Lunar Terrain and Traverse Data

for

Lunar Roving Vehicle Design Study

by

H. J. Moore
R. J. Pike
G. E. Ulrich

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Section A

Traverse Profile for a Hypothetical Lunar Roving Vehicle Mission

by

G. E. Ulrich

Section A

TRAVERSE PROFILE FOR A HYPOTHETICAL LUNAR ROVING VEHICLE MISSION

Introduction

This report summarizes the preliminary results of on-going studies in the Terrain Analysis, Trafficability, Crater Studies, and Advanced Systems Traverse Research Projects of the U.S. Geological Survey under NASA Contracts W-12,388 and R-09-020-041. The information included herein has been prepared under the auspices of the Science and Traverse Planning Panel for the Lunar Roving Vehicle Study Management Team. It is intended to provide a base line LRV traverse plan from the best currently available supporting data on lunar terrain characteristics and geologic interpretations both of which will critically affect the use and application of roving vehicle concepts in Post-Apollo lunar exploration. It should be made clear that this is a preliminary effort and subsequent revisions should be expected.

Procedure

The traverse profile proposed here is intended to be representative of a wide range of scientific mission objectives and lunar terrain types for an unmanned LRV mission having a map-distance range of 1000 km and a one-year duration. It is not derived from any single area of the Moon but rather it is an assortment of selected sites of scientific interest and terrain types for which data were already available or could be readily obtained for this study. The traverse presents the variety of terrains and sites to be expected in the course of a number of LRV traverses. The geographic locations from which the data are obtained are not cited except where acknowledgment for the work by other than the author must be made.

This first section of the report attempts to place the hypothetical traverse in a geological context and in a logical sequence of traverse segments alternating with relevant sites of major scientific interest (Table 1). The budgeting of time, distance, and vehicle velocity is dependent on the combined effects of slopes, craters, and blocks based on analyses by H. J. Moore and R. J. Pike of measurable lunar data for broad terrain categories as set forth in the sections following in this report. The primary sources of information on the lunar surface to date are the published and unpublished results from the Ranger, Surveyor, Lunar Orbiter, and Apollo 8 missions. The importance of topographic definition of the lunar surface on both large and small scales has become increasingly evident with the growing demands for definitive mission plans and mobility concept studies (Ulrich, 1968). The primary methods of obtaining such data for this report have been photogrammetry, photoclinometry and shadow measurements.

There are limitations in the accuracy of quantitative data gleaned from spacecraft photography when using photogrammetric, photoclinometric and other measurement techniques. Thus, the data listed here should be considered a current best estimate which will require revision as more information is obtained.

Primary Assumptions

In addition to the constraints imposed by lunar terrain and trafficability estimates, certain basic assumptions concerning LRV traverse concepts must be made on which to base the mission profile. The following assumptions have been generally agreed upon by the Science and Traverse Planning Panel for purposes of the present study:

1. The mission duration is one year, consisting of approximately 4000 hours of lunar daylight. Effective mission operation will continue around the clock throughout each lunar day, except for 1/2 day at each end when sun elevation is less than 7°.

2. The mission profile is for an LRV in the unmanned mode, deployed from a Lunar Payload Module (LPM) at the traverse origin. The LRV will rendezvous with a manned mission at its terminus to deliver samples for return to earth and to provide mobility for one or two astronauts for up to 120 hours of 3-hour sorties, each up to 30 km long. An example of a 3-day manned mission profile is given by Karlstrom, McCauley, and Swann (1968) and a comparison of the gross time allotments for the manned and unmanned missions is shown in Figure 1.

3. The unmanned LRV traverse is 1000 km in map distance consisting of about 50% mare and 50% upland terrain.

4. The traverse is further divided into four general terrain types for which preliminary data are available: smooth mare, rough mare, hummocky upland, and rough upland. Data are also available for large fresh craters such as Tycho, Aristarchus, and Copernicus and are included, on a preliminary basis, for this terrain category.

5. Average velocities of the LRV, on the basis of map distance attainable for the several terrain categories are estimated as follows and in Table 2:

Smooth mare	1.7 kph
Rough mare	1.5 kph
Hummocky upland	1.0 kph
Rough upland	0.5 kph
Large fresh crater	0.3 kph

These velocities are considered reasonable for the LRV operating in a continuous mode. To the extent that they turn out to be pessimistic, they may also be reasonable for the step mode of operation as well.

6. Frequency of stops required to update geographic position and to evaluate hazards and landmarks in areas to be crossed:

Mare--every 0.5 km (total of 1000 stops)

Upland--every 50 m (total of 10,000 stops)

Time for a single, routine LRV stop-and-go including communication delay is estimated to be 40 seconds.

7. Time for shut-down or warm-up procedures before and after lunar night, and use of time and power during lunar night is not determined here. The half day periods when sun is 0.7° above horizon may satisfy the first item.

8. Scientific investigations are to include the following basic group of experiments selected by the Science and Traverse Planning Panel as generally applicable to all unmanned LRV traverses:

a. Facsimile camera system with the option of small field magnification and stereo capability (in addition to the navigation TV, stabilized to operate continuously on moving vehicle; both cameras have 360° scan capability.

b. Samplers for rock core (or fragment) and particulate materials

c. Sample storage for 400 samples, under 1/2 lb. each

d. X-ray diffractometer/spectrometer, including sample preparation and introduction

e. Gravimeter, deployable/retrievable

f. Magnetometer, continuous reading (if applicable)

g. Three deployable Remote Geophysical Monitors (passive seismic)

Additional experiments may be added for special application on particular missions. The LRV and its various appendages will provide engineering experiments in soils mechanics that are not charged to science.

9. Scientific operations with respect to time consumption are divided into two categories (Figure 2):

(a) Major Science sites (Table 1) each of which is allotted 50 hours for local maneuvering and traversing operations (40%), camera scanning for science and general purposes (20%), sample collection (20 samples at 15 minutes each), preparation, insertion, and storage/discard (12 min. each), sample analysis (20 min. each), and 20 gravimeter stations (12 min. each).

(b) Routine station stops at an average map distance of 0.5 km enroute between major science sites; 360° camera scan (5-10 min.), collection of grab samples (10-15 min.), and a gravity measurement (10-12 min.) comprising 1/2 hour at each station for a total of 2000 stations. Analysis of sample is performed while enroute, and one in every ten collected is retained.

10. The LRV must avoid mature, young, and fresh craters which are two meters across and larger and blocks which are one meter across and larger. The width of the vehicle for purposes of obstacle calculations is two meters.

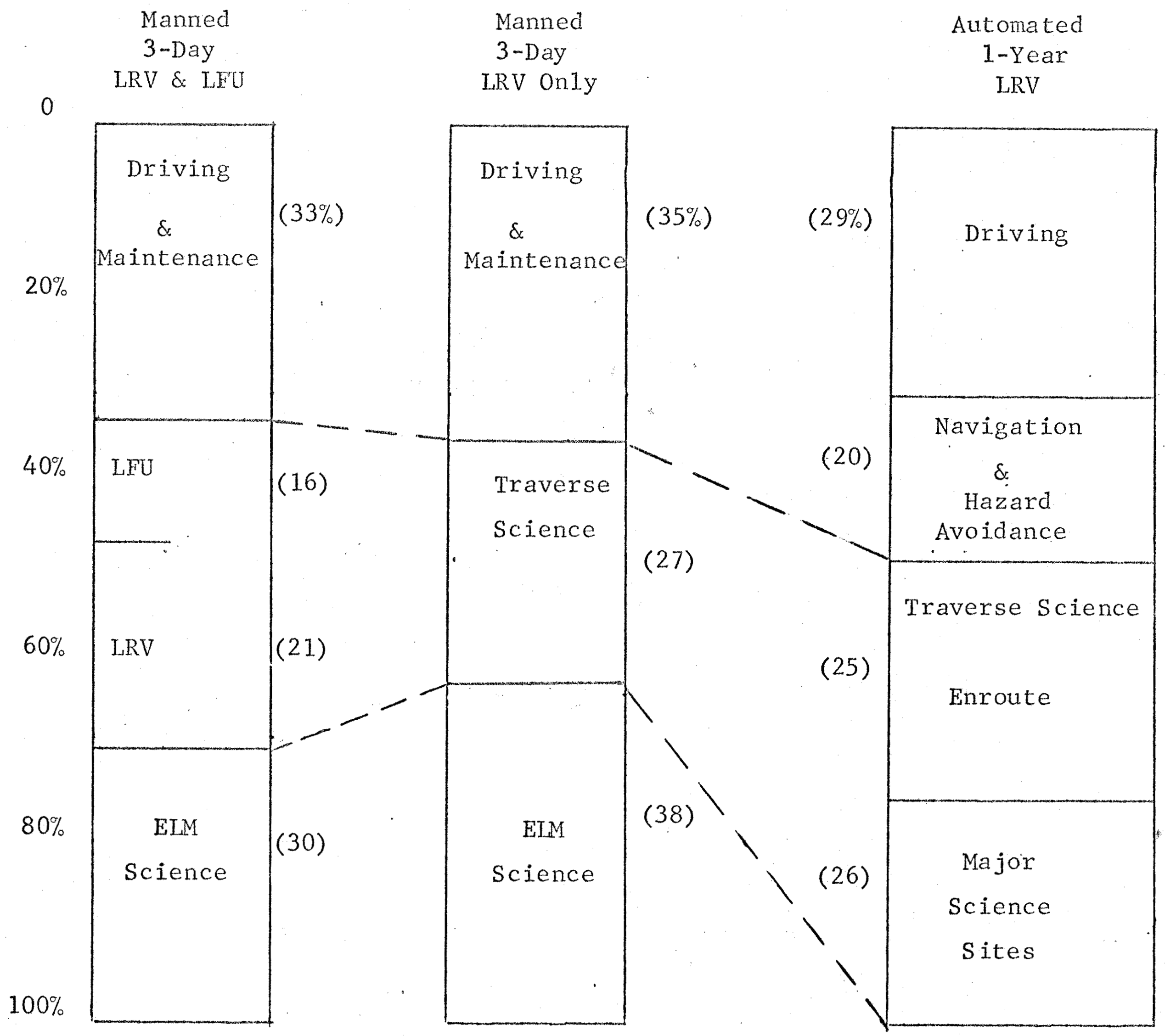

Figure 1.--Comparison of gross time allotment in manned and automated mission concepts. (Manned mission allotments modified after Karlstrom, McCauley, and Swann (1968))

UNMANNED LRV 1000 KM TRAVERSE

Hours--1 year traverse		% of operational traverse time
1000	Driving	25
150	Routine stop and start	4
400	Hazard contingencies	10
400	Navigation	10
1000	Routine sampling and geophysics (1/2-km interval)	25
1050	Major science sites (21)	26
4000		100

MAJOR SCIENCE SITE

Hours at site		% of site time available
20	Maneuvering for vantage points, hazard appraisal and avoidance, sample collection, and local geophysical investigations. (Magnetometry, if applicable, should record continuously while vehicle is operating)	40
10	Facsimile and TV site study	20
5	Sample collection 20--Keep 10	10
4	Sample preparation, presentation to instruments, and storage (or discard)	8
7	Diffractometry and spectrometry	14
4	Gravimetry--20 stations	8
50		100

Figure 2.--Gross budget of time consumption on overall LRV traverse and at individual major science sites.

Table 1.--Major Science Sites

		Sequence in 1000-km Traverse	Terrain Type or equivalent
I.	Volcanic sites		
V-1	Lava flow front and top with linear depressions	2	rough mare
V-2	Mare ridge with terrace	5	rough mare
V-3	Caldera or pit crater	14	rough mare-rough upland
V-4	Low lava dome	16	rough mare
V-5	Crater-top dome (or steep-sided dome)	17	hummocky-rough upland
V-6	Maar crater (or chain crater)	18	rough upland
V-7	Dark halo craters and associated rille	20	rough mare-hummocky upland
V-8	Transient phenomenon/thermal anomaly	21	smooth-rough mare
II.	Impact crater sites		
I-1	Crater with secondary impacts & blocks	3	rough mare
I-2	Secondary field of small blocky craters and concentric craters in regional ray-covered area	4	rough mare
I-3	Large fresh crater rim	8	large crater
I-4	Normal & inverted stratigraphic succession in wall and rim	9	large crater
I-5	"Ponded" plains on crater rim or wall	10	rough mare
I-6	Floor-wall contact near concentric rille	11	large crater
I-7	Central peaks with block fields and boulder tracks	12	large crater
III.	Tectonic/mass wasting sites		
T-1	Smooth regolith at traverse origin	1	smooth mare
T-2	Mare-upland contact and talus slopes	6	smooth mare-rough upland
T-3	Straight rille with fault scarp	7	rough-hummocky upland
T-4	Debris flow	13	large crater
T-5	Mare rille concentric with basin rim	15	rough mare-rough upland
T-6	Sinuous rille with levees	19	rough mare-rough upland

Table 2.--Distance, Velocity, and Time Constraints derived from Sections B, C, and D

Distance and Velocity	Smooth Mare	Rough Mare	Hummocky Upland	Rough Uplands Slopes non-negotiable 25°(5%)	20°(10%)	15°(20%)	Fresh Large Crater	
%increase over map distance due to:					*			
1. Slopes crossed, L_s	0.2	0.4	1.0	1.9	1.7	1.5	3.5	
2. Slopes too steep, L_{ts}	--	--	--	2.9	5.7	14.3	14.3	
3. Craters, L_C	15.7	16.9	22.4	5.0	5.0	5.0	6.3	
4. Blocks, L_B	0.04	0.4	0.4	0.4	0.4	0.4	6.3	
5. Blocks and craters, L_{B+C}	15.7	17.5	23.1	5.5	5.5	5.5	13.4	
6. Total % increase, L_T	15.9	17.9	24.1	10.3	12.9	21.3	31.2	
7. Ground distance travel per unit map distance	1.16	1.18	1.24	1.10	* 1.13	1.21	1.31	
8. Avg. map velocity (kph)	1.7	1.5	1.0	0.5	0.5	0.5	0.3	
9. Ground velocity (kph)	1.97	1.77	1.24	0.55	0.56	0.60	0.39	
<u>Time</u> Hours per km traverse increment (map distance)								
10. Driving pt-to-pt	.59	.67	1.00	2.00	2.01	2.02	3.36	
11. 2 routine sci. stops	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
12. Stop & go for science	.02	.02	.02	.02	.02	.02	.02	
13. Navigation	.06	.06	.10	.20	.20	.20	.03	
Hazard avoidance					*			
14. No. craters & blocks/km, N_{B+C}	39.1	41.1	41.3	17.5	17.5	17.5	61.1	
15. Stop & go @ each	.43	.46	.46	.19	.19	.19	.68	
16. Drive around	.08	.10	.19	.10	.10	.09	.34	
17. Total stop & go, navigation & hazards	.59	.64	.77	.51	.51	.50	1.07	
18. Total traverse & science	2.18	2.31	2.77	3.51	3.52	3.52	5.43	
<u>Summation exclusive of Science Sites</u>					*			Σ
19. Distance in km: Map:	250	250	190	150	150	150	125	965
20. Distance in km: Ground:	290	295	236	165	170	182	164	1155
21. Time required, hrs.	545	578	526	526	528	528	679	2856
22. % of total time	19	20	18.5	(18)	18.5	(18.5)	24	100
23. % of total distance	25	25.5	20.5	(14)	15	(16)	14	100

*Calculations for rough uplands are based on this column throughout report.

Earth-based mission requirements

The effective use of a complexly instrumented, multipurpose vehicle remotely controlled on the lunar surface clearly places severe requirements on the earth-based control and data handling facility. These requirements should become more clearly defined as the LRV design study progresses. The evolution of a conceptual design for the mission operations center which meets both engineering and scientific needs should parallel that of the LRV.

The hypothetical lunar traverse presented in the following pages is intended partly to illustrate some of the routine demands which will be made on the mission operation center and on the scientific data facility associated with it. Among these are requirements for personnel such as investigators, data handlers, prime vehicle controllers, and operators of remotely controlled scientific instruments. Obvious problems are expected from the simultaneous operation of several vehicle- and instrumented components, the communications time-lags, the power consumption allowable on the vehicle, and the heavy demands from both the scientific and engineering areas on the use of available computers for real-time data handling, decision making, and issuing of commands to the vehicle. In order to operate on a 24-hour basis, four full teams of investigators, data handlers, controllers, and operators will probably be necessary.

All observational data will require real-time interpretative geologic commentary that can be quickly stored and retrieved along with the visual image, as a substitute for observations by an observer aboard the vehicle. Several geophysicists will be required to interpret gravimetry and magnetometry as it is received and plotted; in addition active seismic data from manned missions will require real-time analysis. Geochemists will have to evaluate the textural and analytical data on samples collected in order to select the best working geologic models or hypotheses and as a guide to future sampling. A navigator will be continually responsible for the vehicle's geographic position as well as its elevation, and it will be his job periodically to update the vehicle's navigation system.

Operators or computer-controlled commands with earth overrides will be required for all of the following functions, some of them simultaneously, determined mainly by the scientific mission objectives:

a. TV pan and tilt and 360° scan

b. Facsimile camera pan and tilt, 360° scan, and close up of rock and "soil" samples

c. Sampling of lunar materials

d. Sample preparation and insertion into analytical instruments

e. Storage, retrieval, and discarding of selected samples

f. Deployment, leveling, reading, and retrieval of gravimeter

g. Ranging to artificial or selected natural reflectors or hazards

h. Driving the vehicle: starting, accelerating, decelerating, stopping, backing, and turning

Displays in the science data facility based simply on the vehicle-mounted science package described above for the unmanned rendezvous mission should include at least four XY plots driven by telemetry as received from the vehicle: (1) geographic position and heading of the vehicle on a controlled photographic or photogeologic base map,

(2) gravimeter readings with capability of contouring, profiling, and solving 3-point problems for regional gradient, (3) magnetometer data in both XY and profile form as required, and (4) elevation profile of vehicle position continuously along traverse. In addition geochemical displays will be needed to show sample locations, classification, and position in storage unit, tabulated results of elemental and mineralogical compositions with textural characteristics, and off-line plotter displays for comparison of any combination of geochemical data.

These basic requirements are only a first cut on the projected needs of a science data facility. Terrestrial experiments combining these and other concepts should permit more precise statements of organizational and hardware requirements for the data facility.

Hypothetical Traverse Mission Profile

The remainder of this section presents the chronological sequence of mission segments in which detailed investigations at individual major science sites (Table 1) are linked together by routine traverse sections across uniform types of lunar terrain. Each science site consists of a brief description of scientific objectives, the allotment of time at the site, and the types of terrain and hazards anticipated. Where data is available, maps and profiles are provided as examples of real lunar features. The tabulated terrain characteristics are also given for each site.

The traverse segments between science sites are presented as data sheets, and when each terrain type is visited for the first time a representative sample of topographic profile is also provided.

Table 3 is a summary of the schedule and cumulative increase of distance, time, and geologic sampling for the entire traverse. For engineering studies and comparative analyses, calculations for any length of traverse and any combination of terrain types and science sites can easily be made by cutting out or rearranging portions of the traverse.

The sequence of science sites, lunar nights, and deployment of Remote Geophysical Monitors in relation to traverse distance and cumulative number of earth days is illustrated in Figure 3. This sequence is based on the traverse presented in the following pages, one of many possible combinations that would be equally logical and feasible from a scientific point of view.

Table 3.--Summary of Distance, Time, and Sample Collection Increase on Traverse

Major Science Site or Traverse Segment	Distance, km												Time, hrs					Cumulative Geologic Samples	
	Mare				Uplands				Large Crater		Science Sites Ground Distance	Cumulative Ground Distance			Stop & Go, Navigation Hazards				
	Smooth		Rough		Hummocky		Rough									Cumul. Daylight	Lunar Night Approx.	Collect, Analyze	Retain
	Map	Ground	Map	Ground	Map	Ground	Map	Ground	Map	Ground			Driving	Science					
Site T-1											20	20	15	20	15	50		20	10
0-50 km	50	58										78	30	50	30	160		120	20
Site V-1											15	93	20	30	--	210		140	30
50-100	50	58										151	30	50	30	320	@312	240	40
Site I-1											10	161	20	30		370		260	50
100-150			50	59								200	34	50	32	486		360	60
Site I-2											15	235	20	30		536		380	70
150-200			50	59								294	34	50	32	652	@624	480	80
Site V-2											15	309	20	30		702		500	90
200-300					100	124						433	100	100	77	979	@936	700	110
Site T-2											15	448	20	30		1029		720	120
300-350			50	59								507	34	50	32	1145		820	130
Site T-3											10	517	20	30		1195		840	140
350-400					50	62						579	50	50	38	1333	@1248	940	150
Site I-3											5	584	20	30		1383		960	160
Site I-4											5	589	20	30		1433		980	170
400-450									30	39		628	101	30	32	1596	@1560	1040	176
Site I-5			(10)	(12)							12	640	20	30		1646		1060	186
Site I-6									(10)	(13)	13	653	20	30		1696		1080	196
450-500									45	59		712	151	45	48	1940	@1872	1170	205
Site I-7									(5)	(7)	7	719	20	30		1990		1190	215
500-550					40	50						769	40	40	31	2101		1270	223
Site T-4									(10)	(13)	13	782	20	30		2151		1290	233
550-600									50	66		848	168	50	54	2423	@ @2184	1390	243
Site V-3											10	858	20	30		2473	{2496	1410	253
600-700							100	113				971	201	100	51	2825	{2808	1610	273
Site T-5											15	986	20	30		2875		1630	283
700-750			50	59								1045	34	50	32	2991		1730	293
Site V-4											15	1060	20	30		3041		1750	303
750-800			50	59								1119	34	50	32	3157	@3120	1850	313
Site V-5											10	1129	20	30		3207		1870	323
800-850	50	58										1187	30	50	30	3317		1970	333
Site V-6											5	1192	20	30		3367		1990	343
850-900	50	58										1250	30	50	30	3477	@3432	2090	353
Site T-6											10	1260	20	30		3527		2110	363
900-950							50	57				1317	100	50	26	3703		2210	373
Site V-7											10	1327	20	30		3753	@3744	2230	383
950-1000	50	58										1385	30	50	30	3863		2330	393
Site V-8@											15	1400	15	20	15	3913*		2350	400
Rendezvous																			
	250	290	250 (260)	295 (307)	190	236	150	170	125 (150)	164 (197)	245	---	1641	1575	697	---	---	----	---

*62 hrs shorter for traverse E→W
62 hrs longer for traverse W→E

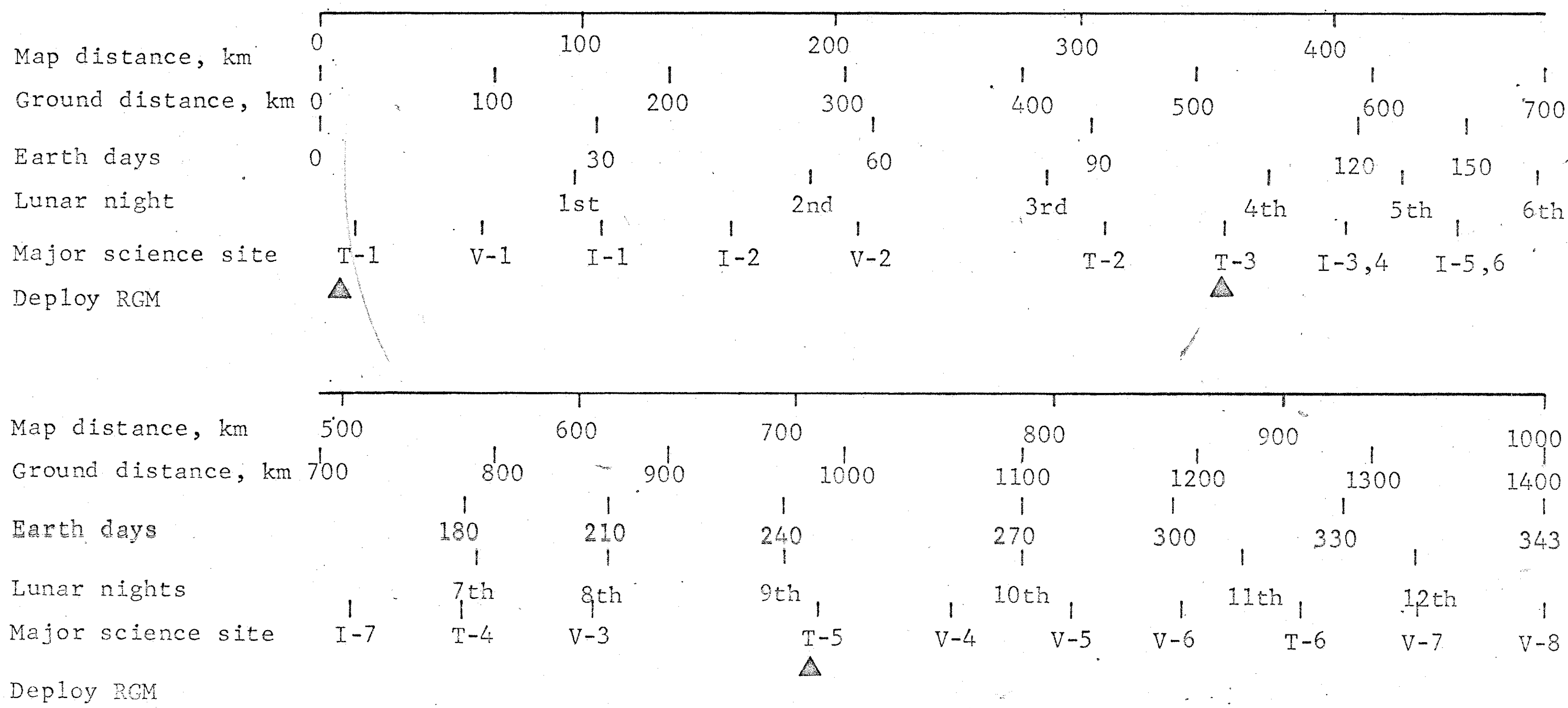

Figure 3 Sequence of science sites and lunar nights in relation to traverse distance and total number of earth days

Definitions of terrain symbols used in Table 2 and in data compilations for each segment of the traverse profile, partly modified from Sections B and E.

Map distance — Distance in km obtained by direct measurement between two points on a map.

Ground distance — True distance in km on the surface between two points which accounts for the statistical irregularities in the surface requiring deviation from a straight, horizontal path.

Map velocity — The map distance divided by the estimated hours required to traverse between two points.

Ground velocity — The true speed in km per hour required to traverse the ground distance so as to achieve the predicted map velocity.

L_s — Percentage of map distance which must be added to get ground distance due to traversing slopes, perpendicular to strike of slope and not allowing for curvature.

L_{ts} — Percentage of map distance which must be added to get ground distance due to slopes too steep to negotiate.

L_C — Percentage of map distance which must be added to get ground distance circumventing craters of mature and younger morphology, 2 m to 2 km in diameter.

L_B — Percentage of map distance which must be added to get ground distance circumventing blocks and boulders, 1 to 30 m in diameter.

L_{B+C} — Percentage of map distance which must be added to get ground distance due to circumvention of craters and boulders.

L_T — Total ground distance increase as percentage of map distance due to the combined effect of slopes, blocks, and craters.

N_C — Number of craters per km of ground distance that must be circumvented (2 m - 2 km in diameter).

N_B — Number of blocks per km of ground distance that must be circumvented (1 m - 30 m in diameter).

N_{B+C} — Number of craters and blocks per km of ground distance that must be circumvented.

PSD — Power spectral density in meters^2 per cycle per meter; given for frequencies of 0.05 and 0.5 cycles per meter.

Abs. mean slope---absolute arithmetic mean slope

Alg. std. deviation---algebraic standard deviation

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Site: T-1 Smooth regolith surface at landing site

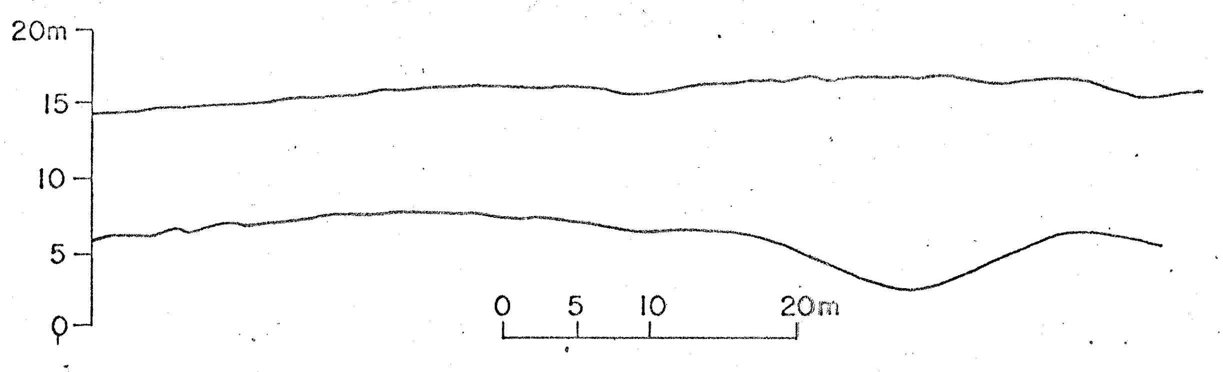
Terrain Type or equivalent: smooth mare

Objectives: to check out LRV and scientific instrument systems; to establish routine observational, geochemical, geophysical, and navigational procedures; to commence automated one-year mission with examination of smooth mare landing site.

