show similarities to the recognized maria, they differ from them in that the occurrence of the marets on the lunar surface appears to be solely

Fig. 5. IV 104H3; 20° E, 83° N. Comparing this maret with that of Figure 4, it is apparent that this feature is considerably older, with a value of $N = 66$. The marets show a range of index crater frequency similar to that of the flat floored craters, as may be seen from the diagram of Figure 6.

due to internal forces, not being associated with large meteorite impacts which excavate circular basins of considerable depth and extent.

The observations suggest that the marets are due to upward migrations of lava in widely separated areas of the Moon which may either spill out on the surface or which may approach sufficiently near to the surface to infiltrate the bottoms of craters and to cause levelling out or settling of considerable surface areas. It is reasonable to suppose that the surface layers of the Moon down to depths of several tens of kilometres, have been shattered by impact (Beals, 1960; Shoemaker, 1960; French, 1968), producing a volume of permeable material, so that lavas could diffuse through such a medium in either a vertical or horizontal direction. The general idea of such a motion of diffusion is reminiscent of the migration of mineralizing agents or 'ichors' of Deville and Sederholm as discussed by Holmes (1964), though the evidence of similarity is not sufficient to establish any close identity. It is possible, depending on relative melting points, that the diffusion of lava through shattered material may result in partial digestion of such material. It is also possible that local conditions may lead to a retardation of motion giving rise to a slowly moving or even a stationary 'lava front'. One very striking characteristic of the marets is their close association with flat-floored craters, an association which may be clearly seen in all four of the Figures 2, 3, 4, and 5 where many lava filled craters are seen to be superposed on the maret features. The idea of a physical association between them is re-inforced by the following considerations.

As a lava front approaches the surface it may encounter a series of previously formed craters, infiltrating them from below, resulting in the formation of flat lava floors. In this connection we may consider the crater Ptolemaeus previously thought by Beals (1971) to be due to an impact on an assumed primordial floating crust. On the basis of the gravity observations of Müller and Sjogren (1968) this crater has been shown to have a negative gravity anomaly, an observation inconsistent with a floating crust origin. It now seems reasonably certain that the flat floor of Ptolemaeus is due to a lava flow, where the lava, infiltrating the crater from below, has been insufficient to reach isostatic equilibrium*. Other similar though less conspicuous examples may be found in the craters, Wargentin, Tsiolkovsky, Aitken and Bell, all (except Wargentin) rather deep, flat-floored craters of a variety of sizes. Here again it seems probable that these craters owe their flat floors to a lava front which infiltrated them from below without actually advancing to the surface.

Depending on unknown time factors, a lava from may remain for a considerable time close to the surface without actually breaking through. During this period a meteorite impact may pierce the surface to a depth sufficient to reach the lava front, resulting in the formation of a flat floored crater on the basis of a modified hypothesis I process. A possible example of this is the unusual crater Plato which occurs on a low ridge between Mare Imbrium and Mare Frigoris. This crater has the characteristics (low but clearly defined rim and flat floor) expected of a hypothesis I crater due to

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* The additional layer of fragmental material, mentioned earlier, does not necessarily alter this conclusion.

impact on a thin crust. It seems quite possible that the region under Plato was infiltrated by diffusion of lava from the neighboring maria in the manner suggested above. On this basis, when the impact occurred, the crust was too thin to form a rim of normal height while the material under the crater was liquid or semi-liquid, inhibiting the formation of a central uplift and providing liquid material for the flat crater floor. There are several other craters of similar character in the vicinity of the large maria but their numbers are small and it may be that the time scale of lava migrations is such as to favour the process of infiltration from below described on p. 77. For the most part the difficulty of distinguishing between different possibilities (i.e. infiltration from below of an already existing crater or formation of a new crater deep enough to reach a stationary lava front) is considerable, and for this discussion it is sufficient to suggest that the migration of lava through large volumes of the Moon's shattered outer layers may be a process of fundamental importance to the thermal history of the lunar surface, presenting a logical explanation not only of flat-floored craters but also of the marets which seem to occur in considerable numbers everywhere on the lunar surface except within the large maria.