Operation	Estimated Time (hours)			
	Driving	Science	Other	Cumulative
Landing of unmanned LM with LRV				0
Deploy LRV, check out driving and instrument controls.	5		5	10
Facsimile and TV scanning for navigational fix, preliminary hazard analysis, and site study.			10	20
Deploy first Remote Geophysical Monitor (RGM)		1		21
Local maneuvering for scientific measurements and sampling.	(10)			
a. Collection of 20 samples (mostly soils)		(5)		
b. Prepare and insert into x-ray diffractometer/ spectrometer		(3)		
c. Diffraction and spectrometry		(6)		
d. Discard 10 and store 10 samples on basis of analytical results		(1)		
e. 20 gravimeter readings spaced 2-3 meters apart.		(4)		
	10	19		50

NOTES:
1) If power permits, items b, c, and d to be performed concomittant with other tasks
2) If magnetic data on the moon are valuable for near-surface geologic interpretation, magnetometer should read continuously while LRV is moving.

Site T-1 Smooth regolith surface



Terrain type: Smooth Mare

Ls	0.2 %
L_{ts}	--
N_B	0.2
N_C	38.9
N_{B+C}	39.1
L_B	0.04%
L_C	15.7 %
L_{B+C}	15.7 %
L_T	15.9 %

	1m	10m	50m
Abs. Mean Slope	2.9°	2.0°	1.4°
Alg. Std. deviation	3.6	2.5	1.7
Abs. Mean Curvature	0.6	1.0	0.8
Alg. Std. deviation	0.8	1.3	0.9

	Max.	Min.
PSD@0.05 (λ=20m):	0.25	0.045
PSD@0.5 (λ=2m):	0.0013	0.00012

Terrain type: Smooth Mare

			1m	10m	50m
Ls	0.2 %				
L_{ts}	--	Abs. Mean Slope	2.9°	2.0°	1.4°
N_B	0.2	Alg. Std. deviation	3.6	2.5	1.7
N_C	38.9	Abs. Mean Curvature	0.6	1.0	0.8
N_{B+C}	39.1	Alg. Std. deviation	0.8	1.3	0.9

			Max.	Min.
L_B	0.04%			
L_C	15.7 %	PSD@0.05 (λ=20m):	0.25	0.045
L_{B+C}	15.7 %	PSD@0.5 (λ=2m):	0.0013	0.00012
L_T	15.9 %			

Map distance, this segment: 50 km

Ground distance, this segment: 58 km

Avg. map velocity: 1.7 kph

Ground velocity: 1.97 kph

Driving time: 30 hrs

Routine science each 0.5 km: 50 hrs

Other operations: 30 hrs

Total time, this segment: 110 hrs

Cumulative ground distance to date: 78 km

Cumulative time to date: 160 hrs

Site: V-1 Lava flow front and top with linear depressions

Terrain Type or equivalent: rough mare

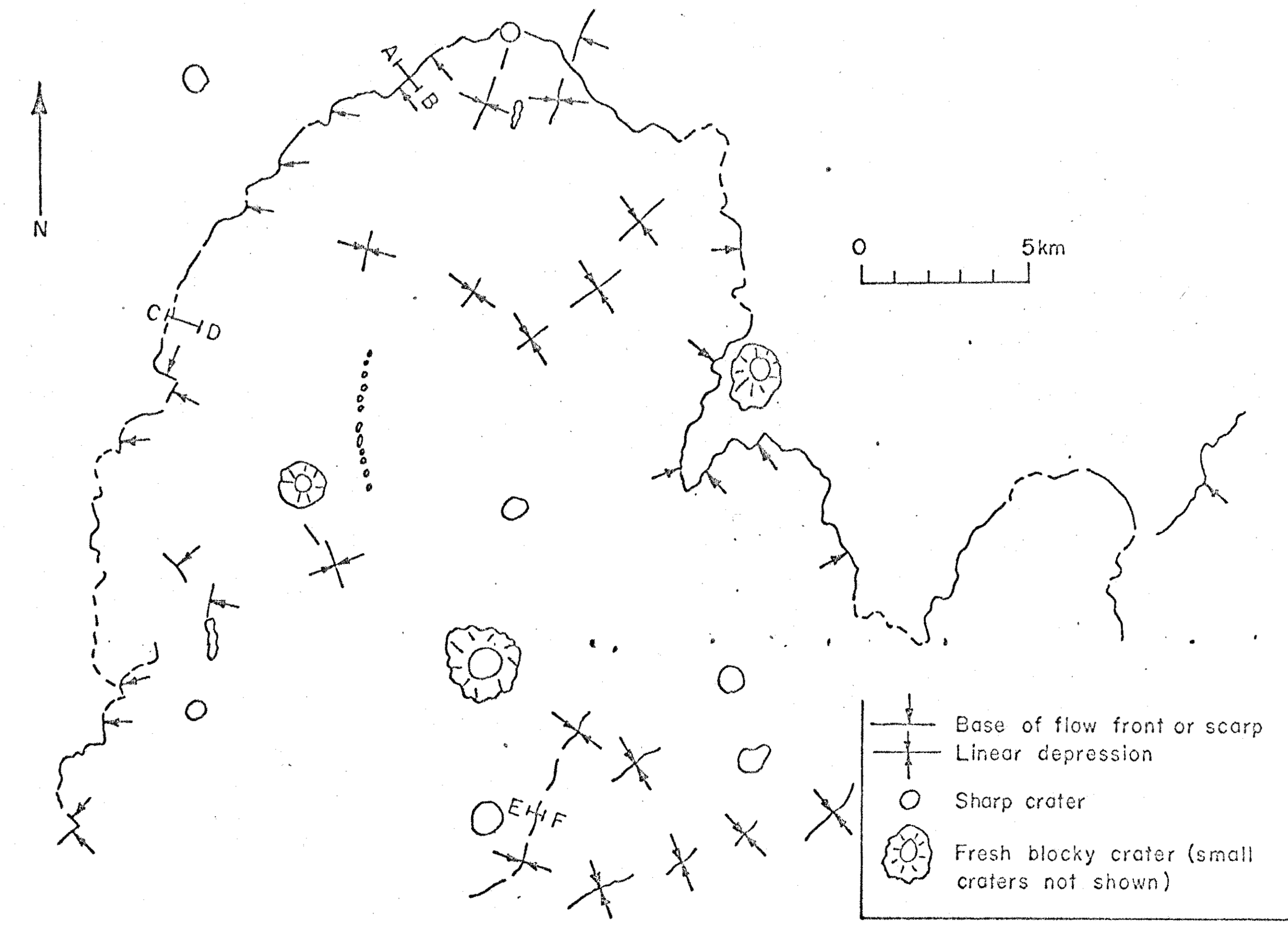
Objectives: Composition and history of lava flow and surrounding plains. Origin of linear depressions: lava tubes, surface flow channels, grabens, or other.

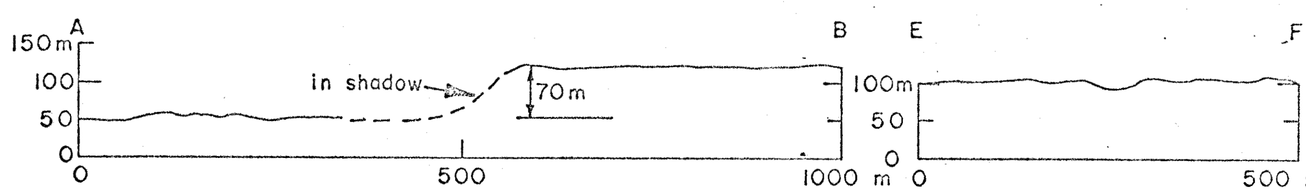
Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering using TV camera for vantage points, hazard appraisal and avoidance, sample collection and geophysics traverses on top of flow and off of flow 200 m beyond front. Linear depressions and flow front slopes are special hazards.	20			180
Facsimile camera for site study and sample collection.		10		190
Collection of 20 samples; away from flow, on flow top, at foot of flow front, and from blocks and outcrops where present.		5		195
Sample preparation, analysis, and selection of 10 for return (to be performed concomittant with other tasks when power permits)		11		206
10 gravimeter readings on flow top and 10 off of flow. Commence on outcrop if possible.		4		210

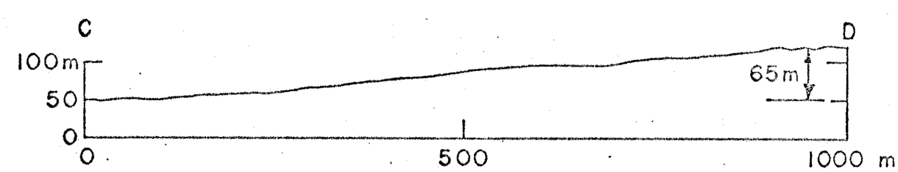
Ls	0.4 %
L_{ts}	--
N_B	2
N_C	39.1
N_{B+C}	41.1
L_B	0.4 %
L_C	16.9 %
L_{B+C}	17.5 %
L_T	17.9 %

	1m	10m	50m
Abs. Mean Slope	5.3°	3.8°	2.5°
Alg. Std. deviation	6.6	4.7	3.1
Abs. Mean Curvature	0.9	1.3	4.1
Alg. Std. deviation	1.3	1.8	5.0

	Max.	Min.
PSD@0.05 (λ=20m):	1.00	0.420
PSD@0.5 (λ=2m):	0.0035	0.0003







L. O. V.

Shadow measurements

Site V-1 Lava flow front and top with linear depressions

Terrain: rough mare

Segment of original 1000-km traverse: 50-100 km

Terrain type: Smooth Mare

			1m	10m	50m
Ls	0.2 %				
L_{ts}	--	Abs. Mean Slope	2.9°	2.0°	1.4°
N_B	0.2	Alg. Std. deviation	3.6	2.5	1.7
N_C	38.9	Abs. Mean Curvature	0.6	1.0	0.8
N_{B+C}	39.1	Alg. Std. deviation	0.8	1.3	0.9
L_B	0.04%				

			Max.	Min.
L_C	15.7 %	PSD@0.05 (λ=20m):	0.25	0.045
L_{B+C}	15.7 %	PSD@0.5 (λ=2m):	0.0013	0.00012
L_T	15.9 %			

Map distance, this segment: 50 km

Ground distance, this segment: 58 km

Avg. map velocity: 1.7 kph

Ground velocity: 1.97 kph

Driving time: 30 hrs

Routine science each 0.5 km: 50 hrs

Other operations: 30 hrs

Total time, this segment: 110 hrs

1st lunar night @ 312 hrs for 360-hour period.

Cumulative ground distance to date: 151 km

Cumulative time to date: 320 hrs

Site: I-1 Crater with secondary impacts and blocks

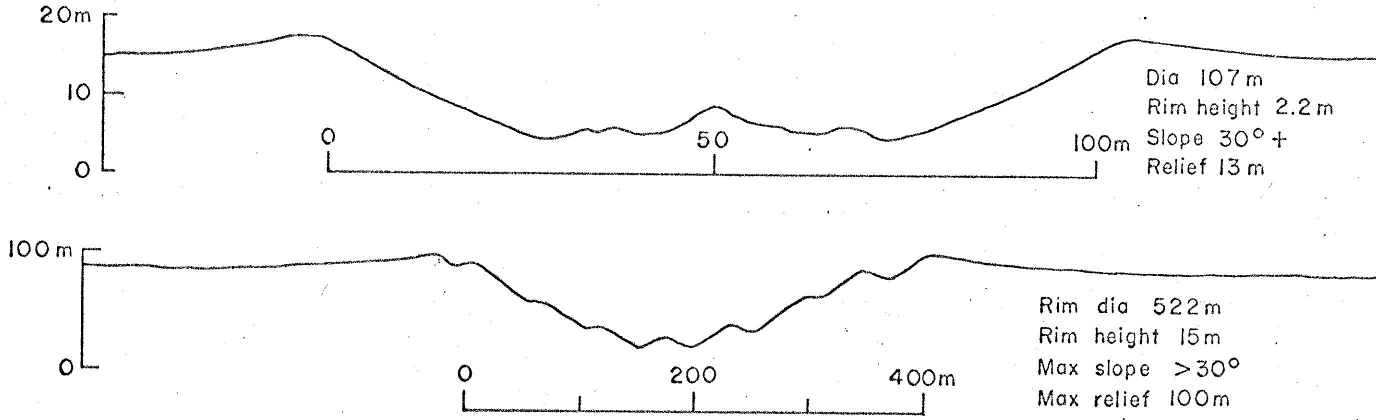
Terrain Type or equivalent: rough mare

Objectives: to examine blocky ejecta and geophysical evidence of stratigraphy beneath the crater rim and origin of various types of secondary craters

NOTE: Lighting angle will be critical to color and textural interpretation of angular blocks

Operation	Estimated Time (hours)			
	Driving	Science	Other	Cumulative
Maneuvering using TV camera for vantage points, hazard appraisal and avoidance, sample collection, and geophysics profiles. Blocks are primary hazards. Secondary craters may be assymetric in shape and contain large boulders or blocks.	20			340
Facsimile camera for site study and sample collection.		10		350
Collection of 20 samples from blocks, rim materials, and surrounding plains		5		355
Sample preparation, analysis, and selection of 10 for return		11		366
20 gravimeter readings from rim outward spaced 5 meters apart.		4		370

Site I-1 Fresh craters



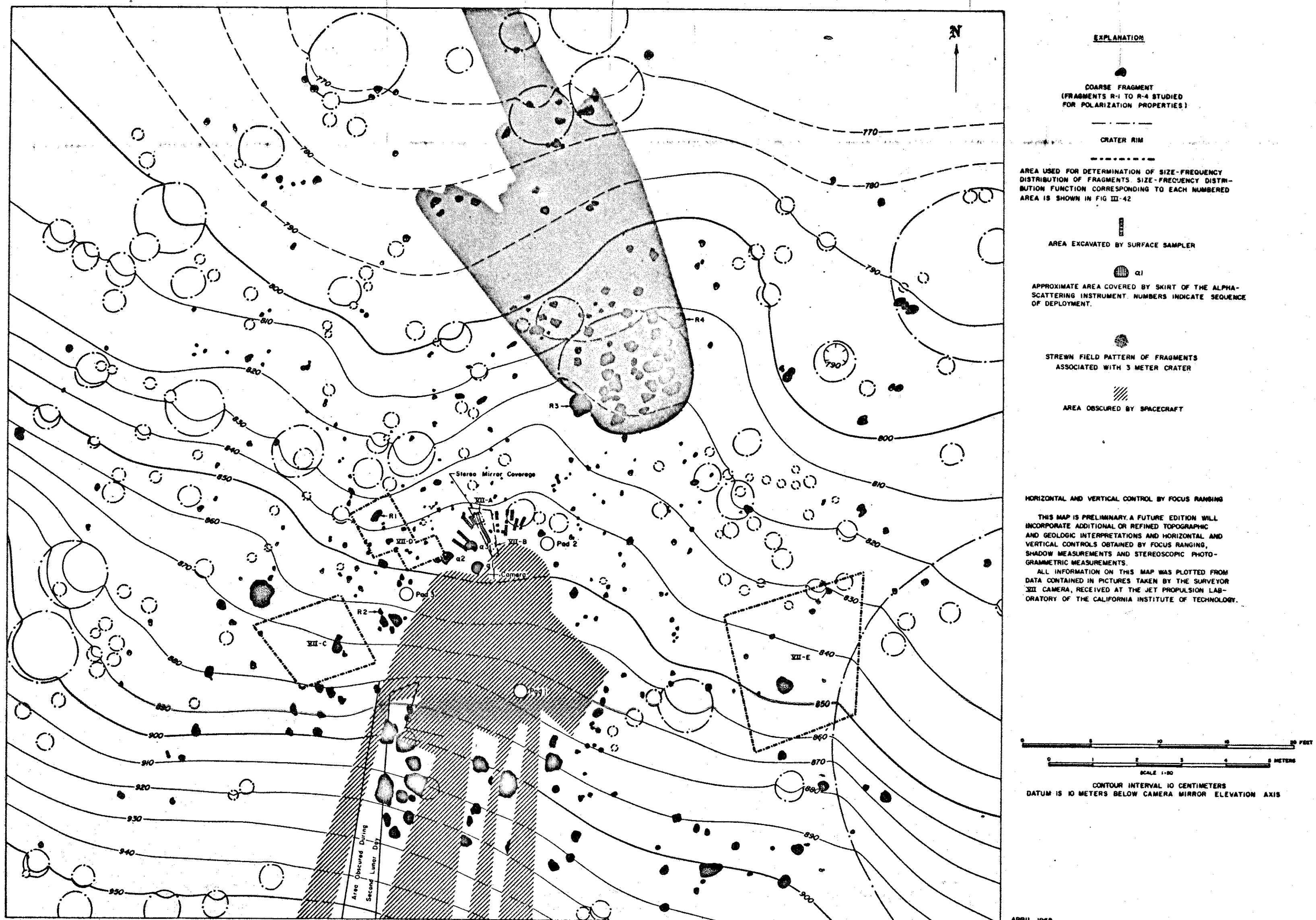
Shadow measurements (Moore)

Terrain type: Rough Mare

L_s	0.4 %
L_{ts}	--
N_B	2
N_C	39.1
N_{B+C}	41.1
L_B	0.4 %
L_C	16.9 %
L_{B+C}	17.5 %
L_T	17.9 %

	1m	10m	50m
Abs. Mean Slope	5.3°	3.8°	2.5°
Alg. Std. deviation	6.6	4.7	3.1
Abs. Mean Curvature	0.9	1.3	4.1
Alg. Std. deviation	1.3	1.8	5.0

	Max.	Min.
PSD@0.05 (λ=20m):	1.00	0.420
PSD@0.5 (λ=2m):	0.0035	0.0003



Topographic map of the near field at the Surveyor VII landing site (topography by R. Jordan).

(from Shoemaker, et al, 1968)

Site I-1 Secondary blocky craters

Site: I-2 Secondary field of small blocky craters and concentric craters in regional ray-covered area

Terrain Type or equivalent: rough mare

Objectives: to determine variety of composition in bedrock and the extent to which depth of over-burden controls the distribution of blocky craters; also the origin of concentric craters

Operation	Driving	Science	Other	Cumulative
	Estimated Time (hours)			
Maneuvering. Blocks and small craters are primary hazards	20			506
Facsimile camera, scanning and sample collection.		10		516
Collection of 20 samples of blocks derived from different small craters.		5		521
Sample preparation, analysis, and selection of 10 for return		11		532
20 gravimeter readings starting with concentric crater whose depth to bedrock is known, with spacing about half the depth		4		536

Ls	0.4 %
L_{ts}	--
N_B	2
N_C	39.1
N_{B+C}	41.1
L_B	0.4 %
L_C	16.9 %
L_{B+C}	17.5 %
L_T	17.9 %

	1m	10m	50m
Abs. Mean Slope	5.3°	3.8°	2.5°
Alg. Std. deviation	6.6	4.7	3.1
Abs. Mean Curvature	0.9	1.3	4.1
Alg. Std. deviation	1.3	1.8	5.0

	Max.	Min.
PSD@0.05 (λ=20m):	1.00	0.420
PSD@0.5 (λ=2m):	0.0035	0.0003

Segment of original 1000-km traverse: 100-150 km

Terrain type: Rough Mare

			1m	10m	50m
Ls	0.4 %				
L_{ts}	--	Abs. Mean Slope	5.3°	3.8°	2.5°
N_B	2	Alg. Std. deviation	6.6	4.7	3.1
N_C	39.1	Abs. Mean Curvature	0.9	1.3	4.1
N_{B+C}	41.1	Alg. Std. deviation	1.3	1.8	5.0

			Max.	Min.
L_B	0.4 %			
L_C	16.9 %	PSD@0.05 (λ=20m):	1.00	0.420
L_{B+C}	17.5 %	PSD@0.5 (λ=2m):	0.0035	0.0003
L_T	17.9 %			

Map distance, this segment: 50 km

Ground distance, this segment: 59 km

Avg. map velocity: 1.5 kph

Ground velocity: 1.77 kph

Driving time: 34 hrs

Routine science each 0.5 km: 50 hrs

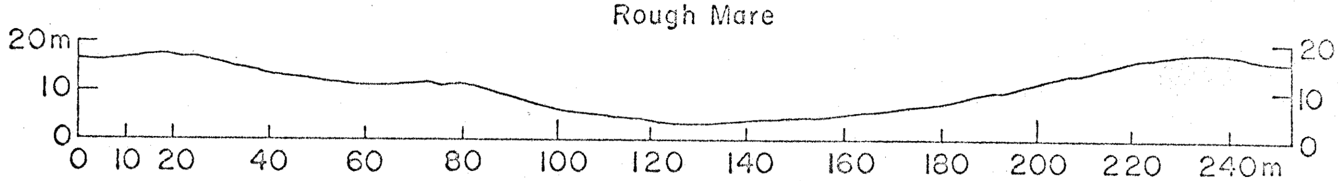
Other operations: 32 hrs

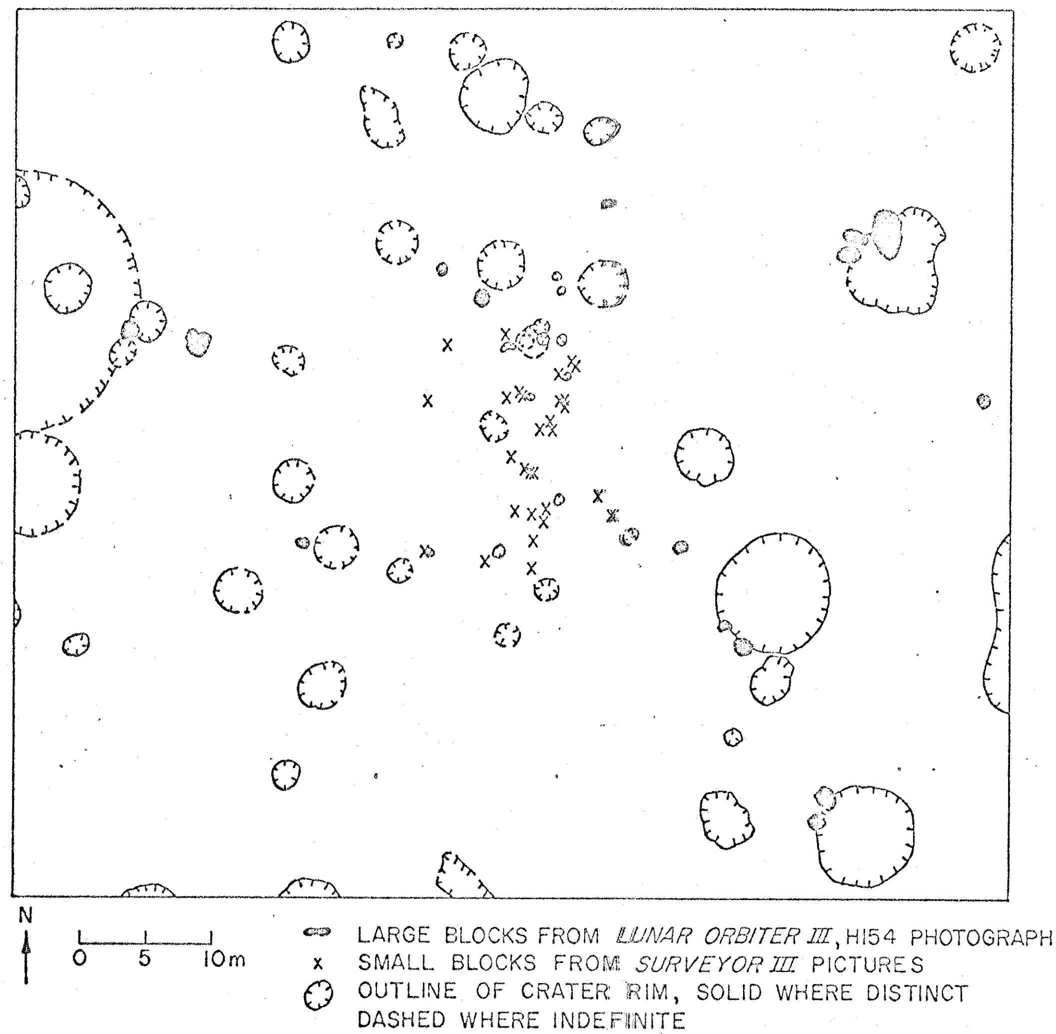
Total time, this segment: 116 hrs

Cumulative ground distance to date: 200 km

Cumulative time to date: 486 hrs

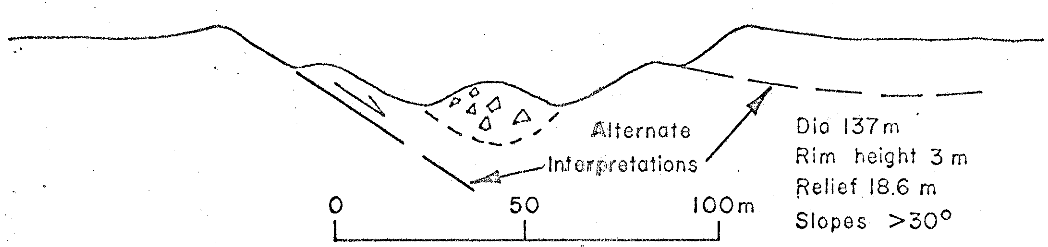
Rough Mare





(Modified from Shoemaker, et al, 1968)

Concentric (double) crater



Shadow measurements (Moore)

Site I-2 Secondary field of small blocky craters and concentric craters in regional ray-covered area.

Segment of original 1000-km traverse: 150-200 km

Terrain type: Rough Mare

			1m	10m	50m
Ls	0.4 %				
L_{ts}	--	Abs. Mean Slope	5.3°	3.8°	2.5°
N_B	2	Alg. Std. deviation	6.6	4.7	3.1
N_C	39.1	Abs. Mean Curvature	0.9	1.3	4.1
N_{B+C}	41.1	Alg. Std. deviation	1.3	1.8	5.0

			Max.	Min.
L_B	0.4 %			
L_C	16.9 %	PSD@0.05 (λ=20m):	1.00	0.420
L_{B+C}	17.5 %	PSD@0.5 (λ=2m):	0.0035	0.0003
L_T	17.9 %			

Map distance, this segment: 50 km

Ground distance, this segment: 59 km

Avg. map velocity: 1.5 kph

Ground velocity: 1.77 kph

Driving time: 34 hrs

Routine science each 0.5 km: 50 hrs

Other operations: 32 hrs

Total time, this segment: 116 hrs

2nd lunar night @ 624 hrs for 360-hour period

Cumulative ground distance to date: 294 km

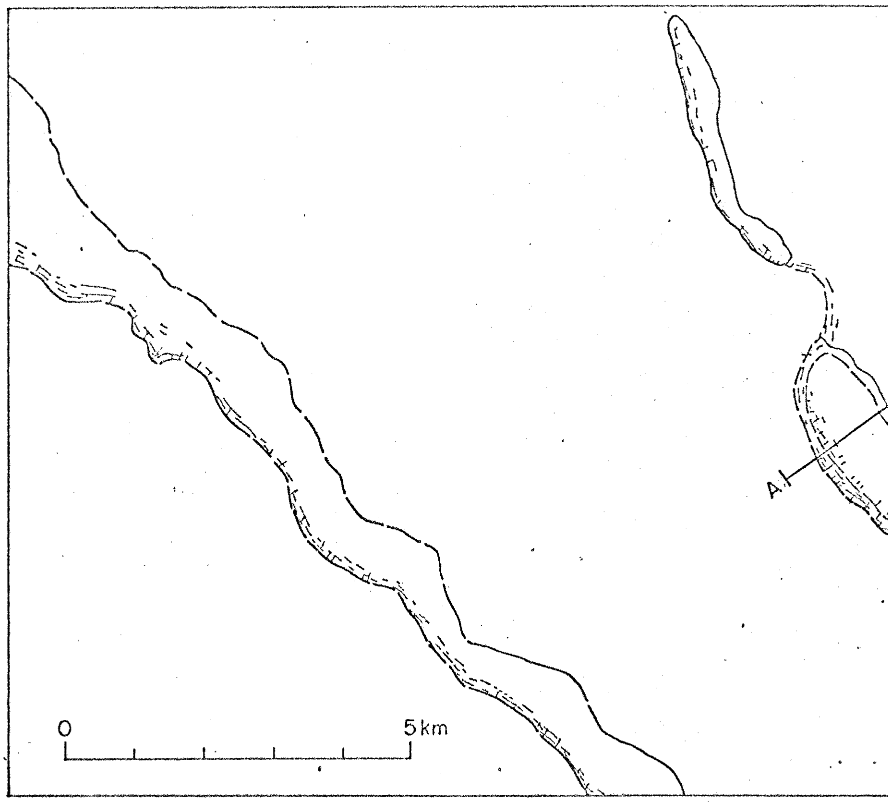
Cumulative time to date: 652 hrs

Site: V-2 Mare ridge with terrace

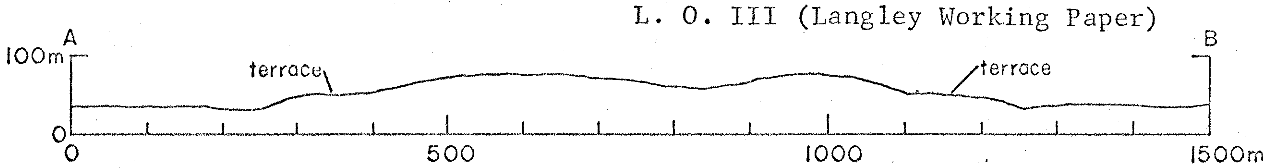
Terrain Type or equivalent: rough mare

Objectives: to analyze the possible mechanisms by which mare ridges are emplaced and the nature of post-emplacement processes

Operation	Estimated Time (hours)			
	Driving	Science	Other	Cumulative
Maneuvering along ridge-mare contact, along terrace, and across ridge. Locally steep, possibly unstable slopes are primary hazards.	20			672
Facsimile camera scanning and sample selection.		10		682
Collection of 20 samples from blocks and soil on ridge top, on terrace surface, and along ridge-mare contact		5		687
Sample preparation, analysis, and selection of 10 for return		11		698
20 gravimeter stations across ridge if terrain corrections are feasible; otherwise take readings at least 500 m away from ridge.		4		702



L. O. III (Langley Working Paper)



Site V-2 Mare ridge with terrace

Terrain type: Rough Mare

Ls	0.4 %
L_{ts}	--
N_B	2
N_C	39.1
N_{B+C}	41.1
L_B	0.4 %
L_C	16.9 %
L_{B+C}	17.5 %
L_T	17.9 %

	1m	10m	50m
Abs. Mean Slope	5.3°	3.8°	2.5°
Alg. Std. deviation	6.6	4.7	3.1
Abs. Mean Curvature	0.9	1.3	4.1
Alg. Std. deviation	1.3	1.8	5.0

	Max.	Min.
PSD@0.05 (λ=20m):	1.00	0.420
PSD@0.5 (λ=2m):	0.0035	0.0003

Segment of original 1000-km traverse: 200-300 km

Terrain type: Hummocky Upland

			1m	10m	50m
Ls	1.0 %				
L_{ts}	--	Abs. Mean Slope	8.2°	5.8°	3.9°
N_B	2	Alg. Std. deviation	10.2	7.2	4.8
N_C	39.3	Abs. Mean Curvature	0.8	2.4	1.5
N_{B+C}	41.3	Alg. Std. deviation	1.2	2.9	1.9
L_B	0.4 %				

			Max.	Min.
L_C	22.4 %	PSD@0.05 (λ=20m):	0.34	0.075
L_{B+C}	23.1 %	PSD@0.5 (λ=2m):	0.0021	0.000013
L_T	24.1 %			

Map distance, this segment: 100 km

Ground distance, this segment: 124 km.

Avg. map velocity: 1.0 kph

Ground velocity: 1.24 kph

Driving time: 100 hrs

Routine science each 0.5 km: 100 hrs

Other operations: 77 hrs

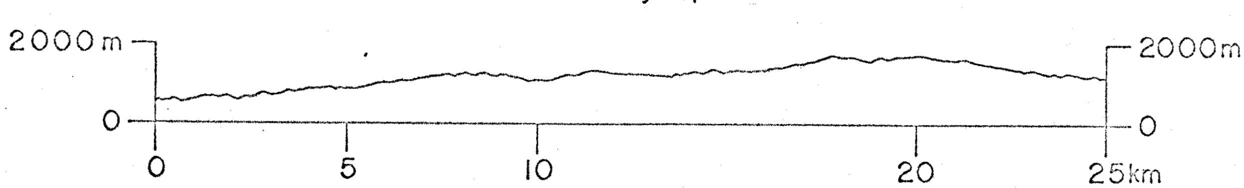
Total time, this segment: 277 hrs

3rd lunar night @ 936 hrs for 360-hour period

Cumulative ground distance to date: 433 km

Cumulative time to date: 979 hrs.

Hummocky Upland



Apollo 8 farside, photogrammetry (Wu, 1969)

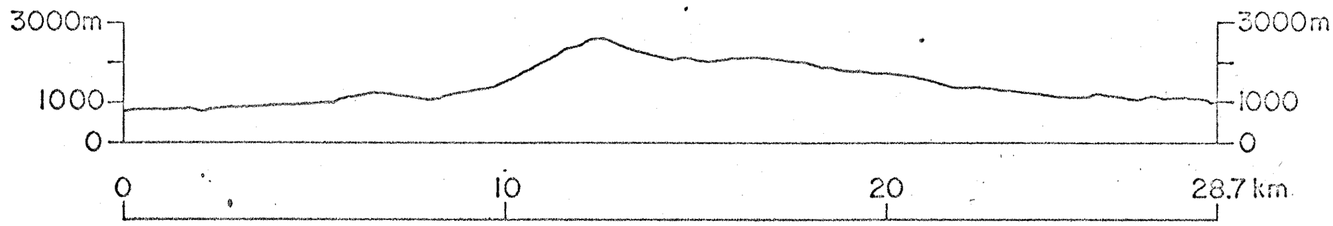
Site: T-2 Mare-uplands contact and talus slopes

Terrain Type or equivalent: smooth mare-rough upland

Objectives: Comparative study of composition and geologic processes in adjacent mare and upland areas

Operation	Estimated Time (hours)			
	Driving	Science	Other	Cumulative
Maneuvering along base of upland slopes for sampling and possible access route up onto upland. Loose talus slopes and abundant blocks are primary hazards.	20			999
Facsimile camera for scanning and detailed textural analysis of fresh blocks and boulders		8		1007
TV and Facsimile camera for landmark study and navigation			2	1009
Collection of 20 samples from mare & upland (or from blocks at foot of talus slopes)		5		1014
Sample preparation, analysis, and selection of 10 for return		11		1025
20 gravimeter stations, probably on mare		4		1029

Site I-2 Mare-uplands contact



Apollo 8 farside, photogrammetry (Wu, 1969)

Terrain type: Smooth Mare - Rough Upland

Ls	0.2 - 1.7 %
L_{ts}	0 - 5.7 %
N_B	0.2 - 2
N_C	15.5 - 38.9
N_{B+C}	17.5 - 39.1
L_B	0.04 - 0.4 %
L_C	5.0 - 15.7 %
L_{B+C}	5.5 - 15.7 %
L_T	12.9 - 15.9 %

	1m	10m	50m
Abs. Mean Slope	2.9 - 11.0°	2.0 - 7.7°	1.4 - 5.2°
Alg. Std. deviation	3.6 - 13.7	2.5 - 9.6	1.7 - 6.5
Abs. Mean Curvature	0.6 - 2.0	1.0 - 2.7	0.8 - 3.8
Alg. Std. deviation	0.8 - 3.1	1.3 - 3.4	0.9 - 3.4

	Max.	Min.
PSD@0.05 (λ=20m):	0.25 - 0.50	0.045 - 0.200
PSD@0.5 (λ=2m):	$13 - 80 \times 10^{-4}$	$1.2 - 4 \times 10^{-4}$

Segment of original 1000-km traverse: 300-350 km

Terrain type: Rough Mare

			1m	10m	50m
Ls	0.4 %				
L_{ts}	--	Abs. Mean Slope	5.3°	3.8°	2.5°
N_B	2	Alg. Std. deviation	6.6	4.7	3.1
N_C	39.1	Abs. Mean Curvature	0.9	1.3	4.1
N_{B+C}	41.1	Alg. Std. deviation	1.3	1.8	5.0

			Max.	Min.
L_B	0.4 %			
L_C	16.9 %	PSD@0.05 (λ=20m):	1.00	0.420
L_{B+C}	17.5 %	PSD@0.5 (λ=2m):	0.0035	0.0003
L_T	17.9 %			

Map distance, this segment: 50 km

Ground distance, this segment: 59 km

Avg. map velocity: 1.5 kph

Ground velocity: 1.77 kph

Driving time: 34 hrs

Routine science each 0.5 km: 50 hrs

Other operations: 32 hrs

Total time, this segment: 116 hrs

Cumulative ground distance to date: 507 km

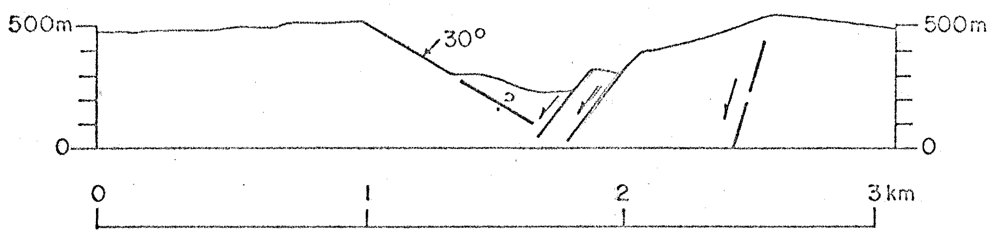
Cumulative time to date: 1145 hrs

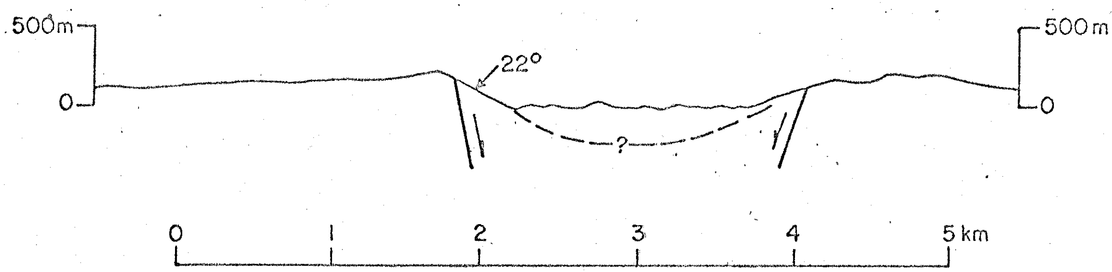
Site: T-3 Straight rille with fault scarps

Terrain Type or equivalent: rough-to-hummocky upland

Objectives: to investigate top, floor, and wall of straight rille and establish whether origin is volcanic, structural, erosional, or some combination of these

Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering along upper edges and floor of rille if accessible. Abrupt slope breaks, steep slopes, and blocks at bases of scarps are principal hazards.	20			1165
Deploy 2nd Remote Geophysical Monitor		1		1166
Facsimile camera scanning of scarps and floor from various vantage points, close ups of blocks		10		1176
Collection of 20 samples from above and below fault scarps, blocks at scarp base, and rille floor.		5		1181
Sample preparation, analysis, and selection of 10 for return.		10		1191
10 gravimeter stations on upland surface above scarp and 10 on rille floor, spaced 5-10 meters apart		4		1195





Shadow measurements (Moore)

Site T-3 Straight rille with fault scarps

Terrain type: Rough-Hummocky Upland

Ls	1.0 - 1.7%
L_{ts}	0 - 5.7 %
N_B	2
N_C	15.5 - 39.3
N_{B+C}	17.5 - 41.3
L_B	0.4%
L_C	5.0 - 22.4 %
L_{B+C}	5.5 - 23.1 %
L_T	12.9 - 24.1 %

	1m	10m	50m
Abs. Mean Slope	8.2 - 11.0°	5.8 - 7.7°	3.9 - 5.2°
Alg. Std. deviation	10.0 - 13.7	7.2 - 9.6	4.8 - 6.5
Abs. Mean Curvature	0.8 - 2.0	2.4 - 2.7	1.5 - 3.8
Alg. Std. deviation	1.2 - 3.1	2.9 - 3.1	1.9 - 3.4

	Max.	Min.
PSD@0.05 (λ=20m):	0.34 - 0.50	0.075 - 0.200
PSD@0.5 (λ=2m):	$21 - 80 \times 10^{-4}$	$0.13 - 4 \times 10^{-4}$

Segment of original 1000-km traverse: 350-400 km

Terrain type: Hummocky Upland

			1m	10m	50m
L_s	1.0 %				
L_{ts}	--	Abs. Mean Slope	8.2°	5.8°	3.9°
N_B	2	Alg. Std. deviation	10.2	7.2	4.8
N_C	39.3	Abs. Mean Curvature	0.8	2.4	1.5
N_{B+C}	41.3	Alg. Std. deviation	1.2	2.9	1.9
L_B	0.4 %				

			Max.	Min.
L_C	22.4 %	PSD@0.05 (λ=20m):	0.34	0.075
L_{B+C}	23.1 %	PSD@0.5 (λ=2m):	0.0021	0.000013
L_T	24.1 %			

Map distance, this segment: 50 km

Ground distance, this segment: 62 km

Avg. map velocity: 1.0 kph

Ground velocity: 1.24 kph

Driving time: 50 hrs

Routine science each 0.5 km: 50 hrs

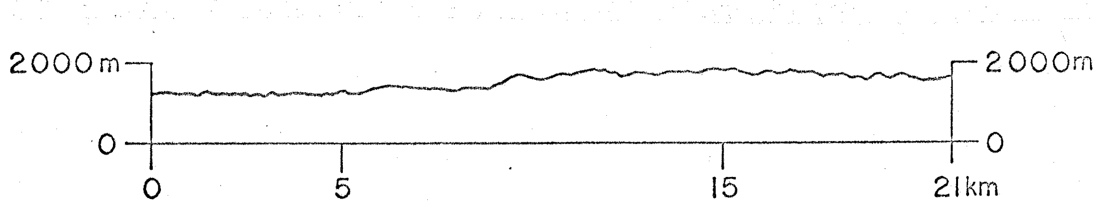
Other operations: 38 hrs

Total time, this segment: 138 hrs

4th lunar night @ 1248 for 360-hour period

Cumulative ground distance to date: 579 km

Cumulative time to date: 1333 hrs



Apollo 8 farside, photogrammetry (Wu, 1969)

Site: I-3 Large fresh crater rim

Terrain Type or equivalent: rough upland

Objectives: to examine changes in composition of surface materials and nature of geophysical gradients radial to a large fresh crater

Operation	Estimate Time (hours) Driving	Science	Other	Cumulative
Maneuvering along a path generally radial to crater for sampling and geophysical measurements. Frequent slope reversals, limited horizon, and large blocks are principal hazards.	20			1353
Facsimile camera scans from high vantage points observing transition from secondary crater fields and radial ejecta to thicker hummocky ejecta.		10		1363
Collection of 20 samples progressively across rim units including blocks of ejecta.		5		1368
Sample preparation, analysis, and selection of 10 for return		11		1379
20 gravimeter stations at 0.25 km intervals		4		1383

L_s	1.7 %
L_{ts}	5.7 %
N_B	2
N_C	15.5
N_{B+C}	17.5
L_B	0.4 %
L_C	5.0 %
L_{B+C}	5.5 %
L_T	12.9 %

	1m	10m	50m
Abs. Mean Slope	11.0°	7.7°	5.2°
Alg. Std. deviation	13.7	9.6	6.5
Abs. Mean Curvature	2.0	2.7	3.8
Alg. Std. deviation	3.1	3.4	3.4

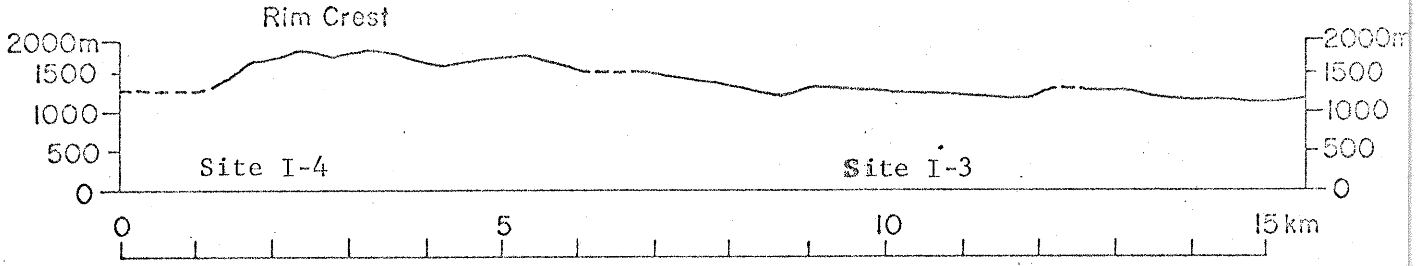
	Max.	Min.
PSD@0.05 (λ=20m):	0.50	0.200
PSD@0.5 (λ=2m):	0.0080	0.0004

Site: I-4 Normal & inverted stratigraphic succession in large crater rim and wall.

Terrain Type or equivalent: Large crater

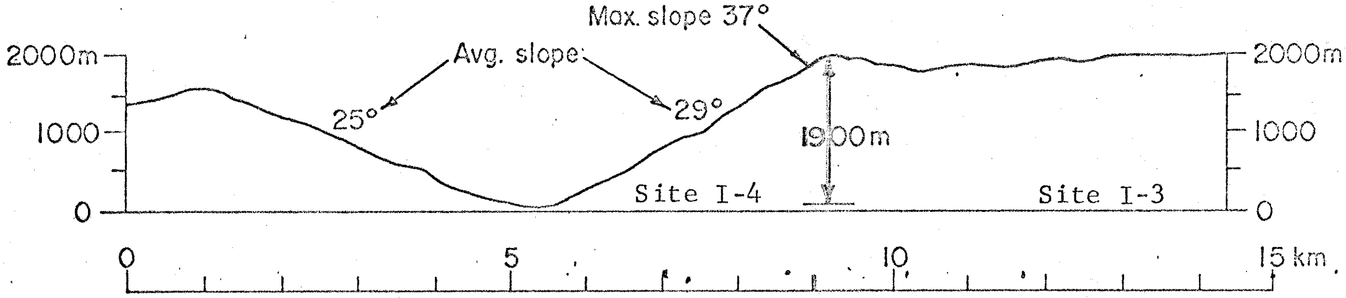
Objectives: to define the nature of any layered geologic rock units below the regolith and exposed in a large crater rim and wall

Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering to cross overturned hummocky rim ejecta, rim crest, and close by best exposures of upper crater wall. Steep slopes, abrupt slope reversals, and limited horizon are principal obstacles	20			1403
Facsimile camera for scanning steeper slopes in search of coherent bedrock. TV camera for point-to-point navigation to reach best access down crater wall. Investigate "tree bark" textures		10		1413
Collection of 20 samples from larger outcrops and blocks progressively across rim and wall.		5		1418
Sample preparation, analysis, and selection of 10 for return.		11		1429
20 gravimeter stations on hummocky rim if terrain corrections are feasible.		4		1433



Dashed where estimated at framelet crossing

L. O. V photogrammetry



Apollo 8 farside photogrammetry (S. Wu, 1969)

Sites I-3 and I-4 Large fresh crater rim and wall

Terrain type: Fresh Large Crater

Ls	3.5 %*		1m	10m	500m
L_{ts}	14.3 %*	Abs. Mean Slope	Rough upland		10°±*
N_B	31.7	Alg. Std. deviation	gives best		12°±*
			available		
N_C	29.4	Abs. Mean Curvature	estimates.		
N_{B+C}	61.1	Alg. Std. deviation			

L_B	6.3 %		Max.	Min.
L_C	6.3 %	PSD@0.05 (λ=20m):	2.2*	0.50*
L_{B+C}	13.4 %	PSD@0.5 (λ=2m):	0.018*	0.008*
L_T	31.2 %			

* Insufficient data. Best guess.

Segment of original 1000-km traverse: 400-450 km

Terrain type: Fresh Large Crater

L_s	3.5 %*
L_{ts}	14.3 %*
N_B	31.7
N_C	29.4
N_{B+C}	61.1
L_B	6.3 %
L_C	6.3 %
L_{B+C}	13.4 %
L_T	31.2 %

	1m	10m	500m
Abs. Mean Slope	Rough upland gives best available estimates.		10°±*
Alg. Std. deviation			12°±*
Abs. Mean Curvature			
Alg. Std. deviation			

	Max.	Min.
PSD@0.05 (λ=20m):	2.2*	0.50*
PSD@0.5 (λ=2m):	0.018*	0.008*

* Insufficient data. Best guess.

Map distance, this segment: 30 km

Ground distance, this segment: 39 km

Avg. map velocity: 0.3 kph

Ground velocity: 0.39 kph

Driving time: 101 hrs

Routine science each 0.5 km: 30 hrs

Other operations: 32 hrs

Total time, this segment: 163 hrs

5th lunar night @ 1560 hrs for 360-hr period

Cumulative ground distance to date: 628 km

Cumulative time to date: 1596 hrs

Site: I-5 "Ponded" plains on crater rim or wall

Terrain Type or equivalent: rough mare (= upland plains)

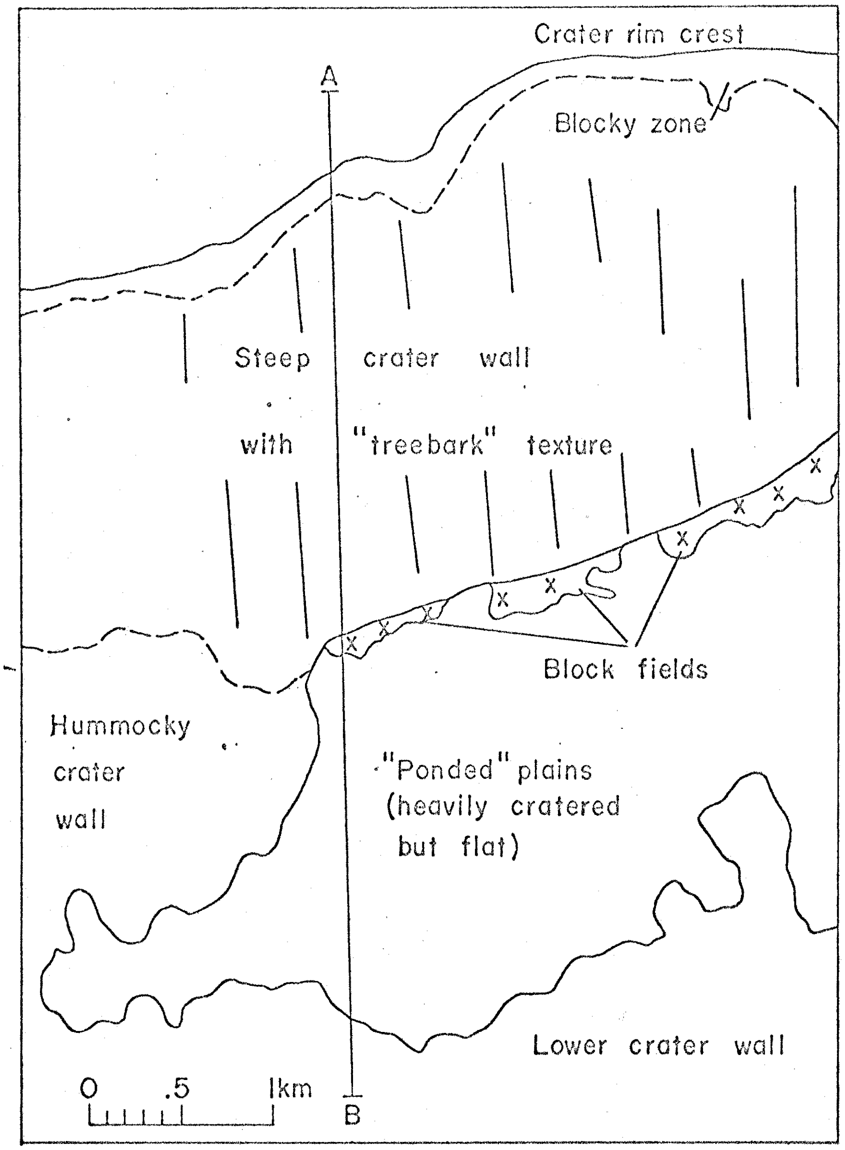
Objectives: to compare with adjacent rim or wall materials of crater and with similar mare plains units elsewhere. Test steep slopes with "tree bark" texture for stability

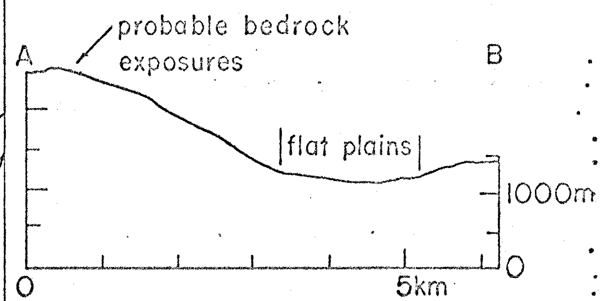
Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering across typical upland plains materials (such as Cayley or Apennine formations in local topographic lows). 10 km map distance enroute to Site I-6. Craters are primary hazards; blocks occur at foot of steep adjacent crater wall slopes	20			1616
Facsimile and TV camera scan. Examine slopes with "tree bark" texture.		10		1626
Collection of 20 samples from plains material and from blocks at base of steep adjacent slopes.		5		1631
Sample preparation, analysis, and selection of 10 for return.		11		1642
20 gravimeter stations at 100 m intervals if terrain corrections are feasible.		4		1646

L_s	0.4 %
L_{ts}	--
N_B	2
N_C	39.1
N_{B+C}	41.1
L_B	0.4 %
L_C	16.9 %
L_{B+C}	17.5 %
L_T	17.9 %

	1m	10m	50m
Abs. Mean Slope	5.3°	3.8°	2.5°
Alg. Std. deviation	6.6	4.7	3.1
Abs. Mean Curvature	0.9	1.3	4.1
Alg. Std. deviation	1.3	1.8	5.0

	Max.	Min.
PSD@0.05 (λ=20m):	1.00	0.420
PSD@0.5 (λ=2m):	0.0035	0.0003





L. O. V, photogrammetry

Site I-5 "Ponded" plains on crater wall terrain

Terrain: rough mare

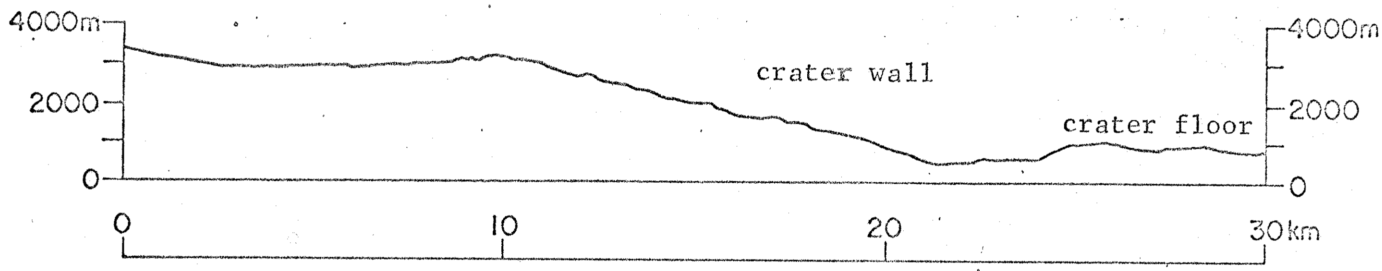
Site: I-6 Floor-wall contact near concentric rilles

Terrain Type or equivalent: large crater

Objectives: to examine relation of crater floor to wall and of concentric rille to each of these; whether processes are primarily structural or volcanic

Operation	Estimated Time (hours)			
	Driving	Science	Other	Cumulative
Maneuvering down side slope of lower crater wall for observation and sampling. 10 km map distance onto crater floor. Steep unstable slopes and blocks at base of slopes are principal hazards.	20			1666
Facsimile camera and TV scanning of fresh crater wall from above and below and of rille walls and floor.		10		1676
Collection of 20 samples from crater wall, floor, rille margins and floor, and blocks at base of slopes		5		1681
Preparation, analysis, and selection of 10 samples for return.		11		1692
20 gravity stations, several km away from crater wall; 10 at 100 m intervals across crater floor and 10 in floor of rille		4		1696

Site I-6 Floor-wall contact



Apollo 8 farside, photogrammetry (Wu, 1969)

Terrain type: Fresh Large Crater

Ls	3.5 %*		1m	10m	500m
L_{ts}	14.3 %*	Abs. Mean Slope	Rough upland		10°+*
N_B	31.7	Alg. Std. deviation	gives best		12°+*
N_C	29.4	Abs. Mean Curvature	available estimates.		
N_{B+C}	61.1	Alg. Std. deviation			
L_B	6.3 %				
L_C	6.3 %				
L_{B+C}	13.4 %				
L_T	31.2 %				

	Max.	Min.
PSD@0.05 (λ=20m):	2.2*	0.50*
PSD@0.5 (λ=2m):	0.018*	0.008*

* Insufficient data. Best guess.

Segment of original 1000-km traverse: 450-500

Terrain type: Fresh Large Crater

L_s	3.5 %*		1m	10m	500m
L_{ts}	14.3 %*	Abs. Mean Slope	Rough upland		10°±*
N_B	31.7	Alg. Std. deviation	gives best		12°±*
N_C	29.4	Abs. Mean Curvature	available estimates.		
N_{B+C}	61.1	Alg. Std. deviation			
L_B	6.3 %			Max.	Min.
L_C	6.3 %	PSD@0.05 (λ=20m):		2.2*	0.50*
L_{B+C}	13.4 %	PSD@0.5 (λ=2m):		0.018*	0.008*
L_T	31.2 %				

* Insufficient data. Best guess.

Map distance, this segment:	45	km
Ground distance, this segment:	59	km
Avg. map velocity:	0.3	kph
Ground velocity:	0.39	kph
Driving time:	151	hrs
Routine science each 0.5 km:	45	hrs
Other operations:	48	hrs
Total time, this segment:	244	hrs

6th lunar night @ 1872 hrs for 360-hr period.