Although the flat-floored craters were the objects of major interest when this investigation was begun, the marets have emerged as probably more important indicators of the physical processes responsible for the observed features of the lunar surface. It is difficult to escape the conclusion that it is the migrating lava responsible for the marets that provides the liquid material for the flat crater floors. In Figure 6 the

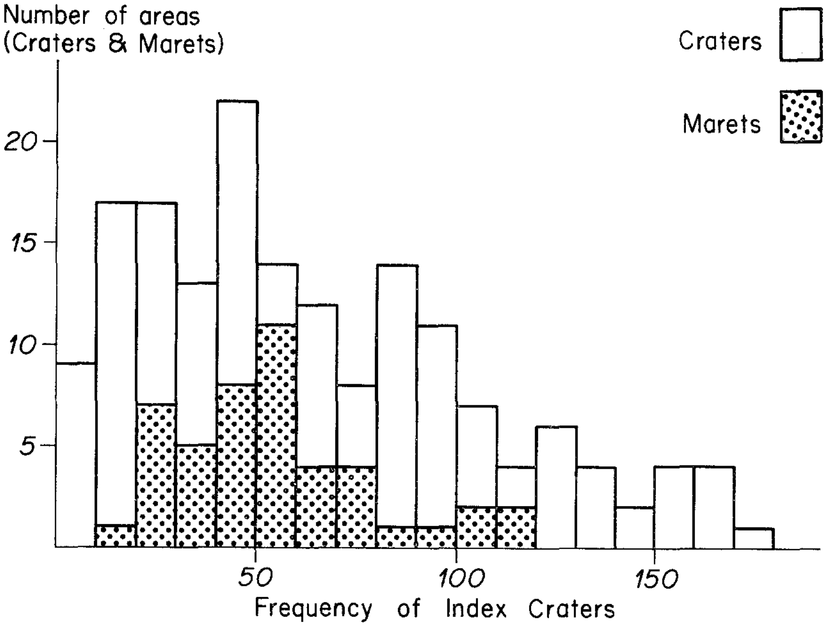

Fig. 6. The numbers of flat-floored craters and marets in similar frequency intervals are plotted against index crater frequency in this diagram. The similarity in distribution of the two sets of data is in reasonable accord with the idea that the two types of objects are physically related.

frequency distribution for flat-floored craters and marets are compared and their similarity is in accord with the idea that they are physically associated. Figure 6 further indicates the considerable range in the N values for the marets and this, combined with their wide distribution over the lunar surface suggests that they are associated with more or less autonomous domains, each with its own movements of lava migration and its own cycle of heating and liquefaction followed by cooling and solidification as it reaches the lunar surface. Although we see only surface manifestations, it seems probable that each domain extends to a considerable distance below the surface, with sufficient rigidity to retain its separate identity and sufficient openness of structure to permit the migration to the surface of the lava which makes possible its identification as a maret and its relative position in an age sequence. The general idea of autonomous domains is scarcely surprising in view of the great variety of surface structures on the moon. It recieves support also from the gravity observation of Müller and Sjogren who have observed massive gravity anomalies on the lunar surface by the method of studying the perturbations of satellite orbits.

3.6. KOPAL'S CONCLUSIONS ON LUNAR MOMENTS OF INERTIA

Some indirect confirmation of the non-homogeneity of the Moon, and, by implication, of the existence of autonomous domains may be found in the conclusions of Kopal (1972) that the observed anomalies of mass distribution in the Moon as revealed by studies of its libration are mainly concerned with its outer layers. He considers that observed departures of the Moon's shape from a regular figure of revolution could not be caused by tides but must be due to irregularities or 'vagaries' in the latest stages of the accumulation of the Moon. Such vagaries of accumulation could not be retained by a body with a continuous fluid surface but require the presence of autonomous domains of anomalous mass with a degree of rigidity capable of maintaining their separate identities throughout subsequent lunar history.

Kopal's conclusions suggest that there may never have been a primordial floating crust, in the universal sense in which the term is ordinarily used. If his interpretation were accepted, it would be necessary to reassess the relative importance of external and internal heating of the Moon. This raises the possibility that lava migration from the interior to the surface may have played an important part in the generation of the terrae. In view of the very considerable amount of evidence indicating low density anorthositic material as the most important constituent of the highlands, any new suggestion for their origin would require a process capable of promoting the chemical and gravitational differentiation of lunar material. One possibility could be that, in place of the ocean of lava which Kopal's conclusions seem to preclude, there might be substituted a series of suitably distributed lava 'lakes' of sufficient depth and extent to make differentiation possible. Lack of observational verification prevents this possibility being taken very seriously at present through future detailed studies could change the situation.

Another speculative possibility is that differentiation might take place in a generally vertical column of lava, migrating toward the surface at a velocity which is low relative to the motions within the liquid due to the sinking of heavy molecules or groups of molecules and their replacement by lighter units.

While the above suggested possibilities run counter to what many scientists believe regarding the origin of the terrae, the uncertainty still associated with lunar models makes it desirable to approach the subject from as many different points of view as possible. The gravity anomalies associated with the maria and some large craters suggest a lunar crust which has retained its stiffness over a period of the order of 3.5 to 4.0 b.y. The retention of these physical characteristics over a further considerable period of time into the past may be a possibility worthy of serious consideration.