Cumulative ground distance to date: 712 km

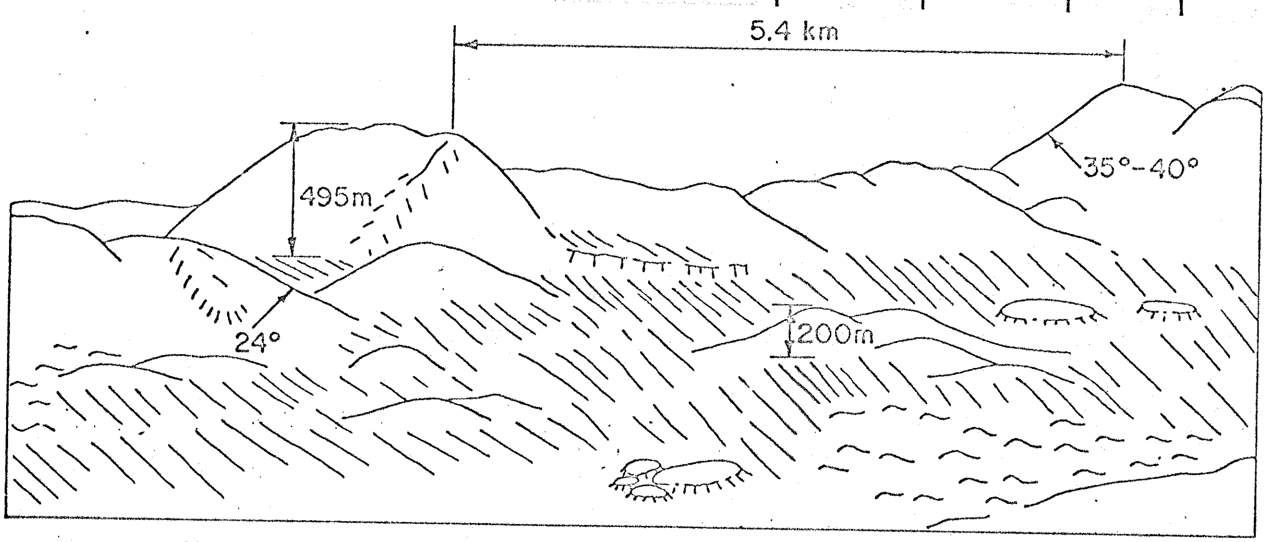
Cumulative time to date: 1940 hrs

Site: I-7 Central peak in large crater floor

Terrain Type or equivalent: Large crater

Objectives: to determine origin of central peaks; whether volcanic, rebounded structures from depth, or other. Possible samples of deep-seated rocks

Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering around base of rugged hills on crater floor to observe and sample variety of materials present in blocks and soils, and if possible, traversing lower hills. Hazards are blocks, abrupt steep slopes and many reversals, limited horizon, and possibly unstable slopes.	20			1960
Facsimile camera and TV scanning and close study of fresh blocks and boulders.		14		1974
Collection, preparation, and analysis of 20 samples; selection of 10 for return.		16		1990
(Gravity experiment deleted due to large uncertainty in terrain corrections)				



Site I-7 Central peaks with block fields and boulder tracks
Terrain: fresh crater
L. O. II, oblique profile; L. O. V, shadow measurements

Segment of original 1000-km traverse: 500-550 km

Terrain type: Hummocky Upland

				1m	10m	50m
L_s	1.0 %					
L_{ts}	--	Abs. Mean Slope		8.2°	5.8°	3.9°
N_B	2	Alg. Std. deviation		10.2	7.2	4.8
N_C	39.3	Abs. Mean Curvature		0.8	2.4	1.5
N_{B+C}	41.3	Alg. Std. deviation		1.2	2.9	1.9
L_B	0.4 %					
				Max.	Min.	
L_C	22.4 %	PSD@0.05 (λ=20m):		0.34	0.075	
L_{B+C}	23.1 %	PSD@0.5 (λ=2m):		0.0021	0.000013	
L_T	24.1 %					

Map distance, this segment:	40	km
Ground distance, this segment:	50	km
Avg. map velocity:	1.0	kph
Ground velocity:	1.24	kph
Driving time:	40	hrs
Routine science each 0.5 km:	40	hrs
Other operations:	31	hrs
Total time, this segment:	111	hrs

Cumulative ground distance to date: 769 km

Cumulative time to date: 2101 hrs

Site: T-4 Debris flow

Terrain Type or equivalent: Large crater

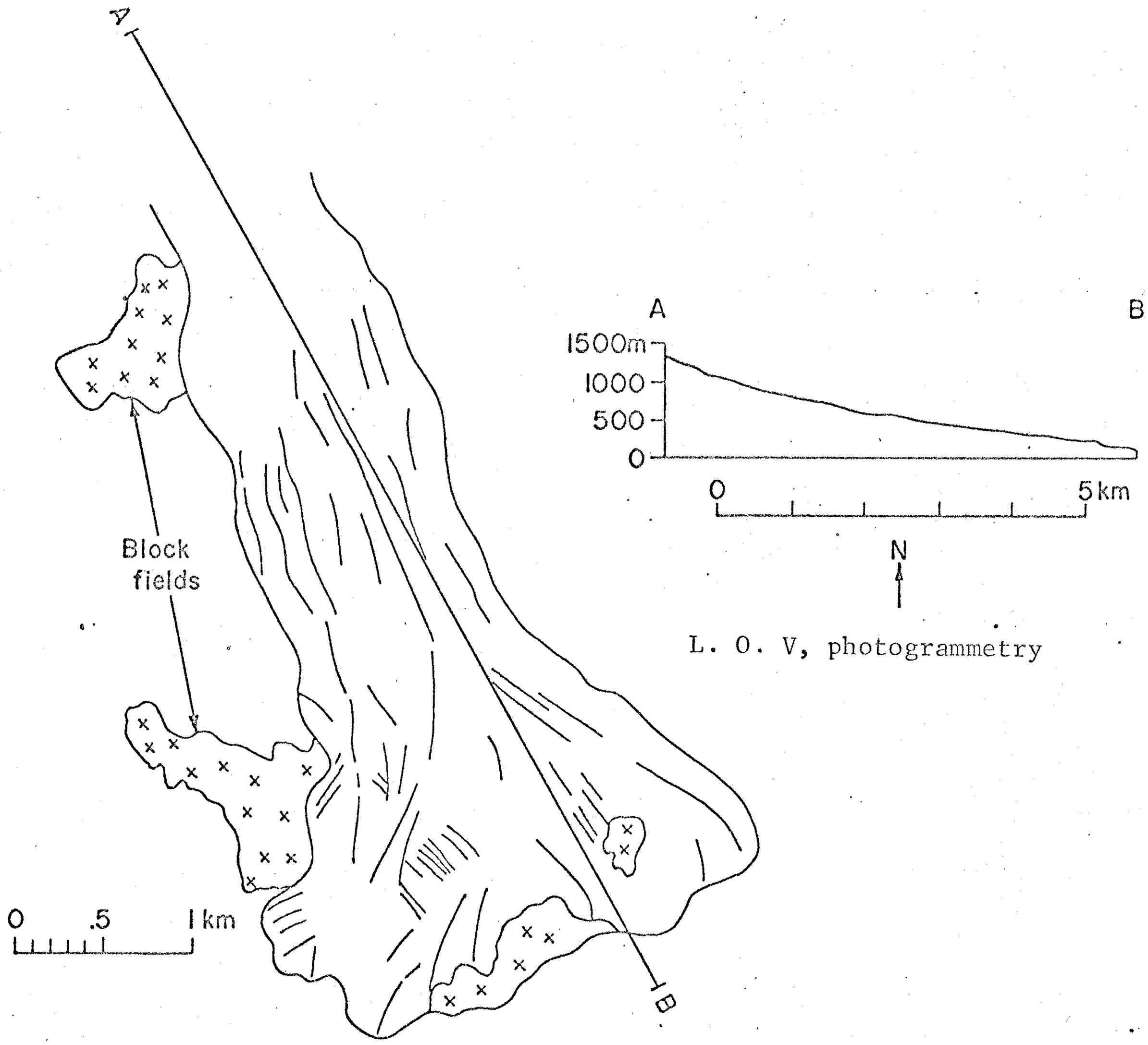
Objectives: to investigate mechanisms of flow from close-up examination of surface materials and fine structures that characterize them; to exit from large crater

Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering up and/or across slopes of debris flow which is least steep part of crater wall (or uplands front). Sample collection and observation are most important. Hazards are blocks, small scale roughness, and possibly unstable slopes	20			2121
Facsimile camera and TV scanning for optimum traverse route and for samples, and small scale surface textures.		14		2135
Collection, preparation, and analysis of 20 samples; selection of 10 for return		16		2151
(Gravity experiment deleted due to large uncertainty in terrain corrections)				

			1m	10m	500m
Ls	3.5 %*				
L_{ts}	14.3 %*	Abs. Mean Slope	Rough upland		10°±*
N_B	31.7	Alg. Std. deviation	gives best		12°±*
N_C	29.4	Abs. Mean Curvature	available estimates.		
N_{B+C}	61.1	Alg. Std. deviation			
L_B	6.3 %				
L_C	6.3 %				
L_{B+C}	13.4 %				
L_T	31.2 %				

	Max.	Min.
PSD@0.05 (λ=20m):	2.2*	0.50*
PSD@0.5 (λ=2m):	0.018*	0.008*

* Insufficient data. Best guess.



L. O. V, photogrammetry

Site T-4 Debris flow

Terrain: large crater

Segment of original 1000-km traverse: 550-600 km

Terrain type: Fresh Large Crater

Ls	3.5 %*		1m	10m	500m
L_{ts}	14.3 %*	Abs. Mean Slope	Rough upland		10°±*
N_B	31.7	Alg. Std. deviation	gives best		12°±*
N_C	29.4	Abs. Mean Curvature	available estimates.		
N_{B+C}	61.1	Alg. Std. deviation			
L_B	6.3 %		Max.		Min.
L_C	6.3 %	PSD@0.05 (λ=20m):	2.2*		0.50*
L_{B+C}	13.4 %	PSD@0.5 (λ=2m):	0.018*		0.008*
L_T	31.2 %	* Insufficient data. Best guess.			

Map distance, this segment: 50 km

Ground distance, this segment: 66 km

Avg. map velocity: 0.3 kph

Ground velocity: 0.39 kph

Driving time: 168 hrs

Routine science each 0.5 km: 50 hrs

Other operations: 54 hrs

Total time, this segment: 272 hrs

7th lunar night @ 2184 hrs for 360-hr period

Cumulative ground distance to date: 848 km

Cumulative time to date: 2423 hrs

Site: V-3 Caldera or pit crater

Terrain Type or equivalent: Rough mare-rough upland

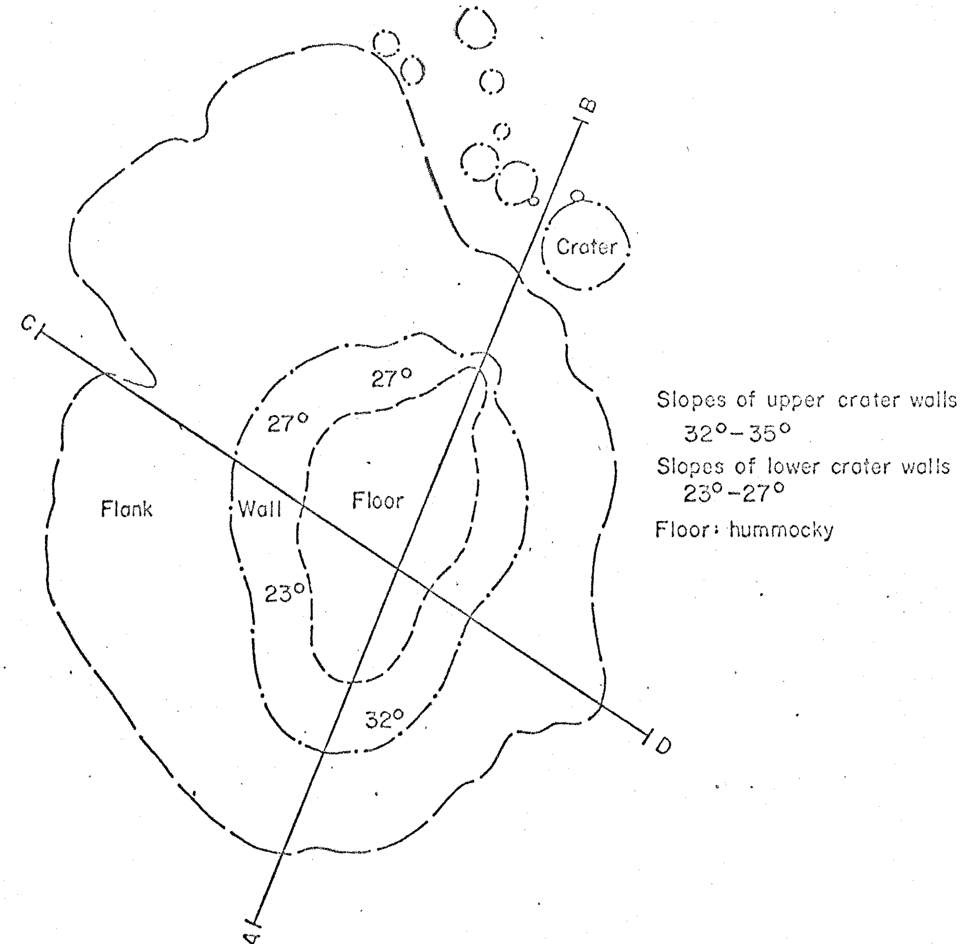
Objectives: to determine degree of explosion, collapse, and mass wasting as processes in formation and modification of low-rimmed volcanic craters

Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering around rim to observe and sample ejecta if present and to find access to crater floor. Principal hazards are abrupt steep slope segments and large blocks.	20			2443
Facsimile camera and TV scanning for blocks, bombs, and outcrops and for access to crater floor		10		2453
Collection, preparation, and analysis of 20 samples; selection of 10 for return		16		2469
20 gravity recordings spaced at 100-200 m on crater rim, away from crest. Floor will likely be inaccessible for terrain corrections of gravity stations.		4		2473

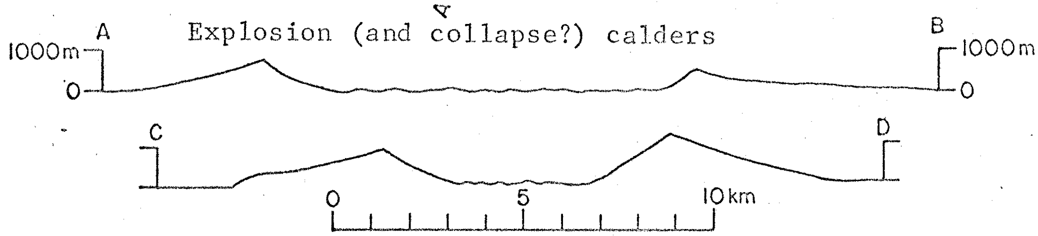
L_s	0.4 - 1.7 %
L_{ts}	0 - 5.7 %
N_B	2
N_C	15.5 - 39.1
N_{B+C}	17.5 - 41.1
L_B	0.4 %
L_C	5.0 - 16.9 %
L_{B+C}	5.5 - 17.5 %
L_T	12.9 - 17.9 %

	1m	10m	50m
Abs. Mean Slope	5.3 - 11.0°	3.8 - 7.7°	2.5 - 5.2°
Alg. Std. deviation	6.6 - 13.7	4.7 - 9.6	3.1 - 6.5
Abs. Mean Curvature	0.9 - 2.0	1.3 - 2.7	3.8 - 4.1
Alg. Std. deviation	1.3 - 3.1	1.8 - 3.4	3.4 - 5.0

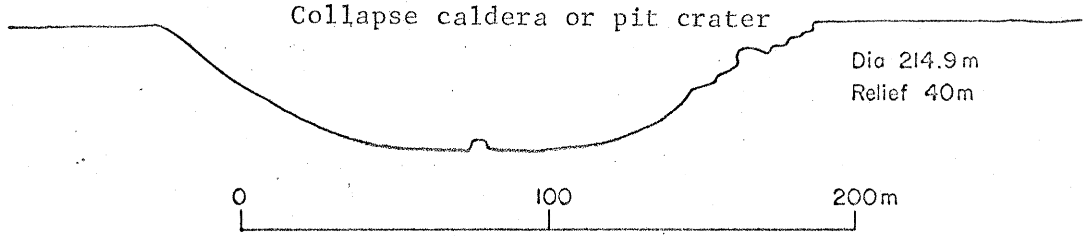
	Max.	Min.
PSD@0.05 (λ=20m):	0.50 - 1.00	0.200 - 0.420
PSD@0.5 (λ=2m):	35 - 80 x 10^{-4}	3 - 4 x 10^{-4}



Explosion (and collapse?) calders



Collapse caldera or pit crater



Shadow measurements (Moore)

Site V-3 Caldera and pit crater

Terrain: Rough mare-rough upland

Segment of original 1000-km traverse: 600-700 km

Terrain type: Rough Upland

Ls	1.7 %
L_{ts}	5.7 %
N_B	2
N_C	15.5
N_{B+C}	17.5
L_B	0.4 %
L_C	5.0 %
L_{B+C}	5.5 %
L_T	12.9 %

	1m	10m	50m
Abs. Mean Slope	11.0°	7.7°	5.2°
Alg. Std. deviation	13.7	9.6	6.5
Abs. Mean Curvature	2.0	2.7	3.8
Alg. Std. deviation	3.1	3.4	3.4

	Max.	Min.
PSD@0.05 (λ=20m):	0.50	0.200
PSD@0.5 (λ=2m):	0.0080	0.0004

Map distance, this segment: 100 km

Ground distance, this segment: 113 km

Avg. map velocity: 0.5 kph

Ground velocity: 0.56 kph

Driving time: 201 hrs

Routine science each 0.5 km: 100 hrs

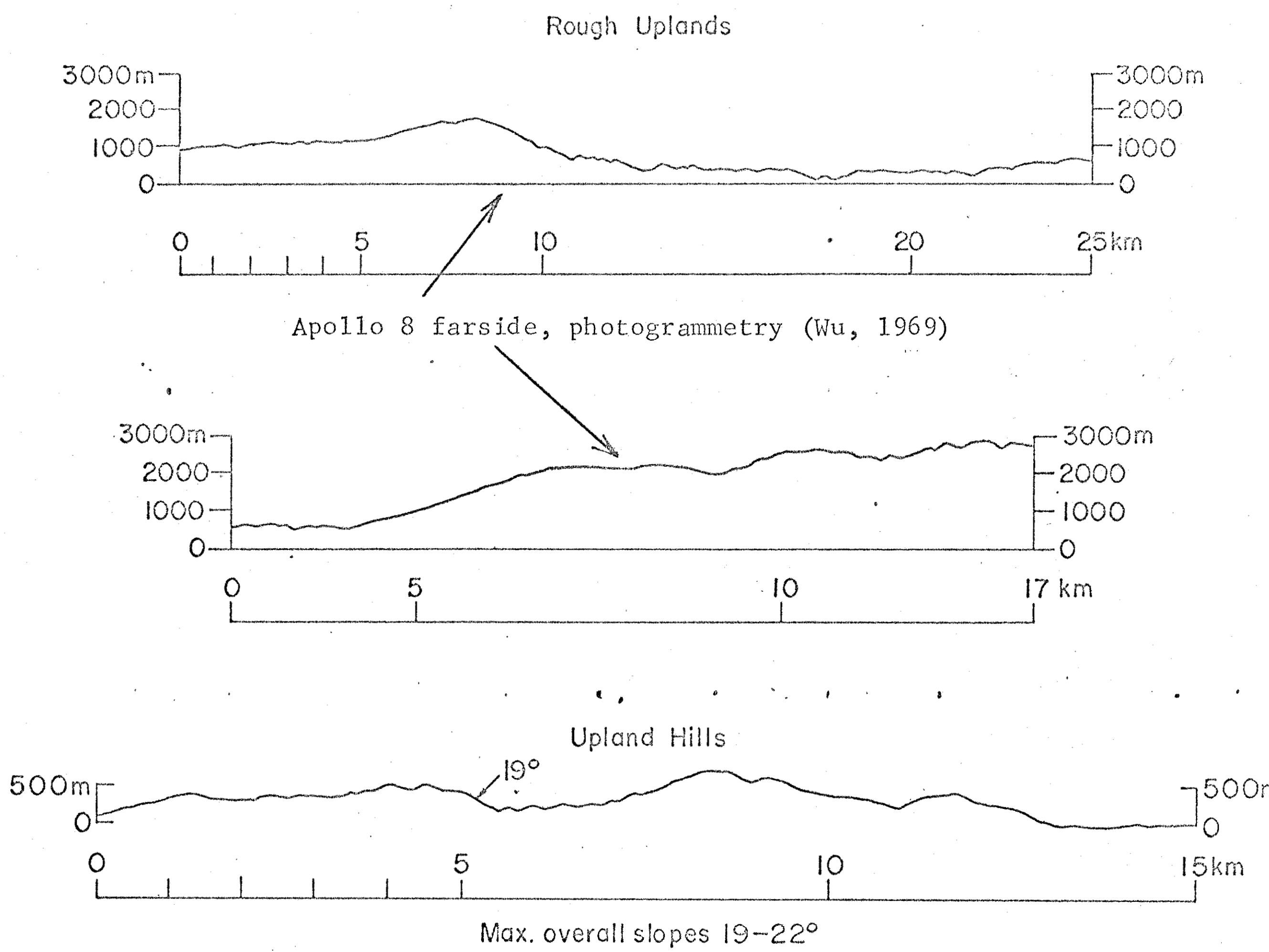
Other operations: 51 hrs

Total time, this segment: 352 hrs

8th and 9th lunar nights @ 2496 and 2808 hrs for 360-hr periods

Cumulative ground distance to date: 971 km

Cumulative time to date: 2825 hrs



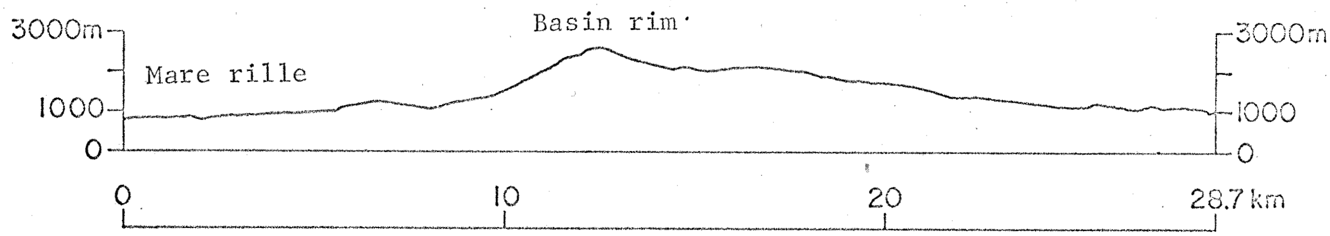
Shadow measurements (Moore)

Site: T-5 Mare rilles concentric with basin rim

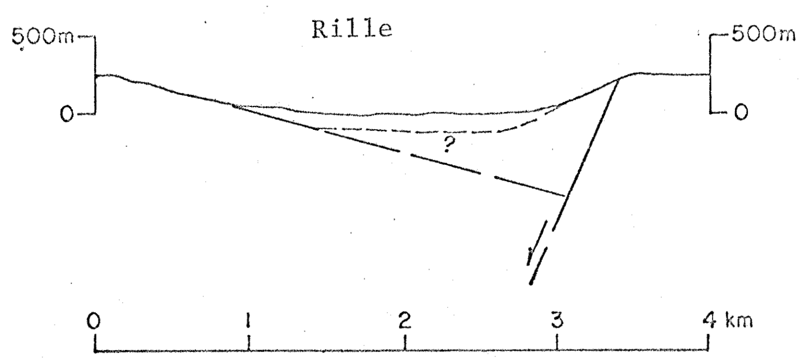
Terrain Type or equivalent: Rough mare--rough upland

Objectives: to examine structure of concentric rilles and establish relationship to nearby highland rim. Compare with earlier rille sites I-6 and T-3

Operation	Estimated Time (hours)			
	Driving	Science	Other	Cumulative
Maneuvering between basin rim and rilles and down into rilles to examine walls visually and floor geophysically. Principal hazards are craters on mare and steep slopes and blocks at mare contacts with rilles and upland.	20			2845
Deploy 3rd Remote Geophysical Monitor on uniform mare surface.		1		2846
Facsimile and TV scanning of steep slopes for stratigraphic correlation and close ups for sample collection		10		2856
Collection, preparation, and analysis of 20 samples; select 10		15		2871
20 gravimeter stations at 5-10 m intervals: 10 on rille floor and 10 on mare surface		4		2875



Apollo 8 farside, photogrammetry (Wu, 1969)



Shadow measurements (Moore)

Site T-5 Mare rille concentric with basin rim.

Segment of original 1000-km traverse: 700-750 km

Terrain type: Rough Mare

			1m	10m	50m
Ls	0.4 %				
L_{ts}	--	Abs. Mean Slope	5.3°	3.8°	2.5°
N_B	2	Alg. Std. deviation	6.6	4.7	3.1
N_C	39.1	Abs. Mean Curvature	0.9	1.3	4.1
N_{B+C}	41.1	Alg. Std. deviation	1.3	1.8	5.0

			Max.	Min.
L_B	0.4 %			
L_C	16.9 %	PSD@0.05 (λ=20m):	1.00	0.420
L_{B+C}	17.5 %	PSD@0.5 (λ=2m):	0.0035	0.0003
L_T	17.9 %			

Map distance, this segment: 50 km

Ground distance, this segment: 59 km

Avg. map velocity: 1.5 kph

Ground velocity: 1.77 kph

Driving time: 34 hrs

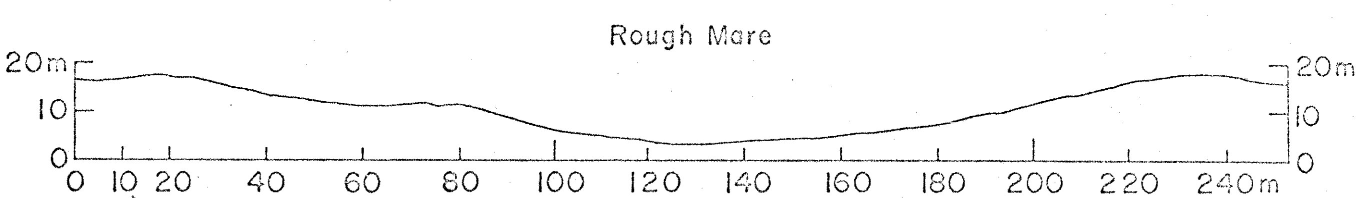
Routine science each 0.5 km: 50 hrs

Other operations: 32 hrs

Total time, this segment: 116 hrs

Cumulative ground distance to date: 1045 km

Cumulative time to date: 2991 hrs



Site: V-4 Low lava dome

Terrain Type or equivalent: Rough mare

Objectives: to investigate volcanic materials and processes of flat-top dome as related to differentiation of magmas and in comparison with other volcanic features

Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering from mare terrain around and, if possible, onto top of lava dome for sampling and geophysical investigation. Craters and locally steep slopes on dome sides are main hazards.	20			3011
Facsimile camera and TV viewing of mare-dome contact and of dome's upper surface; particularly looking for outcrops, blocks		10		3021
Collection, preparation, and analysis of 20 samples; selection of 10 for return		16		3037
10 gravity stations on mare 1.5 km from base of dome and 10 on top of dome spaced at 100-200 meters.		4		3041

Segment of original 1000-km traverse: 750-800 km

Terrain type: Rough Mare

			1m	10m	50m
Ls	0.4 %				
L_{ts}	--	Abs. Mean Slope	5.3°	3.8°	2.5°
N_B	2	Alg. Std. deviation	6.6	4.7	3.1
N_C	39.1	Abs. Mean Curvature	0.9	1.3	4.1
N_{B+C}	41.1	Alg. Std. deviation	1.3	1.8	5.0
L_B	0.4 %		Max.		Min.
L_C	16.9 %	PSD@0.05 (λ=20m):	1.00		0.420
L_{B+C}	17.5 %	PSD@0.5 (λ=2m):	0.0035		0.0003
L_T	17.9 %				

Map distance, this segment: 50 km

Ground distance, this segment: 59 km

Avg. map velocity: 1.5 kph

Ground velocity: 1.77 kph

Driving time: 34 hrs

Routine science each 0.5 km: 50 hrs

Other operations: 32 hrs

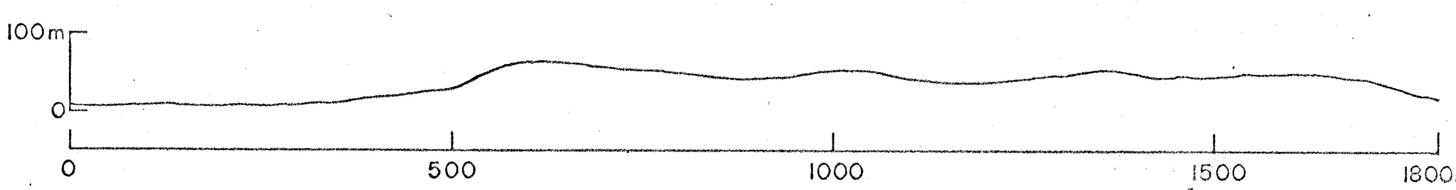
Total time, this segment: 116 hrs

10th lunar night @ 3120 hrs for 360-hr period

Cumulative ground distance to date: 1119 km

Cumulative time to date: 3157 hrs

Site V-4 Low lava dome



L. O. III (Langley Working Paper)

Site: V-5 Crater-top dome (or steep-sided dome)

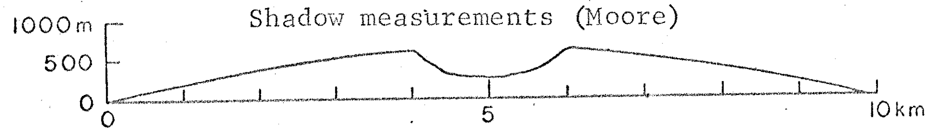
Terrain Type or equivalent: Hummocky-to-rough upland

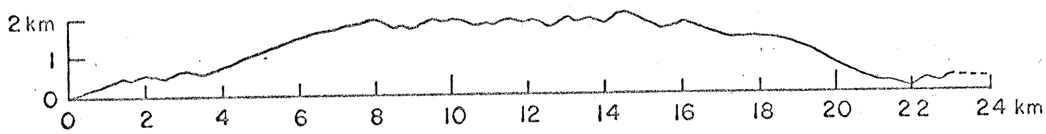
Objectives: to investigate evidence for volcanism and magmatic differentiation in dome-forming processes

Operation	Estimated Time (hours)			
	Driving	Science	Other	Cumulative
Maneuvering from mare around and, if possible, onto moderate-to-steep-walled dome. Locally steep slopes, craters, and blocks are primary hazards	20			3177
Facsimile camera and TV scanning of close up surface to determine changes in rock type, surface characteristics, or increasing hazards.		10		3187
Collection, preparation, and analysis of 20 samples; selection of 10 for return.		16		3203
Gravity stations on top of dome at 0.5 km intervals, if terrain corrections are feasible		4		3207

Site V-5 Crater-top dome (or steep-sided dome)

Shadow measurements (Moore)





L. O. V photogrammetry

Terrain type: Hummocky-Rough Upland

			1m	10m	50m
Ls	1.0 - 1.7 %				
L_{ts}	0 - 5.7 %	Abs. Mean Slope	8.2 - 11.0°	5.8 - 7.7°	3.9 - 5.2°
N_B	2	Alg. Std. deviation	10.0 - 13.7	7.2 - 9.6	4.8 - 6.5
N_C	15.5 - 39.3	Abs. Mean Curvature	0.8 - 2.0	2.4 - 2.7	1.5 - 3.8
N_{B+C}	17.5 - 41.3	Alg. Std. deviation	1.2 - 3.1	2.9 - 3.1	1.9 - 3.4

			Max.	Min.
L_B	0.4 %			
L_C	5.0 - 22.4 %	PSD@0.05 (λ=20m):	0.34 - 0.50	0.075 - 0.200
L_{B+C}	5.5 - 23.1 %	PSD@0.5 (λ=2m):	$21 - 80 \times 10^{-4}$	$0.13 - 4 \times 10^{-4}$
L_T	12.9 - 24.1 %			

Segment of original 1000-km traverse: 800-850

Terrain type: Smooth Mare

			1m	10m	50m
Ls	0.2 %				
L_{ts}	--	Abs. Mean Slope	2.9°	2.0°	1.4°
N_B	0.2	Alg. Std. deviation	3.6	2.5	1.7
N_C	38.9	Abs. Mean Curvature	0.6	1.0	0.8
N_{B+C}	39.1	Alg. Std. deviation	0.8	1.3	0.9

			Max.	Min.
L_B	0.04%			
L_C	15.7 %	PSD@0.05 (λ=20m):	0.25	0.045
L_{B+C}	15.7 %	PSD@0.5 (λ=2m):	0.0013	0.00012
L_T	15.9 %			

Map distance, this segment:	50	km
Ground distance, this segment:	58	km
Avg. map velocity:	1.7	kph
Ground velocity:	1.97	kph
Driving time:	30	hrs
Routine science each 0.5 km:	50	hrs
Other operations:	30	hrs
Total time, this segment:	110	hrs

Cumulative ground distance to date: 1187 km

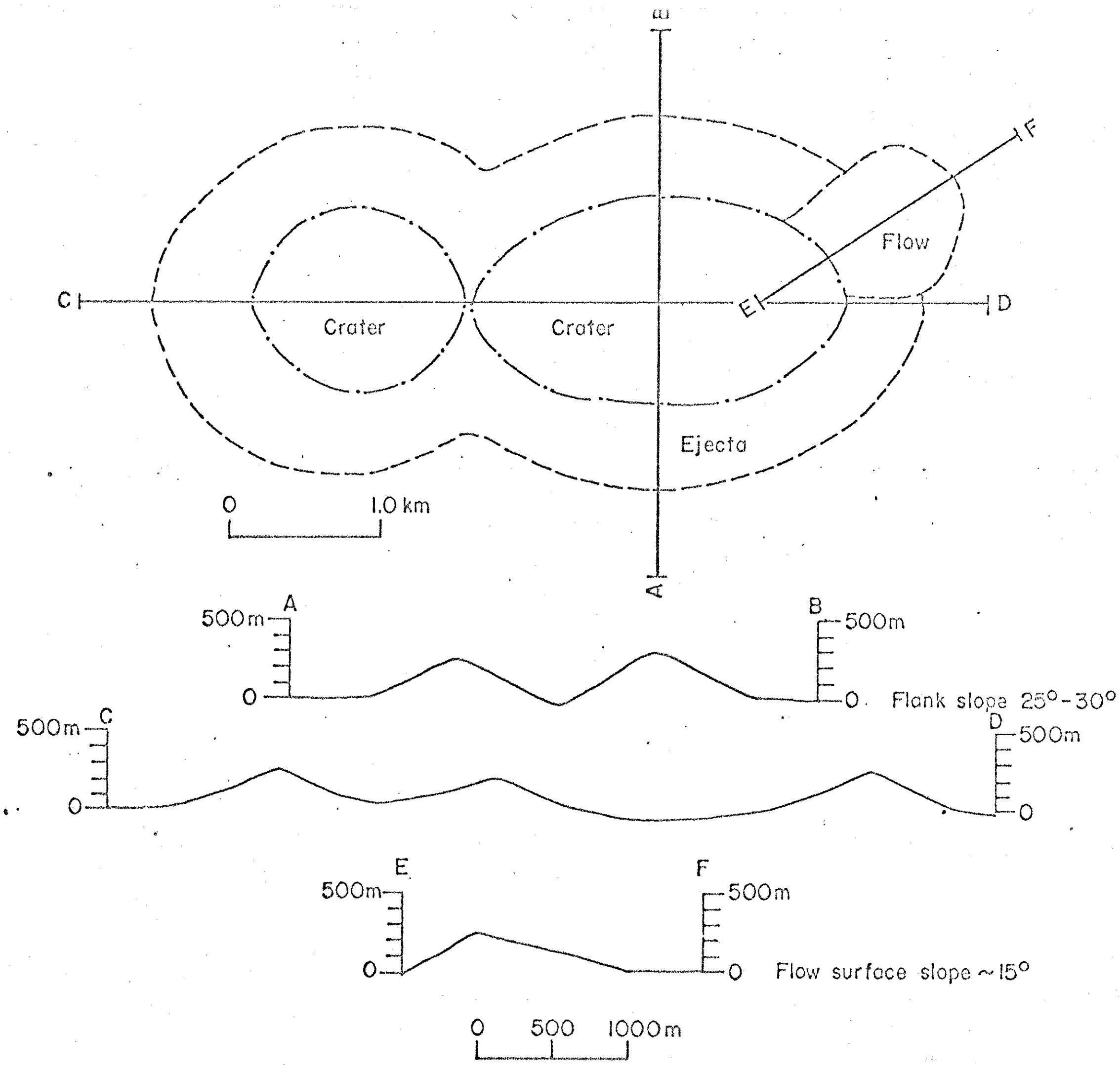
Cumulative time to date: 3317 hrs

Site: V-6 Maar or chain crater

Terrain Type or equivalent: Rough upland

Objectives: to investigate a complex class of crater thought to be volcanic in origin and primarily explosive in mechanism. Possible samples of deep-seated rocks

Operation	Estimated Time (hours)			
	Driving	Science	Other	Cumulative
Traversing around flank of low-to-moderate rim crater to examine variety of material in ejecta and to look for access into interior. Steep slopes are main hazard.	20			3337
Facsimile camera and TV observation of inner and outer crater slopes and closeups of rim material for exotic inclusions of deep-seated material.		10		3347
Collection, preparation, and analysis of 20 samples; selection of 10 for return.		16		3363
20 gravity stations across crater and onto smooth mare at 0.5 km intervals, if terrain corrections are feasible. Otherwise, conduct experiment at 50 m spacing on mare, at least 1 km from crater.		4		3367



Shadow measurements (Moore)

Site V-6 Maar or chain crater

Terrain type: Rough Upland

Ls	1.7 %
L_{ts}	5.7 %
N_B	2
N_C	15.5
N_{B+C}	17.5
L_B	0.4 %
L_C	5.0 %
L_{B+C}	5.5 %
L_T	12.9 %

	1m	10m	50m
Abs. Mean Slope	11.0°	7.7°	5.2°
Alg. Std. deviation	13.7	9.6	6.5
Abs. Mean Curvature	2.0	2.7	3.8
Alg. Std. deviation	3.1	3.4	3.4

	Max.	Min.
PSD@0.05 (λ=20m):	0.50	0.200
PSD@0.5 (λ=2m):	0.0080	0.0004

Segment of original 1000-km traverse: 850-900

Terrain type: Smooth Mare

			1m	10m	50m
Ls	0.2 %				
L_{ts}	--	Abs. Mean Slope	2.9°	2.0°	1.4°
N_B	0.2	Alg. Std. deviation	3.6	2.5	1.7
N_C	38.9	Abs. Mean Curvature	0.6	1.0	0.8
N_{B+C}	39.1	Alg. Std. deviation	0.8	1.3	0.9
L_B	0.04%				
			Max.	Min.	
L_C	15.7 %	PSD@0.05 (λ=20m):	0.25	0.045	
L_{B+C}	15.7 %	PSD@0.5 (λ=2m):	0.0013	0.00012	
L_T	15.9 %				

Map distance, this segment: 50 km

Ground distance, this segment: 58 km

Avg. map velocity: 1.7 kph

Ground velocity: 1.97 kph

Driving time: 30 hrs

Routine science each 0.5 km: 50 hrs

Other operations: 30 hrs

Total time, this segment: 110 hrs

11th lunar night @ 3432 for 360-hr period

Cumulative ground distance to date: 1250 km

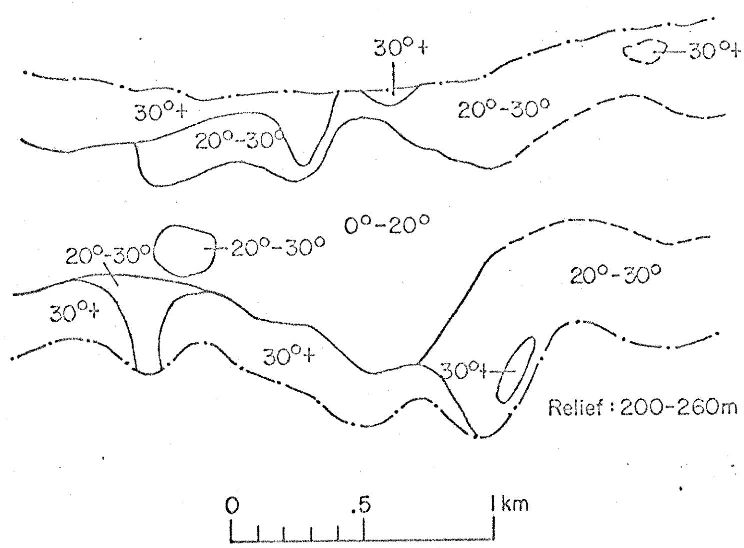
Cumulative time to date: 3477 hrs

Site: T-6 Sinuous rille

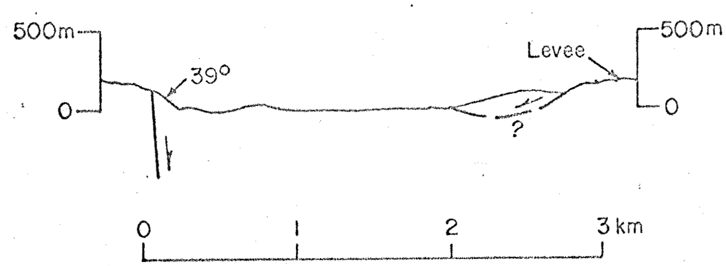
Terrain Type or equivalent: Rough mare

Objectives: to determine origin of meandering patterns and nature of floor wall, and rim (levee), if present; whether volcanic constructional, erosional, or structural. Compare with other rille sites I-6, T-3, and T-5

Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering along mare rille contact to search for levees, down into rille where access is possible, and along floor. Primary hazards are craters, steep slopes of rille walls, and blocks at base of slopes	20			3497
Facsimile and TV camera scanning and close ups at sample localities		10		3507
Collection of 20 samples from mare, rille walls, levees, and floor		5		3512
Preparation, analysis, and selection of 10 samples		11		3523
20 gravimeter stations at 5-10 m intervals: 10 on mare and 10 on rille floor		4		3527



Slope map and shadow measurements (Moore)



Site T-6 Sinuous rille with levees

Terrain type: Rough Mare

			1m	10m	50m
Ls	0.4 %				
L_{ts}	--	Abs. Mean Slope	5.3°	3.8°	2.5°
N_B	2	Alg. Std. deviation	6.6	4.7	3.1
N_C	39.1	Abs. Mean Curvature	0.9	1.3	4.1
N_{B+C}	41.1	Alg. Std. deviation	1.3	1.8	5.0

			Max.	Min.
L_B	0.4 %			
L_C	16.9 %	PSD@0.05 (λ=20m):	1.00	0.420
L_{B+C}	17.5 %	PSD@0.5 (λ=2m):	0.0035	0.0003
L_T	17.9 %			

Segment of original 1000-km traverse: 900-950 km

Terrain type: Rough Upland

			1m	10m	50m
Ls	1.7 %				
L_{ts}	5.7 %	Abs. Mean Slope	11.0°	7.7°	5.2°
N_B	2	Alg. Std. deviation	13.7	9.6	6.5
N_C	15.5	Abs. Mean Curvature	2.0	2.7	3.8
N_{B+C}	17.5	Alg. Std. deviation	3.1	3.4	3.4
L_B	0.4 %				

			Max.	Min.
L_C	5.0 %	PSD@0.05 (λ=20m):	0.50	0.200
L_{B+C}	5.5 %	PSD@0.5 (λ=2m):	0.0080	0.0004
L_T	12.9 %			

Map distance, this segment:	50	km
Ground distance, this segment:	57	km
Avg. map velocity:	0.5	kph
Ground velocity:	0.56	kph
Driving time:	100	hrs
Routine science each 0.5 km:	50	hrs
Other operations:	26	hrs
Total time, this segment:	176	hrs

Cumulative ground distance to date: 1317 km

Cumulative time to date: 3703 hrs

Site: V-7 Dark halo craters and associated rille

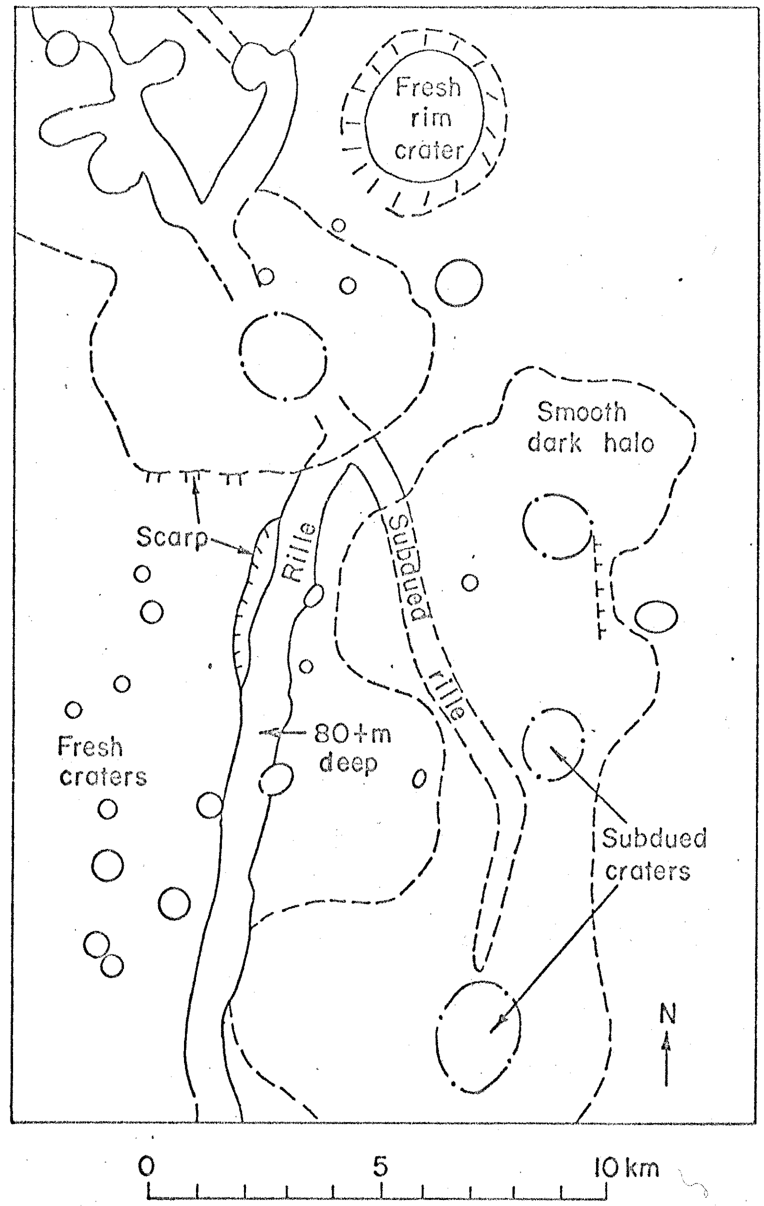
Terrain Type or equivalent: Rough mare-hummocky upland

Objectives: to examine the nature of dark low-rim crater and rille material apparently of volcanic origin, blanketing surrounding area

Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering over smooth gentle slopes to sample material around craters and in adjoining rilles; traversing from crater across partly filled rille to fresh, sharp rille. Dark smooth surfaces may have low bearing capacities and no cohesion.	20			3723
Facsimile camera and TV viewing of surface materials, particularly for blocks, bombs, or outcrops.		10		3733
Collection of 20 samples		5		3738
20 gravity stations spaced 5-10 m apart, commencing at outcrop if possible.		4		3742
At commencement of 12th lunar night: Preparation, analysis, and selection of 10 samples for return.		11		3753
Shutdown for lunar night		No time estimate		

			1m	10m	50m
Ls	0.4 - 1.0 %				
L_{ts}	--	Abs. Mean Slope	5.3 - 8.2°	3.8 - 5.8°	2.5 - 3.9°
N_B	2	Alg. Std. deviation	6.6 - 10.2	4.7 - 7.2	3.1 - 4.8
N_C	39.1 - 39.3	Abs. Mean Curvature	0.9 - 0.8	1.3 - 2.4	1.5 - 4.1
N_{B+C}	41.1 - 41.3	Alg. Std. deviation	1.2 - 1.3	1.8 - 2.9	1.9 - 5.0
L_B	0.4 %				

			Max.	Min.
L_C	16.9 - 22.4 %	PSD@0.05 (λ=20m):	0.34 - 1.00	0.075 - 0.420
L_{B+C}	17.5 - 23.1 %	PSD@0.5 (λ=2m):	$21 - 35 \times 10^{-4}$	$0.013 - 3 \times 10^{-4}$
L_T	17.9 - 24.1 %			



Site V-7 Dark halo craters and associated rille
Terrain: Rough mare-hummocky upland
Ranger IX, shadow measurements

Segment of original 1000-km traverse: 950-1000 km

Terrain type: Smooth Mare

			1m	10m	50m
Ls	0.2 %				
L_{ts}	--	Abs. Mean Slope	2.9°	2.0°	1.4°
N_B	0.2	Alg. Std. deviation	3.6	2.5	1.7
N_C	38.9	Abs. Mean Curvature	0.6	1.0	0.8
N_{B+C}	39.1	Alg. Std. deviation	0.8	1.3	0.9

			Max.	Min.
L_B	0.04%			
L_C	15.7 %	PSD@0.05 (λ=20m):	0.25	0.045
L_{B+C}	15.7 %	PSD@0.5 (λ=2m):	0.0013	0.00012
L_T	15.9 %			

Map distance, this segment: 50 km

Ground distance, this segment: 58 km

Avg. map velocity: 1.7 kph

Ground velocity: 1.97 kph

Driving time: 30 hrs

Routine science each 0.5 km: 50 hrs

Other operations: 30 hrs

Total time, this segment: 110 hrs

Cumulative ground distance to date: 1385 km

Cumulative time to date: 3863 hrs

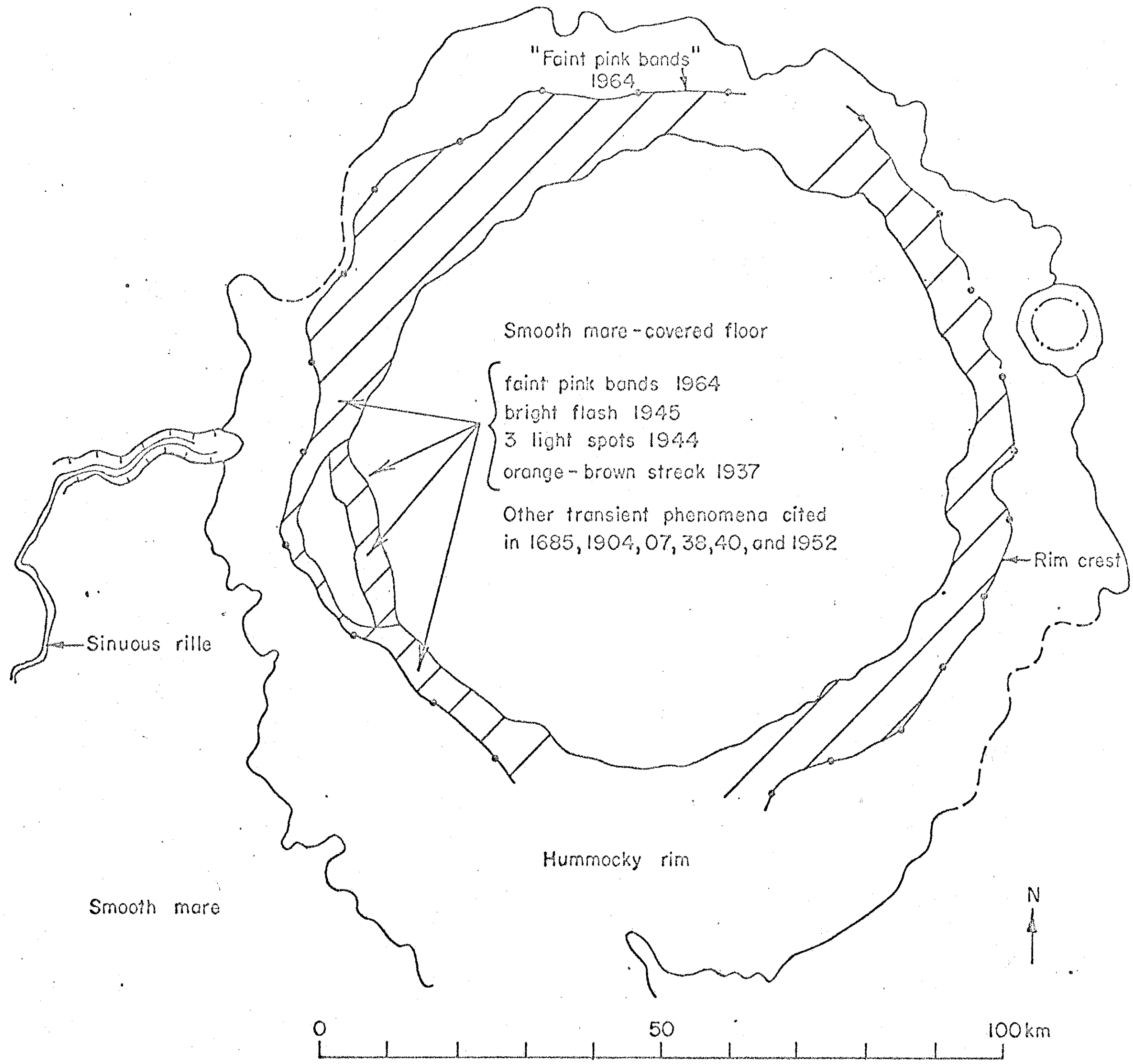
Site: V-8 Transient phenomenon/thermal anomaly

Terrain Type or equivalent: Smooth-to-rough mare

Objectives: To investigate source of thermal anomaly and, if possible, area of active volcanism; to rendezvous with manned mission and deliver lunar samples.

Operation	Estimated Time (hours) Driving	Science	Other	Cumulative
Maneuvering primarily to reach manned landed LM, but also to locate, study, and collect samples of rock units which may be very young. Primary hazards are craters, blocks, and possibly near-surface volcanic cavities.	15			3878
Collection of 15 samples; preparation, analysis, and selection of 7 for return		12		3890
40 gravimeter stations at 100 m intervals beyond range of manned mission		8		3898
Landing site evaluation. Navigation and homing on rendezvous point. Facsimile camera and TV camera scanning to confirm position celestially and by prominant landmarks. Traverse ends with manned landing.			15	3913

			1m	10m	50m
L_s	0.2 - 0.4 %				
L_{ts}	--	Abs. Mean Slope	2.9 - 5.3°	2.0 - 3.8°	1.4 - 2.5°
N_B	0.2 - 2	Alg. Std. deviation	3.6 - 6.6	2.5 - 4.7	1.7 - 3.1
N_C	38.9 - 39.1	Abs. Mean Curvature	0.6 - 0.9	1.0 - 1.3	0.8 - 4.1
N_{B+C}	39.1 - 41.1	Alg. Std. deviation	0.8 - 1.3	1.3 - 1.8	0.9 - 5.0
L_B	0.04 - 0.4 %		Max.	Min.	
L_C	15.7 - 16.9 %	PSD@0.05 (λ=20m):	0.25 - 1.00	0.045 - 0.420	
L_{B+C}	15.7 - 17.5 %	PSD@0.5 (λ=2m):	$13 - 35 \times 10^{-4}$	$1.2 - 3 \times 10^{-4}$	
L_T	15.9 - 17.9 %				



Map modified after preliminary geology map, LAC-12 (Schleicher & M'Gonigle)
Transient phenomena from Middlehurst and Burley (1966)

Site V-8 Transient phenomena/thermal anomaly

Terrain: Smooth-to-rough mare

Section B

Lunar Surface Geometry

by

Richard J. Pike

Section B

LUNAR SURFACE GEOMETRY

Introduction--data

This section provides numerical descriptive information on lunar surface roughness contributed by the geometry of the terrain, without regard for specific features such as craters or blocks. The data were obtained through photoclinometry, the method of deriving slope information from the brightness distribution of monoscopic lunar images by calibrated techniques (Van Diggelen 1951, Watson 1968). Data sources are high resolution imagery (effective resolution one meter) from Lunar Orbiter spacecraft (Missions II, III, and V) and selected terrestrial telescopic photographs (effective resolution 0.75 km).

The photoclinometric method affords a means of gathering large quantities of data in a relatively short time, once the necessary instrumentation and computer software have been assembled. Thus, it has some advantage over the more laborious shadow measurements. As currently developed, the photoclinometric method for reducing spacecraft imagery is suited more to the smoother lunar terrains, the mare, than to the rougher, upland areas (Lambiotte and Taylor, 1967). One meter resolution data for the lunar uplands are comparatively meager and are less reliable than mare data. Hence, considerable reliance has been placed upon the 0.75 km data, originally reduced by Rowan and McCauley (1966). This information has been extrapolated into the resolution range most relevant to vehicle mobility problems.

Photogrammetric terrain data, best obtained from Apollo 8 and Lunar Orbiter V medium resolution images, are not yet available in sufficient quantity. Additionally, photogrammetric reduction of the Orbiter and Apollo 8 imagery does not yield the one meter resolution of which the photoclinometric method is capable, and which is the most useful scale for the present study. The available lunar slope data have been supplemented and enhanced by a slope distribution model of a type previously employed in studies of terrestrial surface roughness conditions.

The most critical question, "How reliable are the high resolution photoclinometric data," has yet to be answered satisfactorily, particularly for the rougher lunar areas. When available, such an evaluation will be made available to users of the information contained in this section. At most, the present terrain models and data should require but a simple recalibration.

Classification of Lunar Terrain

Heterogeneity of the Moon's surface character virtually precludes a complete numerical description of all types of terrain that might be encountered by a lunar roving vehicle. The only meaningful alternative is a sampling of representative lunar terrain types or classes. Such a sampling may be as generalized or as inclusive as time and the availability of large scale terrain data permit. These two constraints thus far have limited the number of lunar terrain classes to four: smooth and rough mare and hummocky and rough upland. These four terrain classes are the principle divisions used by Rowan and McCauley (1966). Table 1 shows the topographic features typically

Table 1

FOUR-PART CLASSIFICATION OF LUNAR TERRAIN

MARE		UPLAND	
Smoother Mare	Rougher Mare	Hummocky Upland	Rough Upland
(1) many Eastern sites	(1) many Western sites	(1) older basin rim material (Fra Mauro fm)	(1) younger basin rim material (Orientale)
(2) dark mare material	(2) rille, dome, & ridge areas	(2) older large craters	(2) younger large craters
(3) older, subdued craters	(3) fresh craters	(3) blanketed craters	(3) scarps
(4) low crater densities	(4) high crater densities	(4) older, subdued crater hash	(4) fresh crater hash
(5) craters with few blocks	(5) blocky craters	(5) outer rim slopes of large craters	(5) inner rim slopes of large craters
	(6) secondary swarms especially on rays	(6) crater floors & basin fill	(6) trenches & rifts
	(7) large crater rims		

included in each category. As increasing data allow, this breakdown will be expanded to a six-part classification (Table 2). It is anticipated that each of these six classes eventually will be subdivided, yielding perhaps as many as two dozen different terrain types.