3.7. Relationship of marets to large maria

In concluding this discussion we draw attention to some possible relationships of marets with the recognized large maria. In Figure 3 is shown a maret area in the neighborhood of Meton. Here it appears that a cluster of moderately large impacts has resulted in a continuous flat area, bounded on the outside by parts of the walls of the craters due to the impacts. If instead of comprising several impacts of moderate size, there had been one very large impact of the order of that producing Mare Imbrium or Mare Crisium, capable of excavating a basin of considerable size, it seems possible that a mare of several hundred km diameter might have been produced with the migrating lava responsible for the maret providing the material for the filling of the basin.

In this connection it is interesting to compare the well known Mare Imbrium, having a lava surface of 1100 km diam with what is generally considered a more recent feature, Mare Orientale. If our crater counts are taken as a criterion of relative age of the flat central mare surface of Mare Orientale, then the value of $N = 14$ is not significantly different from $N = 15$ for the average of the near side Maria as a whole. While our value of N for Mare Imbrium based on random sampling is $N = 10$, again this is not significantly different from that of Mare Orientale where the counts are considered to have been somewhat distorted by secondaries from the recent crater Maunder.

While the ages of the mare surfaces of these two objects, on the basis of such evidence as we have, do not appear to be significantly different, the same cannot be said for the times at which the impacts occurred. In fact there exists good evidence to suggest that the impact that produced Mare Orientale was considerably more recent then any of the other large maria. The most important evidence for a relatively recent age for Orientale is the observation of fresh and extensive damage to the lunar surface over larger areas surrounding the impact. Additional evidence is found in the deposition of fragmental material believed due to the Orientale impact in the form of so-called Cayley plains (Chao *et al.*, 1973) as far away as the Descartes region where the Apollo 16 landing was made. Although it is scarcely possible to assign an exact age to the Orientale impact there seems no doubt that it is considerably more recent than that of the impacts causing the other large maria. If as seems probable, a period of time of the order of one half billion years was required to fill the major mare basins, the Orientale basin may well have had less than half that period so that exhaustion of heat sources may have prevented it from attaining the maturity of the other maria.

It has already been suggested that the most ancient craters of our list (and by inference, the marets) were probably not older than 4 b.y., assigned to the oldest measured samples of lunar material. Baldwin in a private communication has indicated that, on the basis of his crater age class C, our craters extend from $C=4$ to $C=10$ a range which effectively covers the period of time nesessary for the filling of the mare basins. It would appear therefore that the data associated with the marets may provide some indication of the conditions prevailing in the Moon's interior during this important period of lunar history. Such indications may be outlined as follows:

(1) The observations suggest an active interior with numerous sources of heat, capable of producing lava in considerable quantities without outside stimulation.

(2) While we do not know the depth of the heat sources it is reasonable to suppose that such depths are not negligible and that there are therefore important lines of communication between the interior and the surface of the moon.

(3) The indications of relatively large age differences between marets, suggest that heat sources within autonomous domains of the lunar structure may have quite different time cycles; so that observed outbursts of lava may occur at such widely different times as are suggested by successive lava flows on the lunar maria. (Any large impact such as that producing Mare Imbrium would almost certainly cut through a number of domains, each with its separate chronology).

A large meteorite impact, excavating a basin having a depth of the order of 50 km will cause a certain amount of melting by impact and by the removal of load from high temperature material held in the solid state by lithostatic pressure. In addition such an excavation is likely to rejuvenate existing lines of communication with the lunar interior as well as creating new ones by the shattering of material beneath the basin. These various processes, taken together, would appear capable of accounting for both the initial filling of the mare basins and such subsequent lava flows as have been observed on a number of the larger maria.

While the work of previous investigators, combined with the results of the present observations suggest rather strongly that there are numerous heat sources within the body of the Moon, the nature of these heat sources is not known with any certainty. The possibility most commonly invoked is that of radioactivity (LSAPT, 1973) and this possibility is strengthened by the absence of plausible alternatives. It is not easy to devise observations which could provide positive information on this point. The most direct evidence bearing on the material of the lunar interior is to be found in the lava extrusions responsible for the maria, the flat-floored craters and the marets. On page 79 the possibility is suggested that even the terrae may have had their origin in extrusions from the lunar interior. The collection of lunar samples by Apollo astronauts has provided considerable information on the radio activity of the material from the mare basins and to a lesser degree from some terra areas. When the time comes for further sampling of material from the lunar surface it seems logical to suggest that a selection of the marets and flat floored craters could well provide new information of value on the difficult question of the radio activity of the lunar interior.

Another possibility for future observations is a systematic coverage of the surface by color photography. A start has already been made in the color photographs of the Apollo 15 series. When photographs of this kind are combined with visual observations by Apollo astronauts and studies of the colors of lunar samples, the basis of selection of future profitable landing sites by manned or unmanned spacecraft would be considerably broadened.

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