Selection of Descriptive Topographic Parameters

The three parameters chosen to describe the Moon's large scale surface geometry were selected on the following considerations (1) application to profile data, the only format in which photoclinometric data can be obtained reliably; (2) ability to express surface roughness rather than other, interesting, but less appropriate terrain characteristics; (3) ease of interpretation and application to problems of vehicle mobility; (4) ability to characterize surface roughness at any desired base length pertinent to vehicle trafficability problems. The three parameters are power spectral density, slope angle, and angle of slope curvature. The varied expression and presentation of each of these measures for the four gross lunar terrain types is discussed at length below.

Power Spectral Density

This parameter expresses the relief frequency content of a terrain profile as a time series, and is used principally to evaluate the dynamic response of a vehicle to different types of terrain (Jaeger and Schuring, 1966, Rozema, 1968). Like slope curvature, it is a measure of relative terrain roughness, and can be somewhat independent of absolute slope angle and regional slopes. The measure is expressed as a full logarithmic graph of power spectral density, in meters^2/cycle/meter, against frequency, in cycles/meter.

Table 2

SIX-PART CLASSIFICATION OF LUNAR TERRAIN

Large Craters (over 10-20 km diameter)	MARE		UPLANDS		
	Smoother mare	Rougher mare	Smooth Uplands	Hummocky Uplands	Rough Uplands

Figures 1-6 present the most recent power spectral density curves available for the Moon. They are a substantial improvement over previous curves (Pike 1968). Two curves, representing roughest and smoothest terrain conditions within each of the four main lunar terrain types, are shown in each diagram. The upper curve in Figure 5 is an educated hypothesis only. Figure 6 shows the maximum roughness range of the entire Moon. While all curves presented here are subject to revision or replacement by still more representative curves, Figures 1-6 probably include most of the roughness conditions present on the Moon.

Power spectral density functions of terrestrial terrains easily bracket the entire range of lunar curves presented here. Figure 7 shows curves for three freshly formed rough terrains, a lava flow surface, a blocky nuclear crater excavated in basalt, and a volcanic fissure vent. These terrains would be trafficable only with the greatest difficulty, if at all. These curves are displaced well above the roughest lunar curve yet obtained. Thus, most lunar terrains are appreciably smoother than these exceedingly rough terrestrial samples and should be traversable with relative security by a roving vehicle.

The frequency range most applicable to vehicle dynamics lies between 0.05 and 0.5 cycles/meter. Expressed more simply, this means that topographic features having base lengths between two and twenty meters have the greatest effect upon vehicle dynamics. Table 3 gives the power spectral density values of these two critical frequencies for the four lunar terrain classes. Maximum and minimum values, as determined by the bounding power spectral density curves in Figures 1-6, are given for each terrain type.

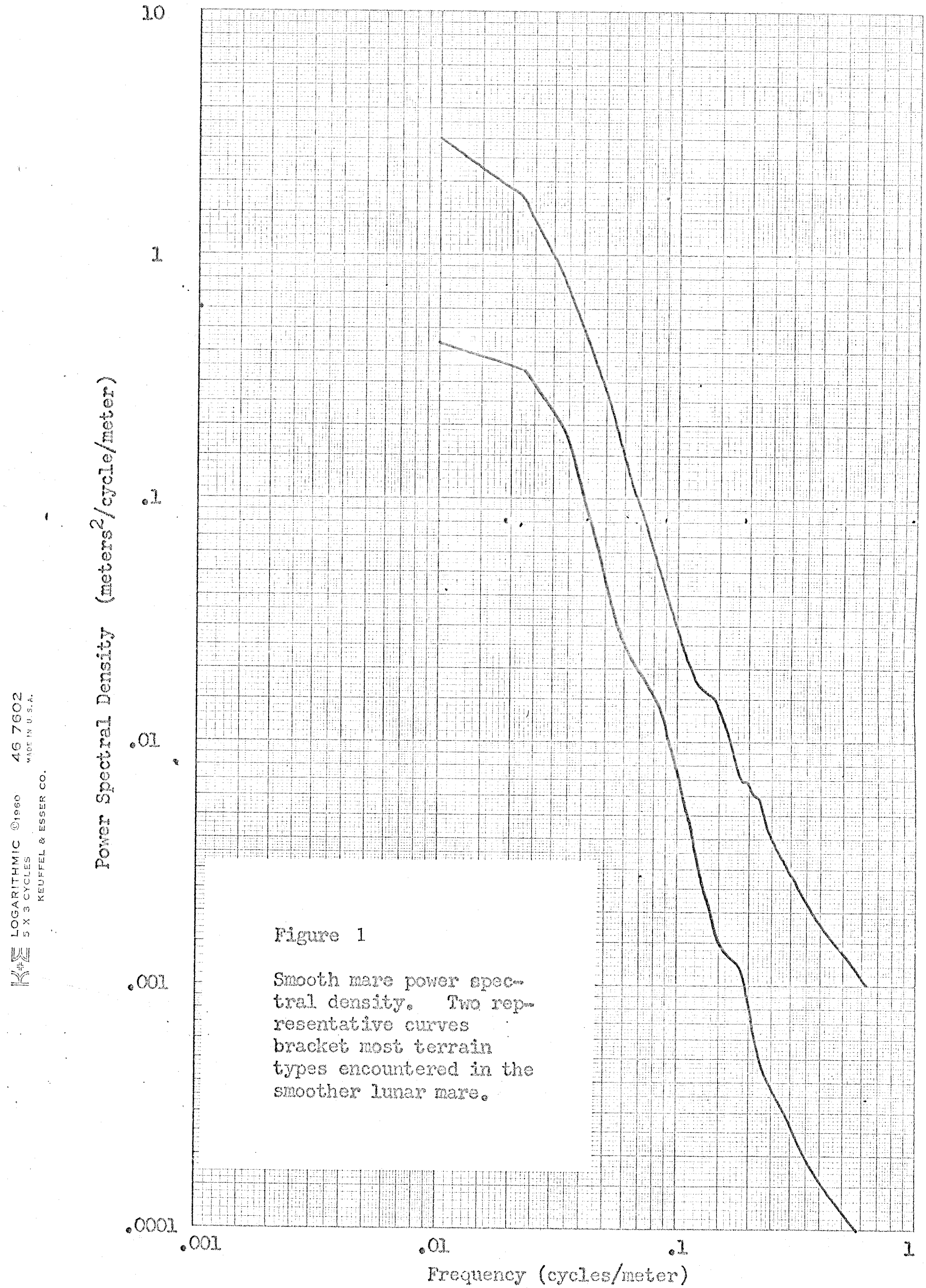


Figure 1

Smooth mare power spectral density. Two representative curves bracket most terrain types encountered in the smoother lunar mare.

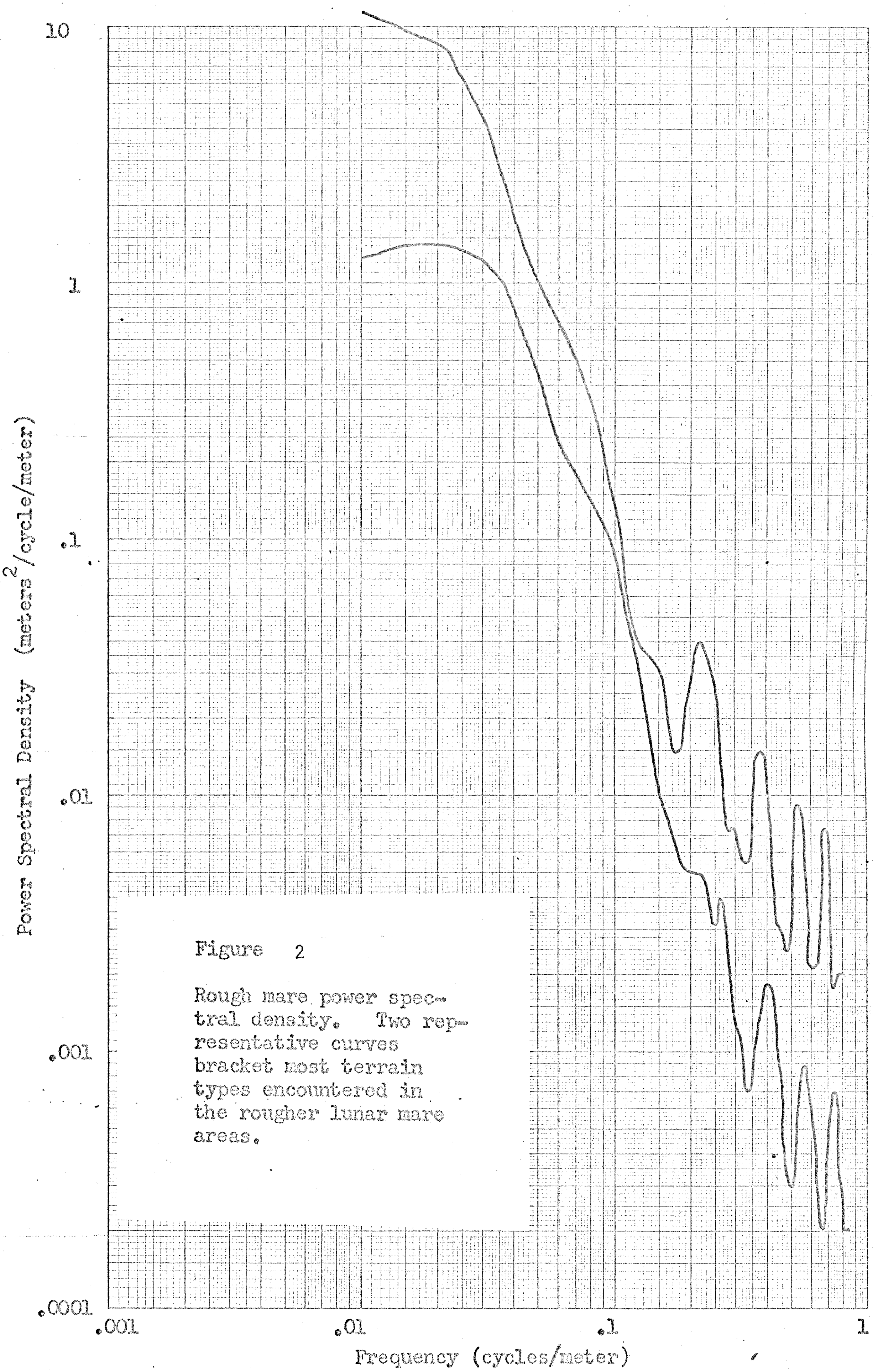


Figure 2

Rough mare power spectral density. Two representative curves bracket most terrain types encountered in the rougher lunar mare areas.

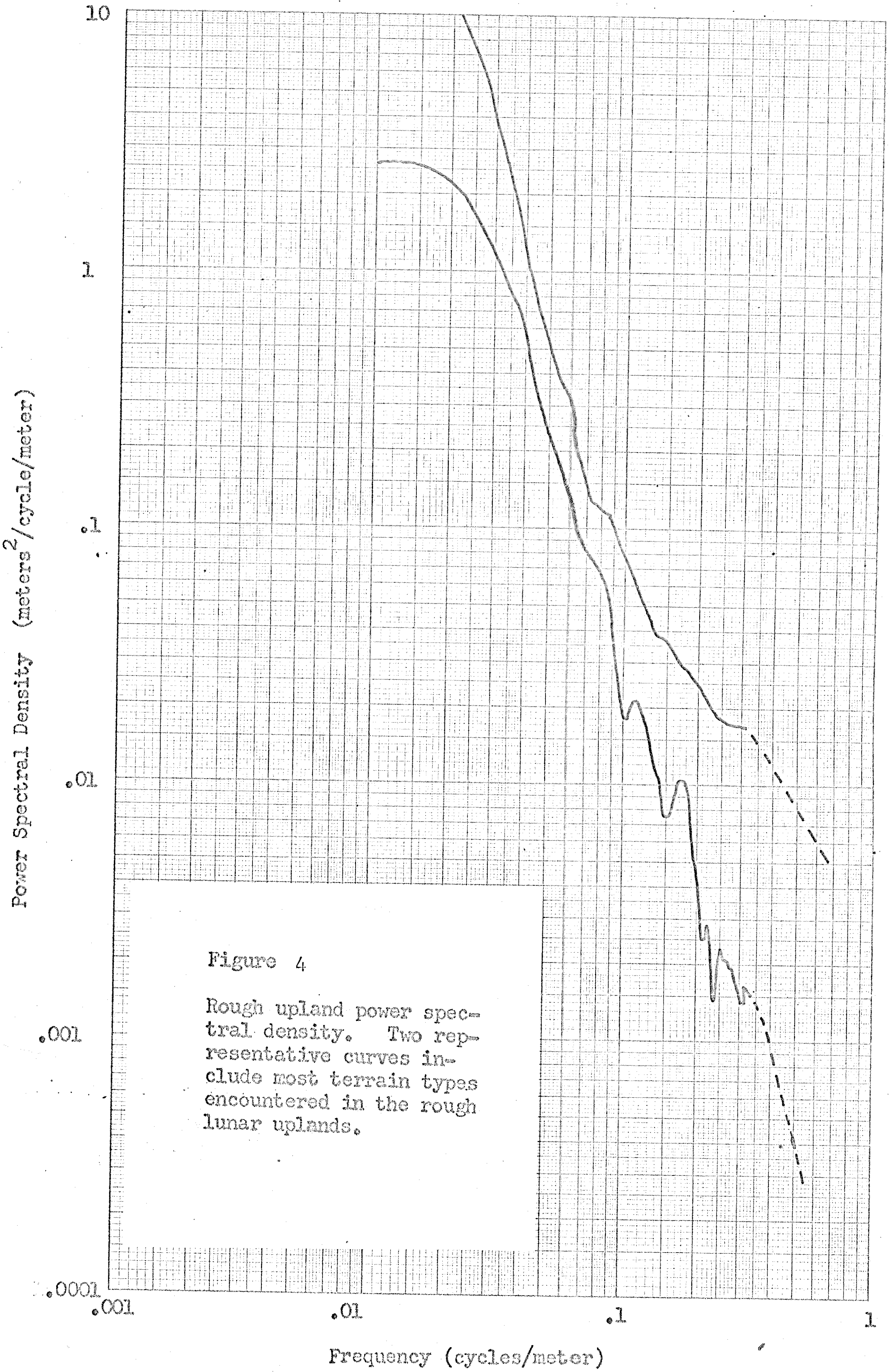


Figure 4

Rough upland power spectral density. Two representative curves include most terrain types encountered in the rough lunar uplands.

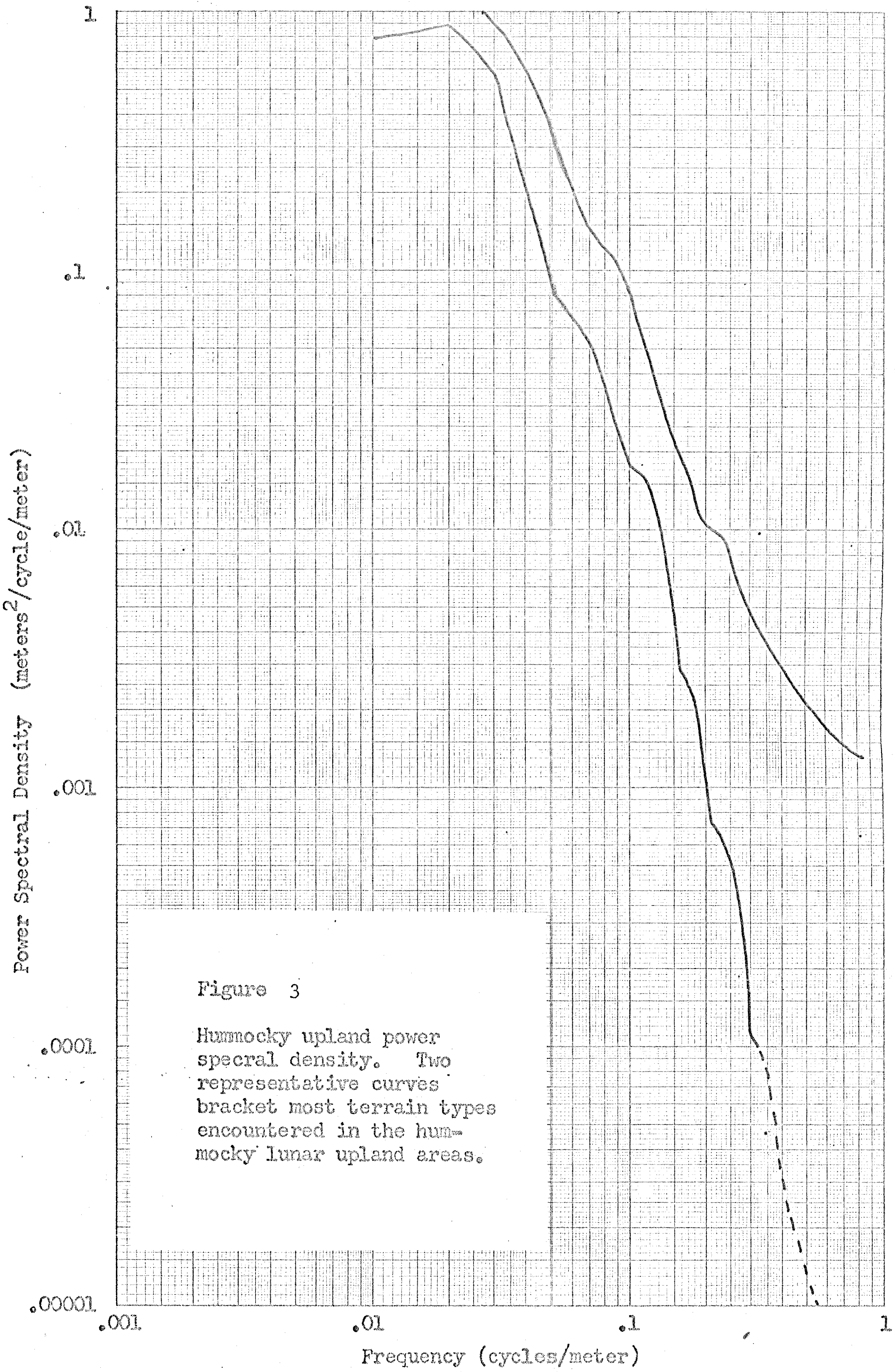


Figure 3

Hummocky upland power specral density. Two representative curves bracket most terrain types encountered in the hummocky lunar upland areas.

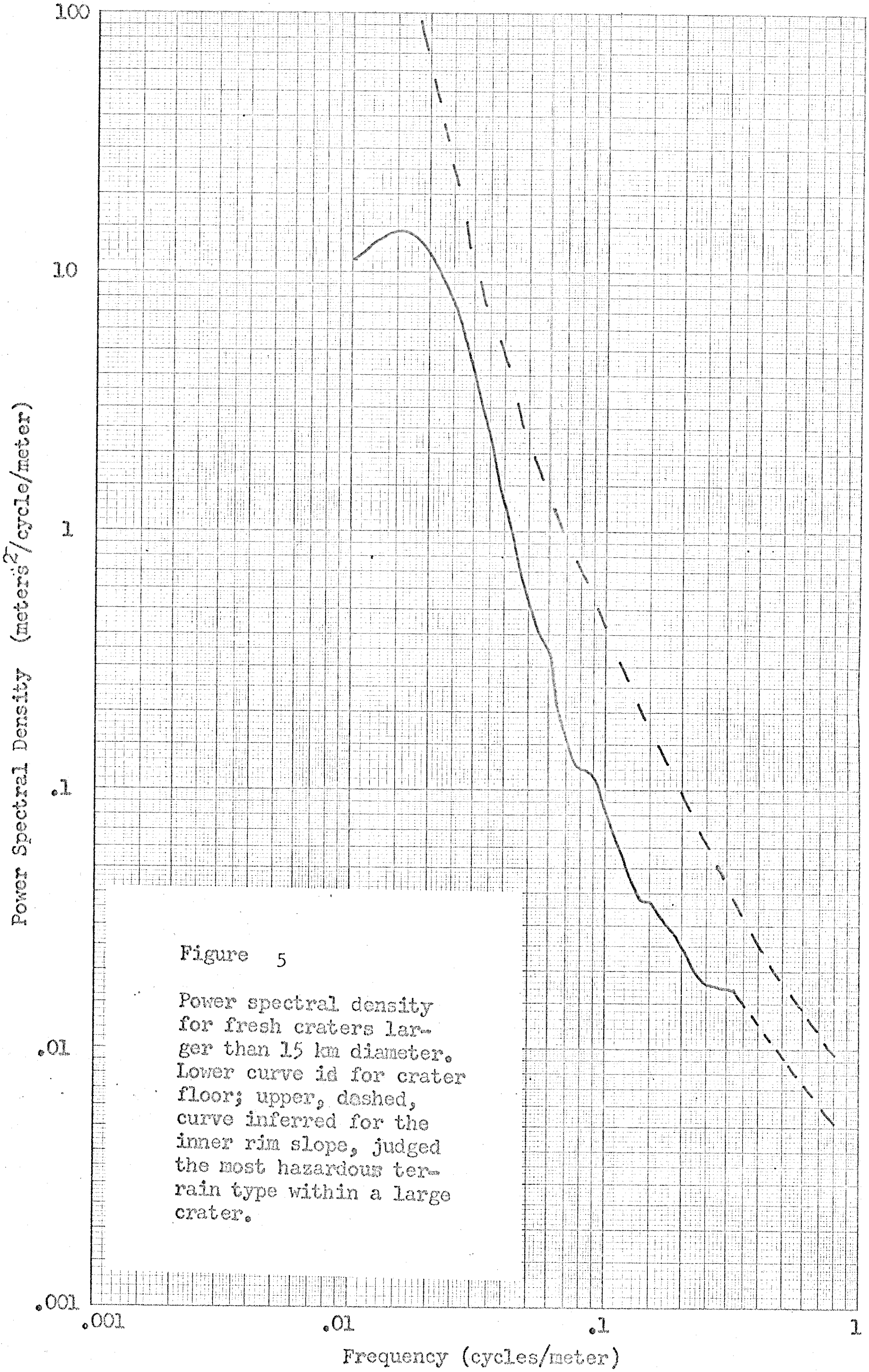


Figure 5

Power spectral density for fresh craters larger than 15 km diameter. Lower curve id for crater floor; upper, dashed, curve inferred for the inner rim slope, judged the most hazardous terrain type within a large crater.

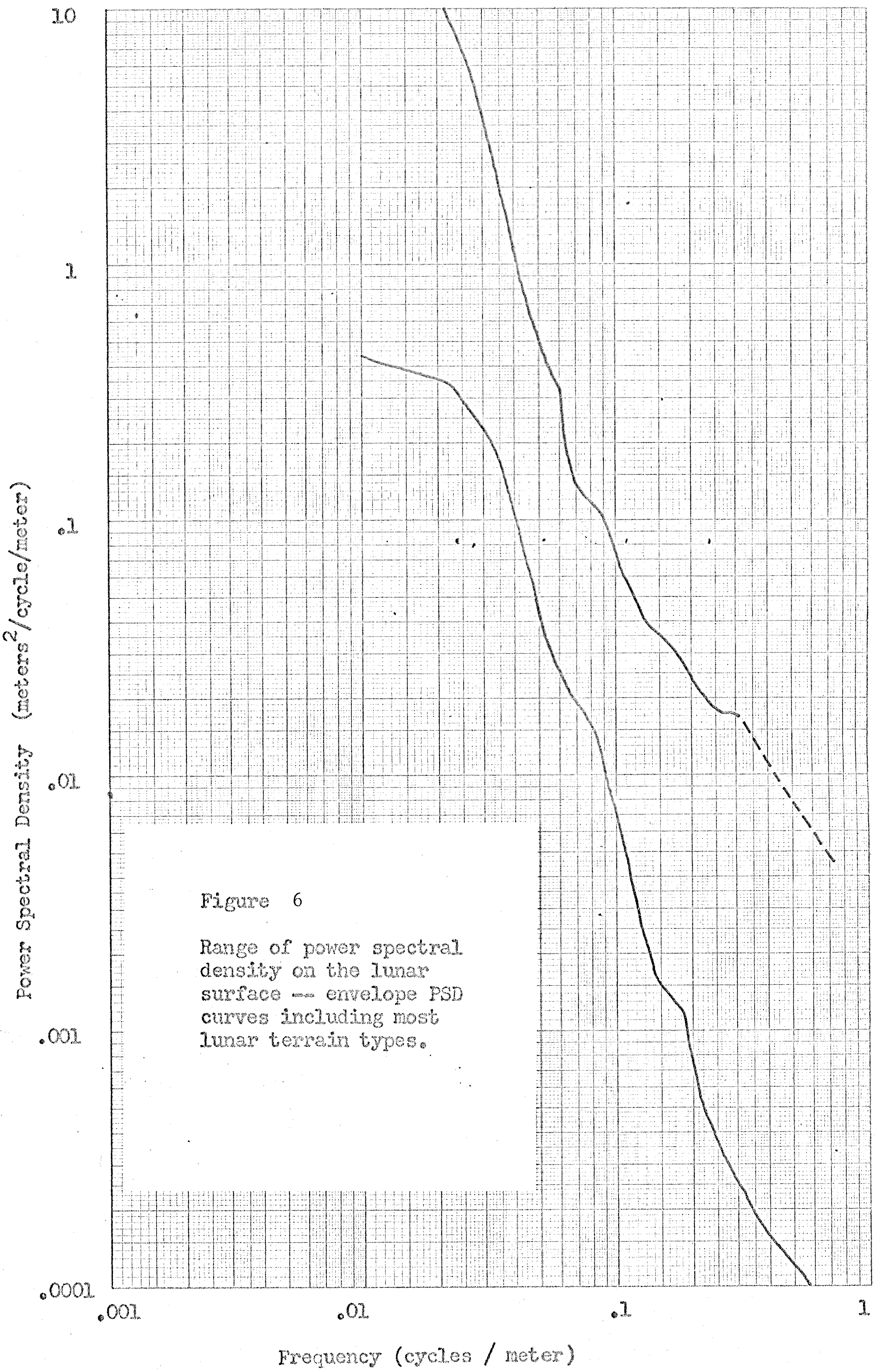


Figure 6

Range of power spectral density on the lunar surface -- envelope PSD curves including most lunar terrain types.

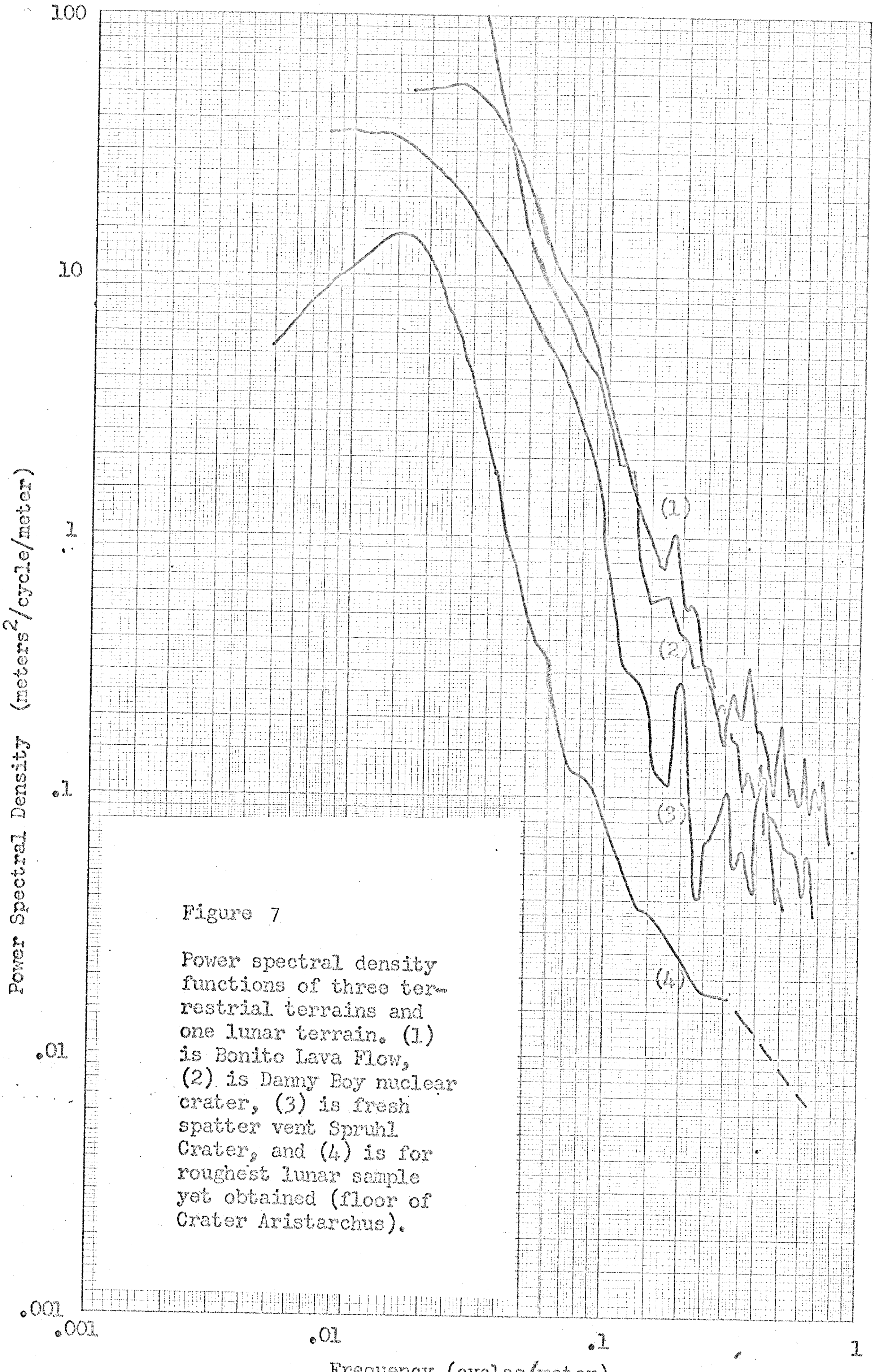


Figure 7

Power spectral density functions of three terrestrial terrains and one lunar terrain. (1) is Bonito Lava Flow, (2) is Danny Boy nuclear crater, (3) is fresh spatter vent Spruhl Crater, and (4) is for roughest lunar sample yet obtained (floor of Crater Aristarchus).

Table 3

Ranges of Power Spectral Density (PSD) Values for Four Gross Lunar Terrain Types at Two Frequencies

Terrain Type	PSD in $meters^2$/cycle/meter	
	0.05 cycles/meter	0.5 cycles/meter
Smooth mare	0.045 - 0.25	0.00012 - 0.0013
Rough mare	0.420 - 1.00	0.0003 - 0.0035
Hummocky upland	0.075 - 0.34	0.000013 - 0.0021
Rough upland	0.200 - 0.50	0.0004 - 0.0080
All terrains	0.075 - 1.00	0.000013 - 0.008

Slope Angle

Measuring the departure of topography from the horizontal, slope angle is an absolute index of terrain roughness. Slope angles measured along a profile may be expressed either as absolute values or as algebraic values, where slopes facing, for example, east, are designated positive, and the west-facing slopes negative.

On the Moon, algebraic slope-frequency distributions typically approach, but never quite achieve, the gaussian configuration. Thus, the usual central tendency and dispersion statistics (mean, mode, median, standard deviation, variance, skewness, and kurtosis) can be applied, albeit with caution, to algebraically expressed lunar slope samples. However, the applicability of all of these statistics to vehicle mobility problems has not been established, so lunar slopes customarily are expressed as absolute values.

Absolute value slope frequency distributions on the Moon are skewed strongly toward low slope angles and only the mean, median, and modal slopes should be extracted from these distributions. If all lunar slope data were available along any desired azimuth, then algebraic slopes would furnish useful information on slope symmetry. However, lunar photoclinometric data can only be obtained along the phase plane, which does not change sufficiently among the five Lunar Orbiter missions to provide the required variation in azimuth.

With comparatively little to be gained from using algebraic slopes, the slope angle data gathered for the present study are expressed mostly in absolute values. Three aspects of slope angle are presented here: (1) mean absolute slope, (2) algebraic standard deviation, and (3) absolute slope frequency distribution. Each of these three parameters is given for slope base lengths of one, ten, and fifty meters for each of the four classes of lunar terrains listed in Table 1.

Scarcity of representative large-scale slope data for all four lunar terrain classes has necessitated extrapolation of small scale photoclinometric data and the derivation of statistical models of slope distributions. The photoclinometric method, designed expressly for the relatively smooth and level mare, is not readily applicable to steeper and rougher upland terrain (Taylor and Lambiotte, 1967). Few slope distributions have been successfully obtained for the upland terrains at the base length of one meter. However, predictive models have been formulated for the uplands using one meter resolution spacecraft data from mare sites together with the 0.75 km resolution terrestrial data for both uplands and mare. Derivation of these models is treated in Pike (1968) and in the appendix to this section, and need not be discussed further here.

Tables 4-8 and Figures 8-11 present slope information for the four lunar terrain types at one, ten, and fifty meter base lengths. Most of these data are straightforward; their calculation is discussed in the appendix. Tables 6-8 show only tentative 100th percentile slope values, which are not shown by the curves in Figures 8-11. Maximum slope values, which commonly are not accurately measured by the photoclinometric method in any but the smoothest areas, vary also according to the number of slope angles inspected in a particular sample, and are not readily predicted.

Table 4

Mean Values of Absolute Slope at Three Base Lengths
for Four Gross Lunar Terrain Types

Terrain Type	Average Mean	Lowest Mean Slope	Highest Mean Slope	Range of Mean Slopes
		Base Length is one meter		
Smooth mare	2.9°	1.2°	4.0°	2.8°
Rough mare	5.3	3.5	7.8	4.3
Hummocky upland	8.2	4.7	10.0	5.3
Rough upland	11.0	8.7	15.0	6.3
		Base Length is ten meters		
Smooth mare	2.0	1.0	2.8	1.8
Rough mare	3.8	2.5	5.6	3.1
Hummocky upland	5.8	3.6	7.0	3.4
Rough upland	7.7	6.2	11.0	4.8
		Base Length is fifty meters		
Smooth mare	1.4	0.7	1.9	1.2
Rough mare	2.5	1.7	3.7	2.0
Hummocky upland	3.9	2.4	4.7	2.3
Rough upland	5.2	4.1	7.3	3.2

Table 5

Mean Values of Algebraic Standard Deviation of Slope Angle for Four Gross Lunar Terrain Types

Terrain Type	Average Standard Deviation	Lowest Standard Deviation	Highest Standard Deviation	Range of Standard Deviations
Base Length is One Meter				
Smooth mare	3.6°	1.5°	5.0°	3.5°
Rough mare	6.6	4.4	9.7	5.3
Hummocky upland	10.2	5.8	12.4	6.6
Rough upland	13.7	10.0	18.6	8.6
Base Length is Ten Meters				
Smooth mare	2.5	1.3	3.5	2.2
Rough mare	4.7	3.1	7.0	3.9
Hummocky upland	7.2	4.4	8.7	4.3
Rough upland	9.6	7.7	13.7	6.0
Base Length is Fifty Meters				
Smooth mare	1.7	0.9	2.4	1.5
Rough mare	3.1	2.1	4.6	2.5
Hummocky upland	4.8	3.0	5.8	2.8
Rough upland	6.5	5.1	9.1	4.0

Table 6

Predicted Distributions of One Meter Slopes for Four Lunar Terrain Types Whose Mean Slope Values are Known or Estimated

Mean Slope Values		2.9°	5.3°	8.2°	11.0°
%N	Model % of Mean Slope	Smooth mare	Rough mare	Hummocky upland	Rough upland
100	(450)	(13°)	(24°)	(37°)	(50°)
98	346	10	18	28	38
95	273	8	14	22	30
90	216	6.2	11	18	24
80	152	4.4	8	12	17
70	116	3.4	6.1	10	13
60	96	2.8	5.1	8	10
50	76	2.2	4.0	6.2	8
40	58	1.7	3.1	4.8	6.4
30	44	1.3	2.3	3.6	4.8
20	28	0.8	1.5	2.3	3.1
10	15	0.4	0.8	1.2	1.7

Table 7

Predicted Distributions of Ten Meter Slopes for Four Lunar Terrain Types Whose Mean Slope Values are Known or Estimated

Mean Slope Values		2.0°	3.8°	5.8°	7.7°
%N	Model % of Mean Slope	Smooth mare	Rough mare	Hummocky upland	Rough mare
100	(450)	(9°)	(17°)	(26°)	(35°)
98	346	6.9	13	20	27
95	273	5.5	10	16	21
90	216	4.3	8	13	17
80	152	3.0	5.8	9	12
70	116	2.3	4.4	6.7	9
60	96	1.9	3.6	5.6	7.4
50	76	1.5	2.9	4.4	5.8
40	58	1.2	2.2	3.4	4.5
30	44	0.9	1.7	2.6	3.4
20	28	0.6	1.1	1.6	2.2
10	15	0.3	0.6	0.9	1.2

Table 8

Predicted Distributions of Fifty Meter Slopes for Four Lunar Terrain Types Whose Mean Slope Values are Known or Estimated

Mean Slope Values		1.4°	2.5°	3.9°	5.2°
%N	Model % of Mean Slope	Smooth mare	Rough mare	Hummocky upland	Rough upland
100	(450)	(6.3°)	(11°)	(18°)	(23°)
98	346	4.8	9	13	18
95	273	3.8	6.8	11	14
90	216	3.0	5.4	8.4	11
80	152	2.1	3.8	5.9	8
70	116	1.6	2.9	4.5	6.0
60	96	1.3	2.4	3.7	5.0
50	76	1.1	1.9	3.0	4.0
40	58	0.8	1.5	2.3	3.0
30	44	0.6	1.1	1.7	2.3
20	28	0.4	0.7	1.1	1.5
10	15	0.2	0.4	0.6	0.8

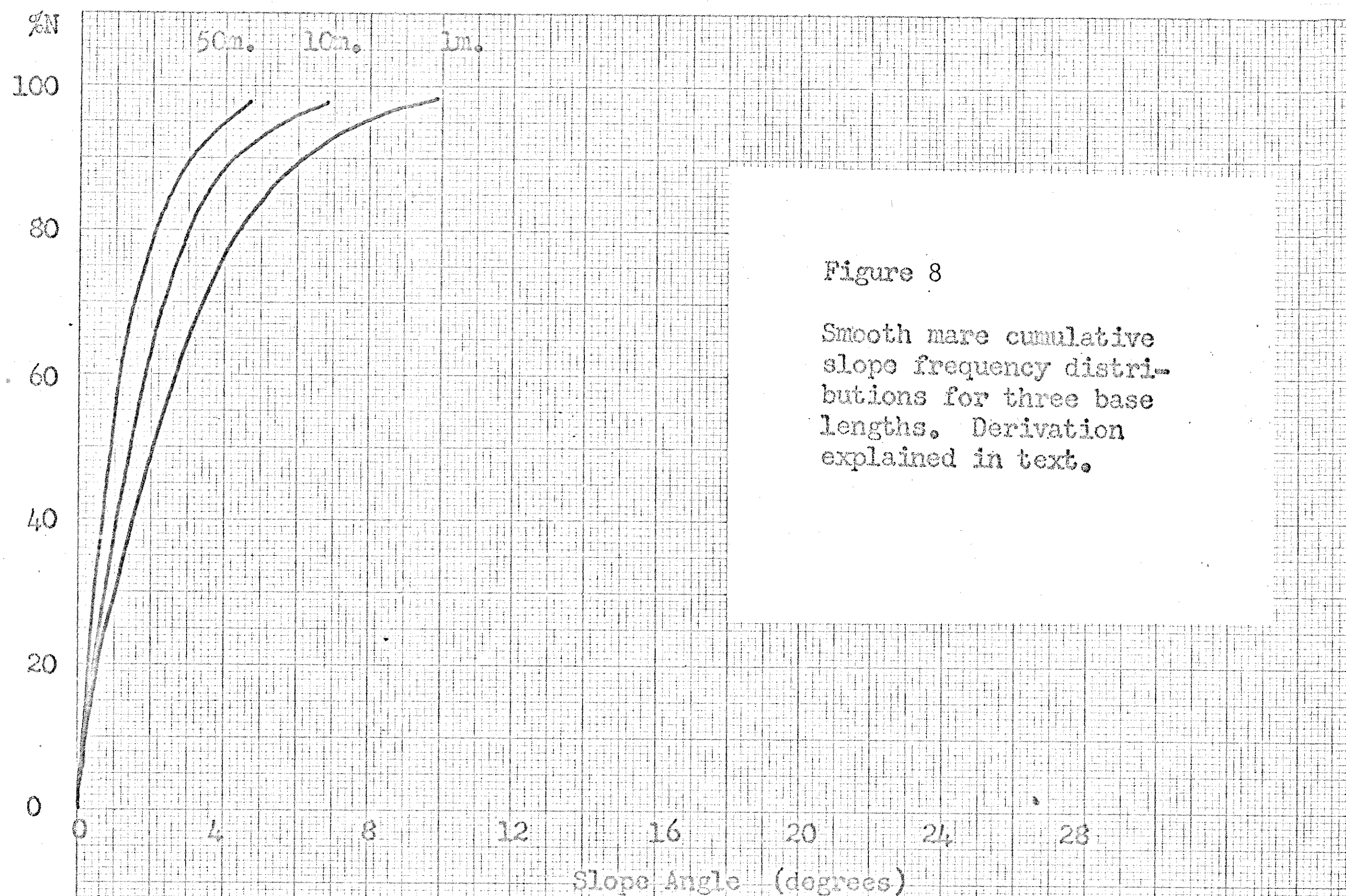


Figure 8

Smooth mare cumulative slope frequency distributions for three base lengths. Derivation explained in text.

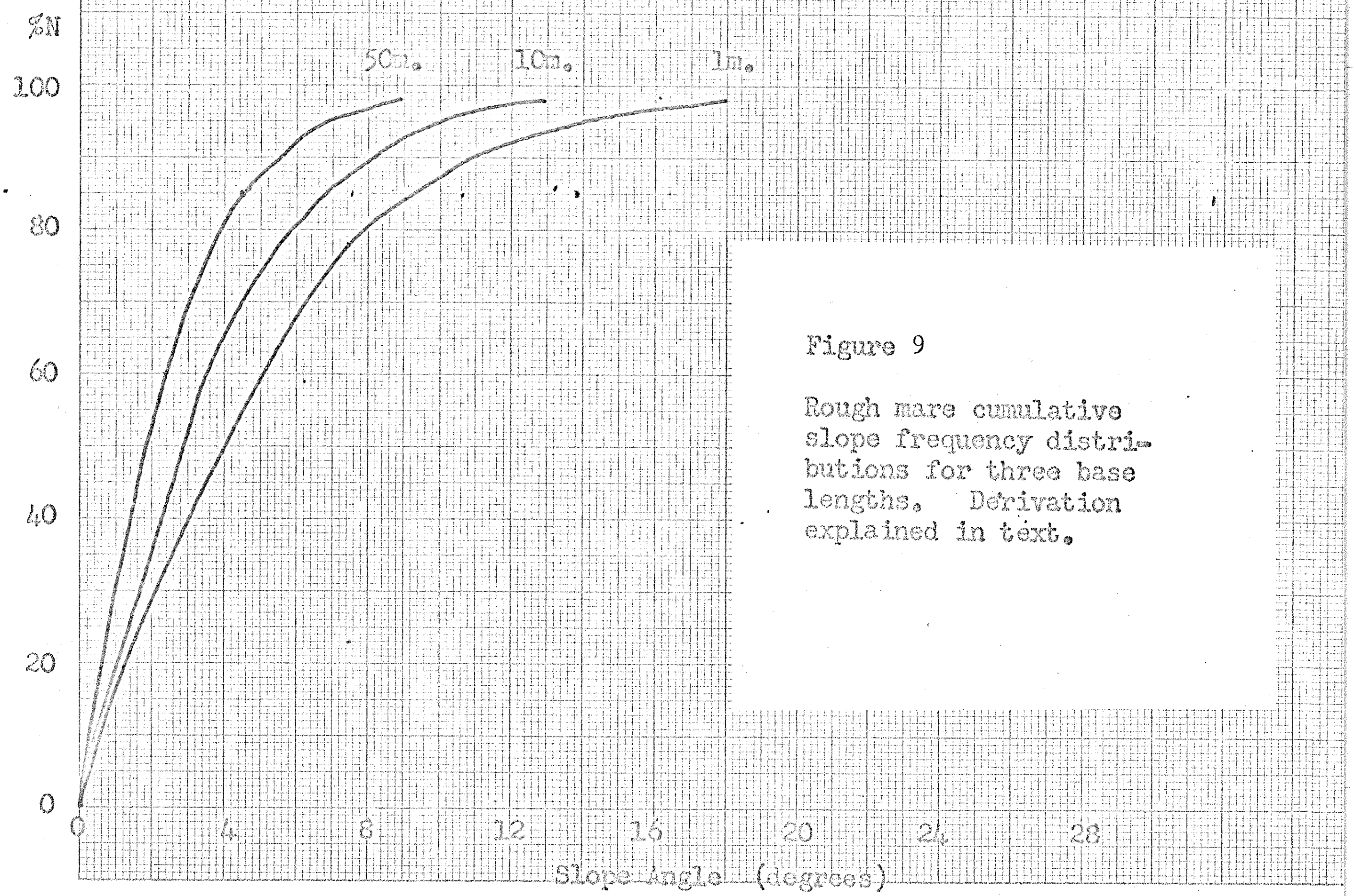


Figure 9

Rough mare cumulative slope frequency distributions for three base lengths. Derivation explained in text.

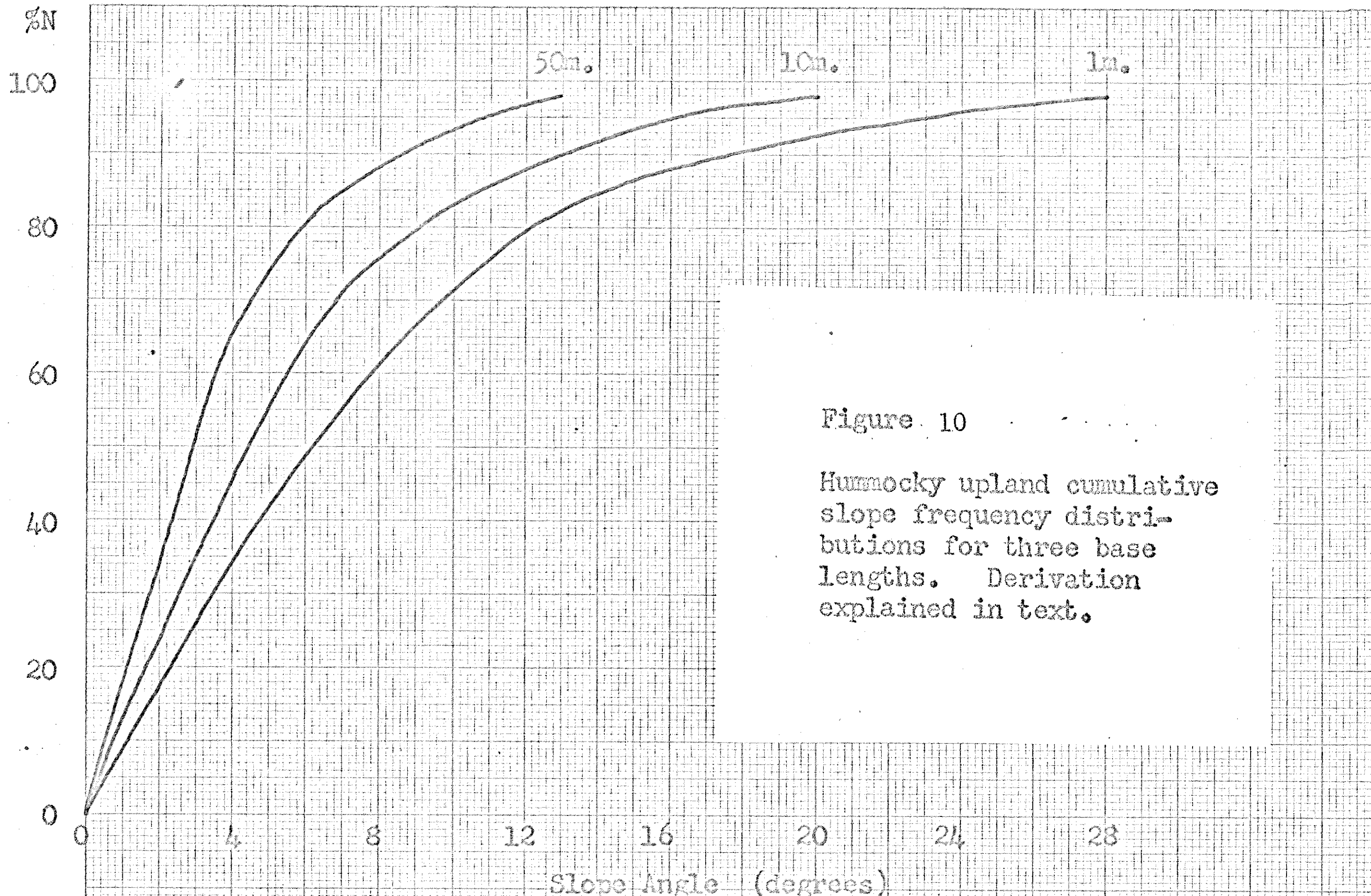


Figure 10

Hummocky upland cumulative slope frequency distributions for three base lengths. Derivation explained in text.

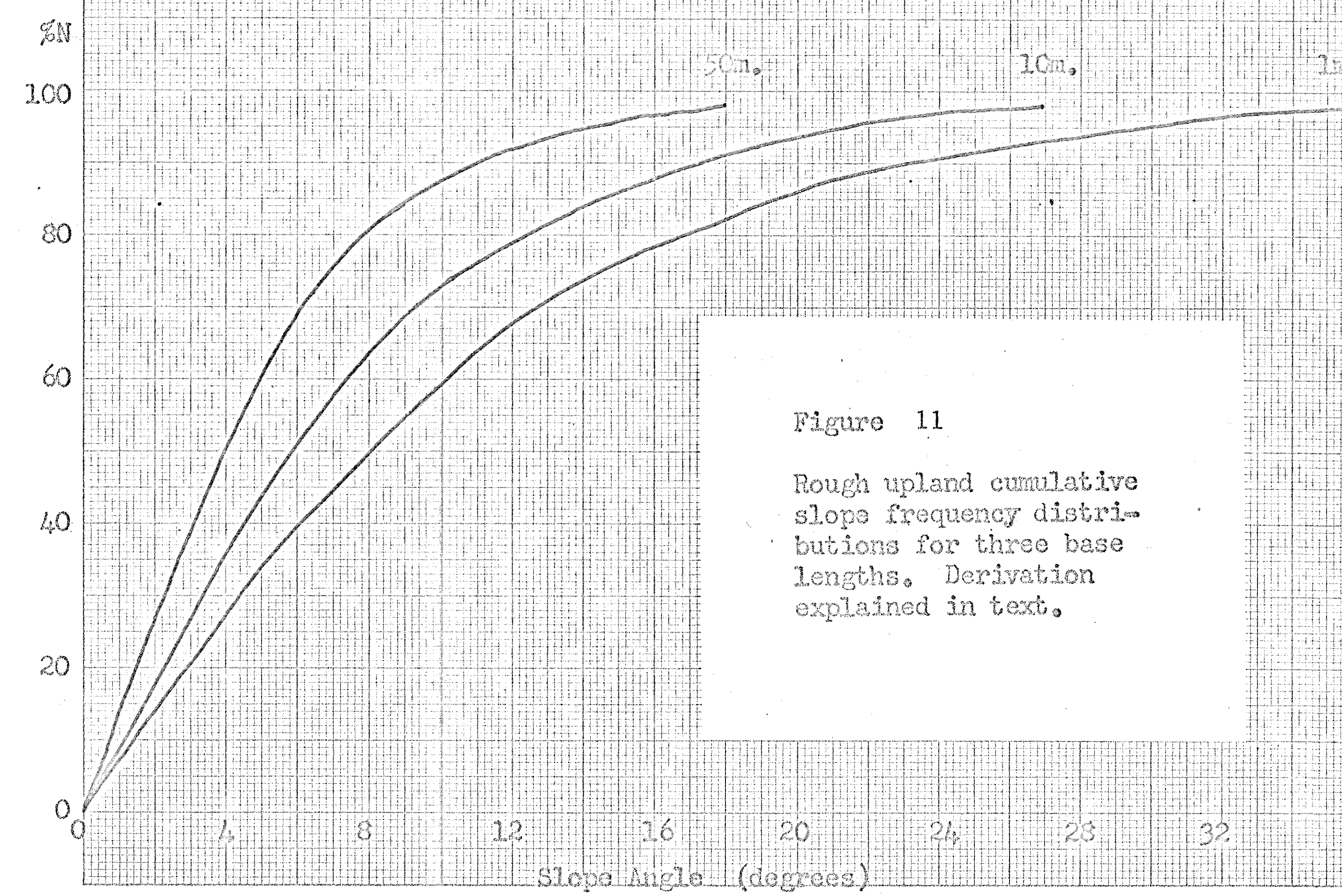


Figure 11

Rough upland cumulative slope frequency distributions for three base lengths. Derivation explained in text.

The slope information presented here suggests that the general terrain geometry will not pose a serious trafficability hazard in average smooth and rough mare areas. Special mare features, including rilles, domes, and fresh craters will have to be considered as specific hazards where encountered. The upland areas, however, can be expected to be totally impassable in places, due to the general terrain geometry alone. Remembering that the upland slope frequency curves in Figures 10 and 11 are only averages, it is a virtual certainty that some of the rougher upland areas will be exceedingly hazardous to a lunar roving vehicle. Of course, such areas still might prove to be trafficable if the vehicle was carefully routed around the most dangerous slopes.

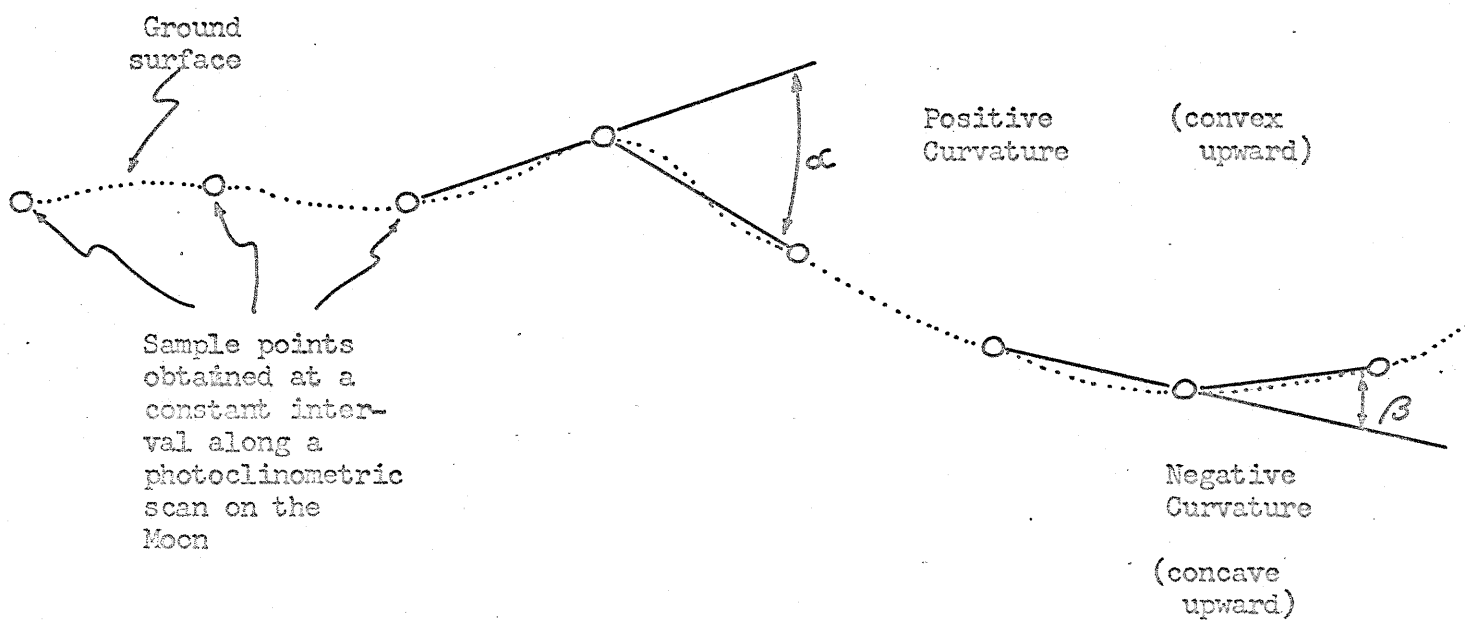
An additional terrain type, large fresh craters (over 15 km in rim diameter), including desireable scientific sites such as Aristarchus, Tycho, and Copernicus, may well be even more hazardous than any of the four basic terrains discussed previously. Preliminary photogrammetric profiles (Wu 1969, and unpublished data) of fresh, large craters both in the mare and in the uplands, indicate that long and steep slopes at, and even exceeding, 30 to 40 degrees may be common in these areas. Data will be made available pending evaluation of the precision.

Angle of Slope Curvature

Like power spectral density, slope curvature is a measure of relative, rather than absolute, surface roughness. Curvature angle as used in the present study and defined in Figure 12 is considerably less complicated than that of Schloss (1965). The statistical properties

Figure 12

DEFINITION OF SLOPE CURVATURE



of slope curvature as defined here are not yet well known. Algebraic curvature frequency distributions on the Moon are not strongly skewed, and, like slope angle, approach normality. While the mean absolute value of slope curvature usually correlates positively with mean absolute value of the slope angle, the degree of correspondence varies for different terrains. The parameter, calculated at several base lengths, is complementary to slope angle and power spectral density, and perhaps somewhat repetitive of the latter, although this redundancy has yet to be demonstrated.

Insufficient information on the properties of slope curvature angle precludes use of generalized predictive models similar to those computed for slope angle, above. Instead, four specific lunar samples were selected to represent each of the four major terrain types. Tables 9 and 10 present curvature absolute means and algebraic standard deviations at base lengths of one, five, ten, and fifty meters. Figures 13 and 14 are curvature angle frequency curves for the four terrain types at a base length of five meters.

Again, the lack of additional lunar and terrestrial curvature information precludes much comparison of the present lunar sites with other areas. However, the data do point up some interesting variations among the four lunar samples. At a base length of five meters, mean curvature values and the frequency curves display a systematic increase in curvature from smooth mare to rough upland. At base lengths of one and fifty meters, however, the progression is not as regular. The variation of curvature with base length likewise shows both systematic

Table 9

Mean Slope Curvature of Four Gross Lunar Terrain Types

At Four Base Lengths

Terrain Type	Values of Mean Slope Curvature in Degrees of Arc			
	One meter	Five meters	Ten meters	Fifty meters
Smooth mare	0.6	0.9	1.0	0.8
Rough mare	0.9	1.2	1.3	4.1
Hummocky Upland	0.8	1.7	2.4	1.5
Rough upland	2.0	2.5	2.7	3.8

Table 10

Algebraic Standard Deviation of Angle of Curvature

Of Four Gross Lunar Terrain Types at Four Base Lengths

Terrain Type	Value of Algebraic Standard Deviation in degrees of arc			
	One meter	Five meters	Ten meters	Fifty meters
Smooth mare	0.8	1.3	1.3	0.9
Rough mare	1.3	1.9	1.8	5.0
Hummocky upland	1.2	2.7	2.9	1.9
Rough upland	3.1	3.3	3.4	3.4

Figure 13 Frequency distributions of slope curvature for the lunar maria. Curves shown represent smooth maria (left), rough maria (right). Base length is 5 meters

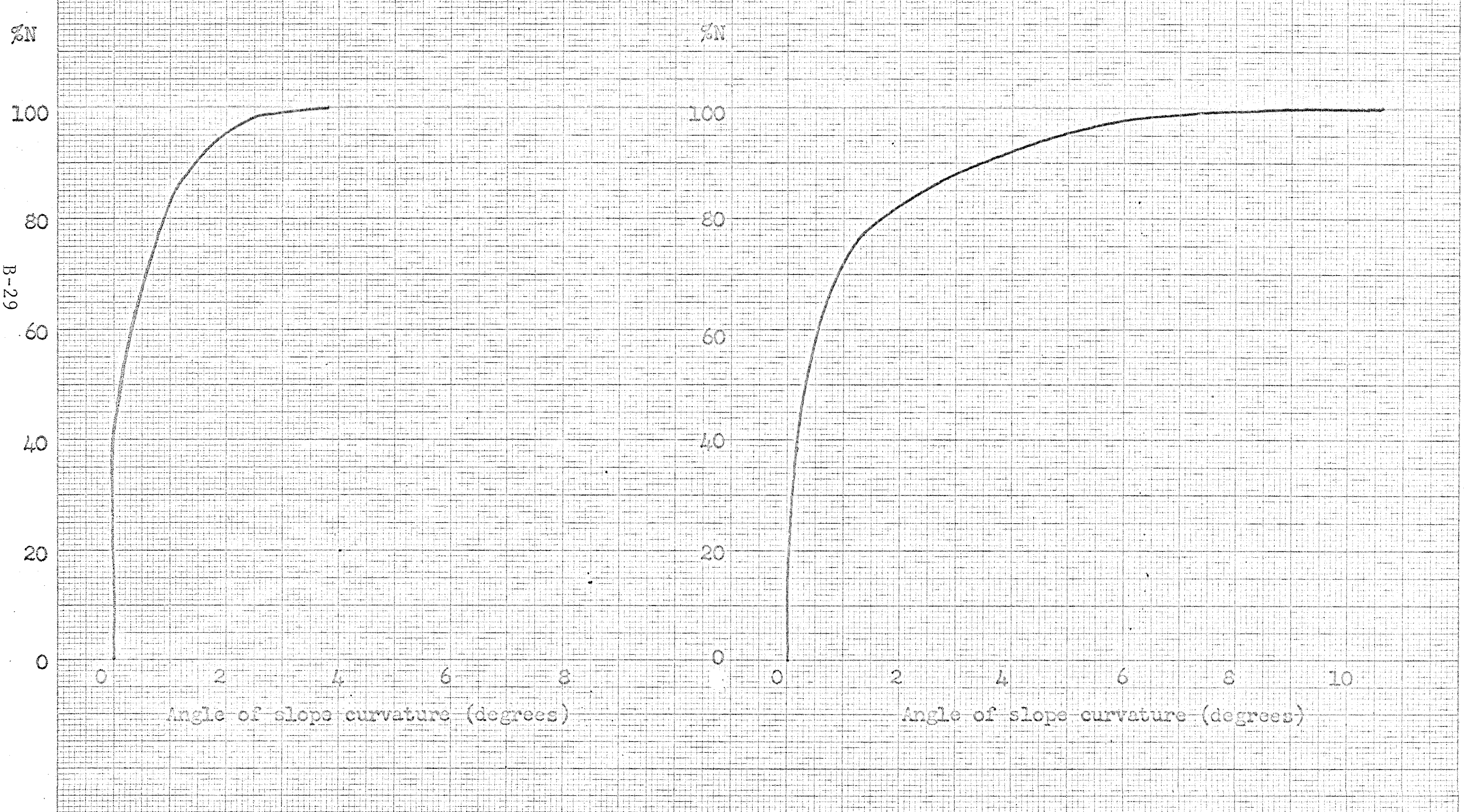
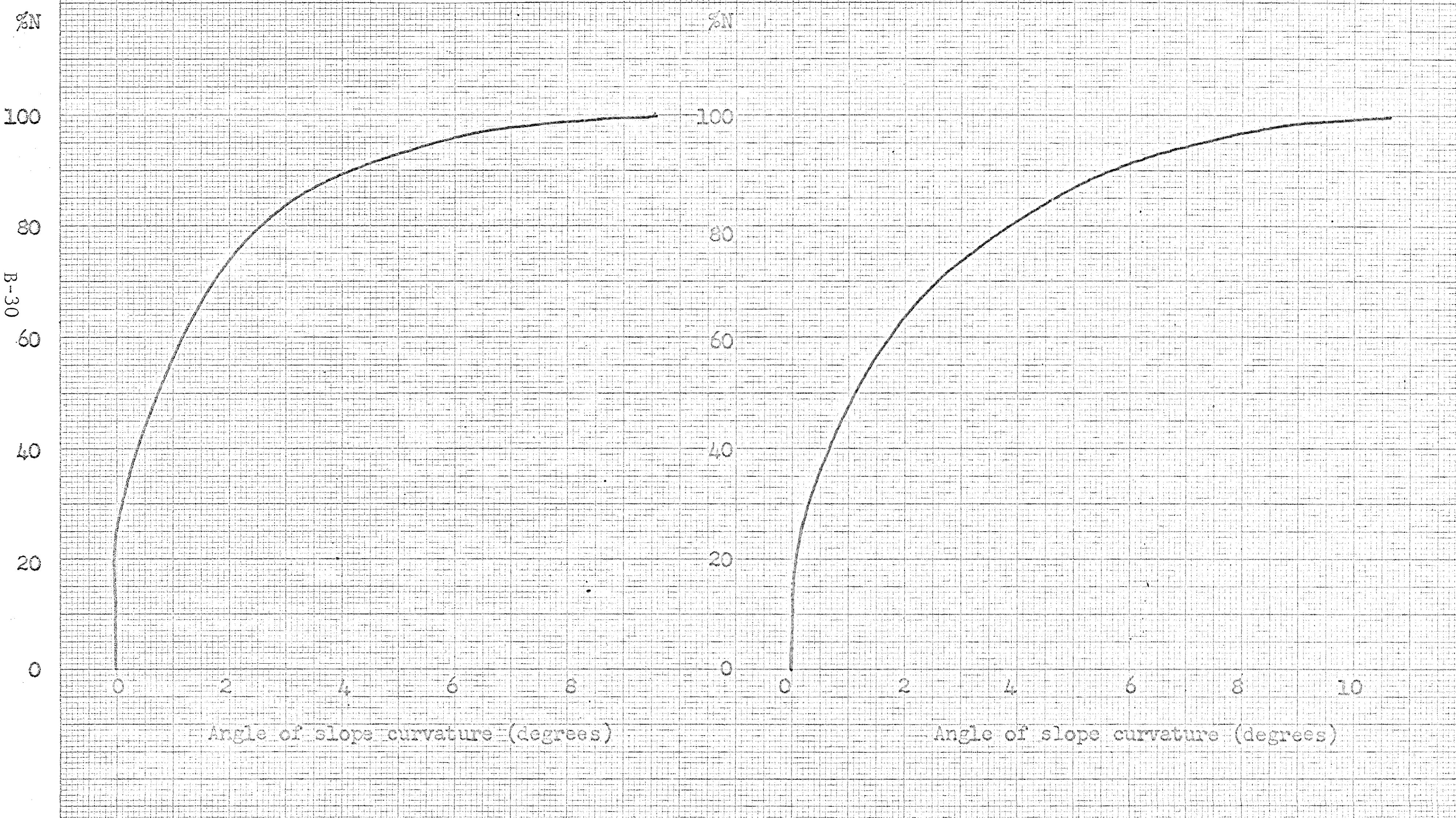


Figure 14 Frequency distributions of slope curvature for the lunar uplands. Curves shown represent hummocky (left) and rough upland (right). Base length is 5 meters



progressions and much less orderly changes, depending upon the terrain type. Such irregularities can readily be interpreted in terms of the varying geomorphic development of the four sample areas. All-in-all, the curvature angles shown in Figures 13 and 14 do not appear to be large enough to severely impede the mobility of a lunar roving vehicle. When available, curvature data for analagous terrestrial terrains will be furnished for comparison with the lunar samples given here.

Surface Geometry and Traverse Distance

Irregularities of the lunar terrain will materially; if but slightly, increase the map distance of any projected vehicular traverse. While avoidance of small steep craters, block fields, steep-walled rilles, and other hazards will contribute most to such an increased distance, the overall surface geometry has some affect as well. The figures in Table 11 were obtained by computing secants of median slope values of seven slope angle classes for each of the one-meter slope frequency curves in Figures 8-11. Percentage increase figures for large, fresh craters were estimated from photogrammetric profiles of the craters Copernicus and Tycho (unpublished data).

Table 11

Probable Contribution of Topographic Slope to Increase of Actual LRV Travel Distance over Planned Map Distance As a Function of Lunar Type

Terrain Type	Average percentage of distance added to map distance by topographic slope (data at one meter base length)
Smooth mare	0.21%
Rough mare	0.40%
Hummocky upland	1.00%
Rough upland	1.86%
Fresh Craters over 15 km diameter	2.3% to 4.6 %

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(Appendix to Section B)

PRELIMINARY MODELS FOR THE PREDICTION OF SLOPE ANGLE ON THE LUNAR SURFACE

by

Richard J. Pike

Flagstaff, Arizona
March 17, 1969

U.S. Geological Survey
Astrogeologic Studies

Mean slope angle values for four lunar terrain types

McCauley (1964) and Rowan and McCauley (1966) in previous photoclinometric studies of lunar surface geometry, obtained abundant slope data at a resolution of 0.75 km and greater. One result of their work (the curve WXYZ on Figure 1), depicts median slope against slope lengths for an "average lunar mare," comprising both smoother and rougher mare types. The slope of this curve, almost exactly -0.25, is very well determined by the four points. Rowan and McCauley also calculated median lunar slope for 53 different lunar localities, and divided the samples into four gross terrain units, Smooth Mare, Rougher Mare, Hummocky Upland, and Rough Upland. By averaging medians of samples in each category, we obtain points B, C, D, and E. Point A, the average for all mare samples, demonstrates the validity of the curve WXYZ, derived earlier by McCauley.

TERRAIN TYPE	CURVE IN FIG. 1	AVERAGE MEDIAN SLOPE at 0.75 km ΔL
Smooth Mare	(B)	0.55°
Rough Mare	(C)	1.03°
Hummocky Upland	(D)	1.56°
Rough Upland	(E)	2.07°

We let the four points in the above table define four curves describing the relationship between median slope and slope length. While the slope of these curves may differ from that of the WXYZ curve, there are no data to show what this difference, if any, might be. Hence, we set the four curves parallel to that for the average mare, assuming it is likely that the median slope:slope length relationship undergoes a similar rate of change with varying slope length, regardless of the terrain type. Since these curves are constructed from so few data, we have omitted confidence intervals, which would be meaningless here.

The four curves are described by the following simple power expressions:

LUNAR TERRAIN TYPE	EQUATION
Smooth Mare	$S_{med} = 2.9\ DL^{0.25}$
Rough Mare	$S_{med} = 5.4\ DL^{0.25}$
Hummocky Upland	$S_{med} = 8.1\ DL^{0.25}$
Rough Upland	$S_{med} = 10.8\ DL^{0.25}$

Where S_{med} is median slope in degrees, and

DL is slope length in meters.

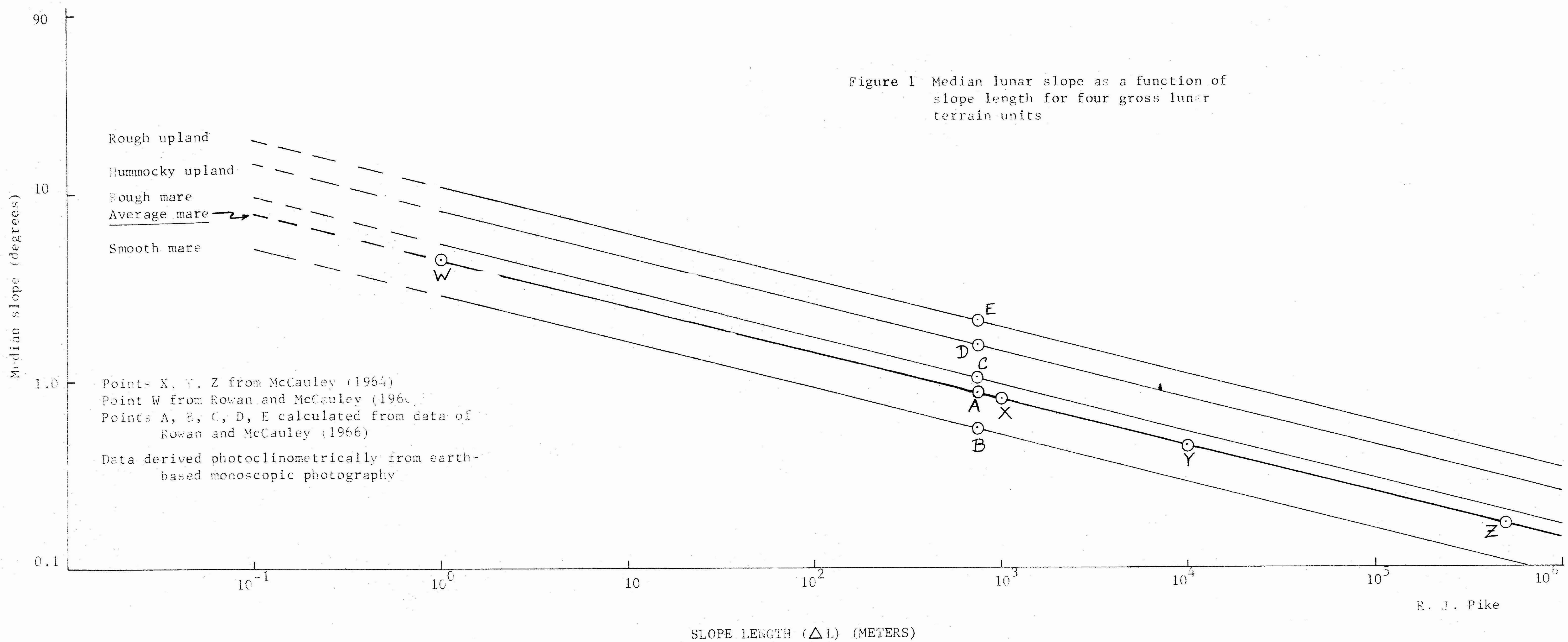


Figure 1 Median lunar slope as a function of slope length for four gross lunar terrain units

R. J. Pike

Although Figure 1 gives useful information concerning the lunar surface, the median is not an especially powerful statistical parameter. Rowan and McCauley (1966) also computed mean slope values for their 53 lunar terrain samples at 0.75 km resolution. Using techniques similar to those by which the previous set of curves was produced, we derive four curves depicting the relationship between mean lunar slope and slope length, Figure 2. The mean slopes at 0.75 km resolution, F, G, H, and I, are listed below for the four gross terrain types:

TERRAIN TYPE	CURVE IN FIG. 2	AVERAGE MEAN SLOPE (at 0.75 km DL)
Smooth mare	(F)	0.70°
Rough mare	(G)	1.29°
Hummocky Upland	(H)	1.96°
Rough Upland	(I)	2.61°

Again, these data were averaged from Rowan and McCauley (1966). It is assumed that the slopes of the curves are similar, and for most of their length, do not depart significantly from the value of -0.25 used for the median slope curves of Figure 1. Confidence in this choice increases somewhat upon calculating the mean slope of samples at base lengths smaller than 0.75 km. Point J is located on a hummocky material near the crater Aristarchus. The slope length is 12.0 meters, and the terrain appears to be older, pre-mare topography best classified as

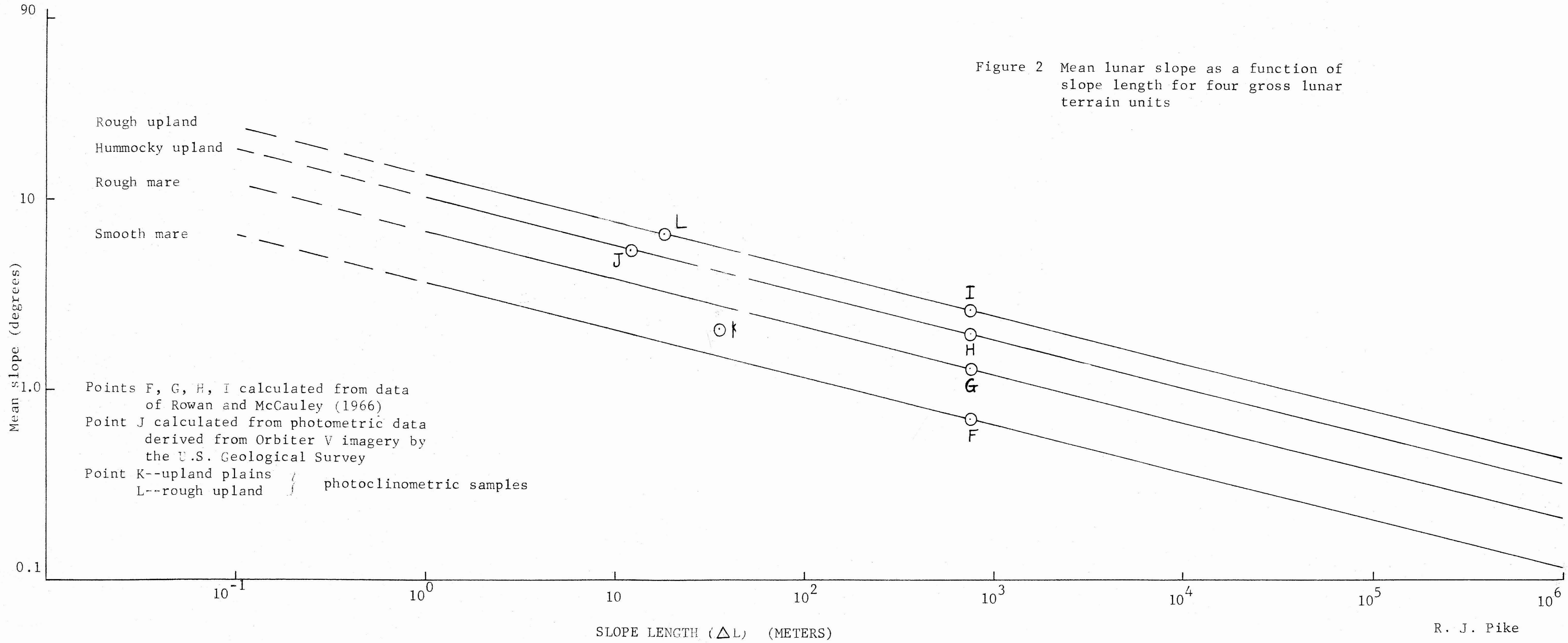


Figure 2 Mean lunar slope as a function of slope length for four gross lunar terrain units

R. J. Pike

Hummocky Upland. Point K is the floor of the crater Ptolemaeus, an upland plains unit rather like an average mare surface. Point L is a sample from the rougher uplands.

Figure 3 shows that the linear model is less satisfactory at base lengths under 10 meters. Point M is the average of 10 smooth mare slope means, and point N the average of 19 rough mare means. These data are at 0.6 m resolution. Since the vertical distance between points M and N is identical to that between G and F on Figure 2 it is likely that the two upland curves also follow below 10 m base lengths, the same trend as do the mare curves.

It is to be emphasized that the curves in Figure 3 are for average lunar terrains within each of the four gross morphologic categories. It is likely, therefore, that specific lunar terrain samples will be both rougher and smoother than the idealized cases depicted here.

Ranges of mean slope values were determined using the data of Rowan and McCauley (1966--their Table 4 and Figure 13) and the 0.6 m resolution spacecraft data generated by the Langley II photoclinometric program. Considerable overlap is present, and is to be expected in a classification as elementary as that available at this time.

The four average mean slope:slope length curves (Figure 3) for base lengths over 10 meters are described by the following simple power functions:

B-41 - missing

TERRAIN TYPE	< 10 m EQUATION
Smooth mare	$\bar{S} = 3.65\ DL^{0.25}$
Rough mare	$\bar{S} = 6.75\ DL^{0.25}$
Hummocky upland	$\bar{S} = 10.40\ DL^{0.25}$
Rough upland	$\bar{S} = 13.80\ DL^{0.25}$

Where $\bar{S}$ is mean slope in degrees, and

DL is slope length in meters

Lunar slope frequency distribution model

Previous experience with terrestrial slope distributions by W. F. Wood (1961, 1962) and the writer (1961) has shown that, given a sufficiently large number of cases ($50 \leq N \leq 100$) all distributions can be "normalized" to yield nearly identical percentage-of-mean slope frequency curves, regardless of how steep or gentle the average slopes might be. The resulting model percentage-frequency curve can be used to predict slope-frequency distributions for any type of terrain for which the mean slope value can be derived.

This technique has been extended to lunar slope distributions in this preliminary investigation. Figure 4 is the model curve derived from existing photoclinometric slope-frequency distributions at 0.6 m resolution. Thirty-two slope-frequency distributions, aggregating 171.025 individual slope values, were plotted for different lunar localities (mostly mare). Each cumulative-frequency curve was then converted into a percentage-frequency curve: cumulative % of cases is plotted on vertical axis, and % of mean slope angle is plotted on the

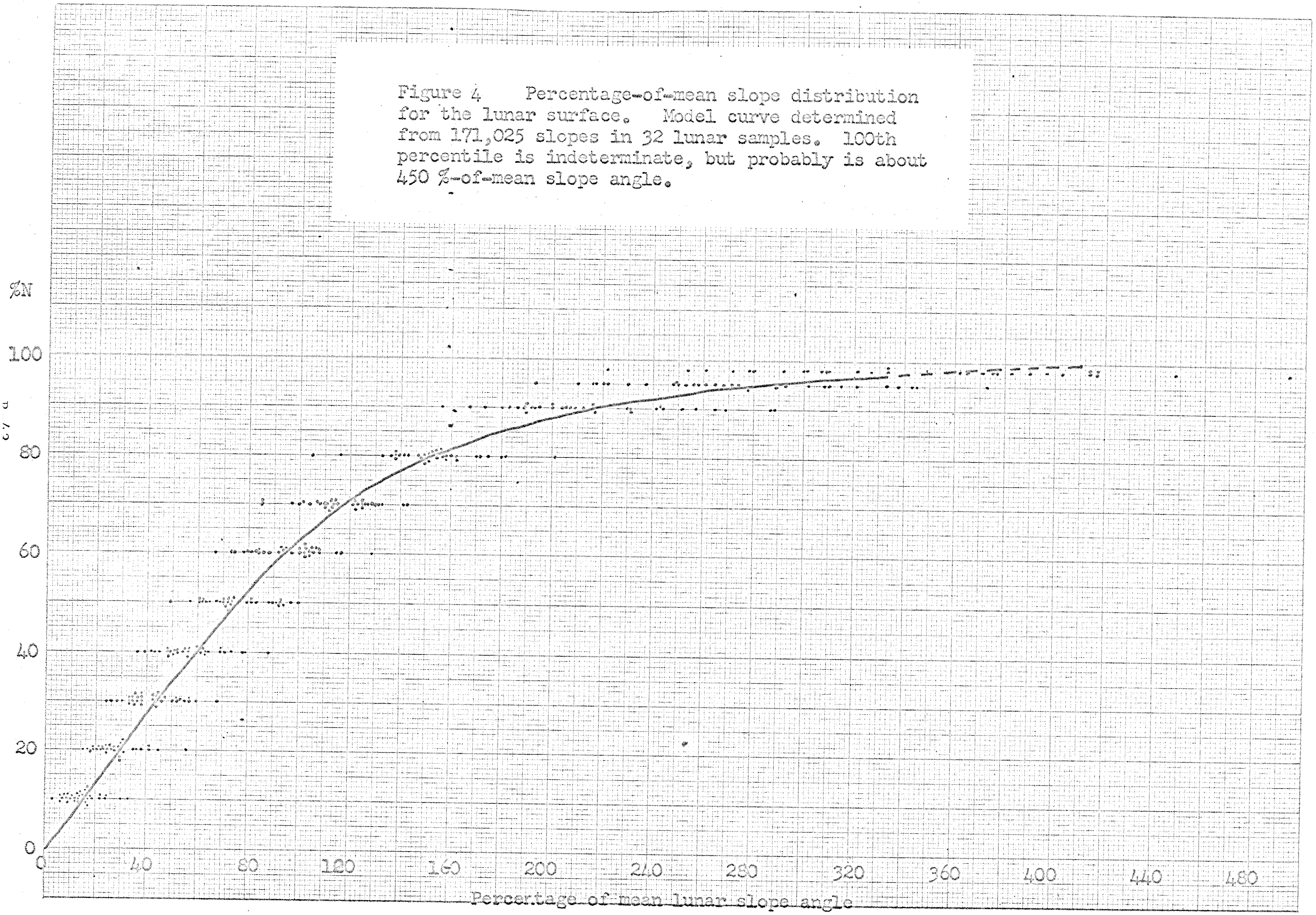


Figure 4   Percentage-of-mean slope distribution for the lunar surface. Model curve determined from 171,025 slopes in 32 lunar samples. 100th percentile is indeterminate, but probably is about 450 %-of-mean slope angle.

horizontal axis (arithmetic coordinates). While all these curves differ slightly from one another, they are remarkably similar in overall configuration. Percentages of mean slope were read from each curve at 11 convenient intervals. These values were averaged at each of the 11 intervals of % N, and the averages plotted as Figure 4, the preliminary lunar slope distribution model. This curve is virtually identical (r = 0.997) to a similar curve derived for terrestrial slope distributions (Table 1). At this stage, no attempt has been made to demonstrate the correspondence of the model lunar curve with the curves from which it was computed. Previous experience with terrestrial distributions suggests that correlation is exceedingly good (probably $> 0.95 = r$) for the lunar data.

This likelihood of high correlation of model with individual curves suggests that the model curve can be used for prediction of real lunar slope-frequency distributions when the mean slope value is known (or can be inferred statistically). Figures 2 and 3 provides estimates of mean slope for four gross lunar terrain units, smooth mare, rougher mare, hummocky upland, and rough upland, at any desired level of generalization. These estimates can be used in conjunction with Figure 4 to compute probable slope-frequency distributions for any of the four terrain types at any slope length. Tables 6 through 8 in the text are nomographs by which this can be accomplished. Values of % mean slope have been converted back to real slope values simply by multiplying the model % mean slope values by all of the mean slope values listed across the top of the table. Slope distributions presented in Tables 6, 7, 8, and Figures 8, 9, 10, and 11 in the text were computed from

Table 1

Comparison of lunar and terrestrial slope distribution models

Cumulative percentage of cases (%N)	Model Percentages of Mean Slope Angle — Lunar Slope Angle (in degrees of arc at a constant base length of about 0.6m-1.0m from photoclinometry of Lunar Orbiter I, II, III, and V imagery) Total N is 171,025	Terrestrial Slope Angle (tangent of valley side slopes comprising linear segments between major slope reversals; variable base length; data from aerial photos of scale 1:20,000) Total N is 2876
(100)	(450)	(531)
98	346	369
95	273	269
90	216	210
80	152	150
70	116	115
60	96	91
50	76	71
40	58	57
30	44	45
20	28	34
10	15	22

Correlation coefficient, r, for above data (omitting 100th percentile) is 0.99774.

mean slope values at one, ten, and fifty meter slope lengths read from Figure 3 of the appendix (Table 4 in the text).

Figure 4 shows that departures of the constituent curves from the average, or model, percentage-of-mean slope curve increases markedly over the 90th percentile of N. Analysis of percentage-of-mean slope values for the 95th, 98th, and 100th percentiles confirms that the dispersion increases sharply with percentile, and that prediction of the 100th percentage-of-mean slope from the model is poor. Analysis shows also that the percentage of mean slope at the 100th percentile of N depends strongly upon the number of slope values included in the sample. Thus, the 100th percentile slope values in Figures 8-11 of the text are only test estimates, relying in part upon terrestrial slope data. Efforts will be made to provide better estimates of the 100th percentile values.

Like all theoretical models, the lunar slope distribution curve (Figure 4) and the predictive nomographs (Tables 6, 7, 8 in text) must be treated with some caution. Visual examination of high-resolution Lunar Orbiter imagery suggests that many terrains which appear exceedingly rough at lower resolutions are in fact quite smooth at slope lengths on the order of a meter. Conversely, other terrain types (crater floors, etc.) which appear smooth at low resolution are quite rough at higher resolution and smaller slope lengths. However, the model derived here should constitute a useful basis from which to proceed in the determination of lunar surface roughness from absolute slope angle data.

Sections C, D, and E

Section C--Crater Frequencies and Morphologies

Section D--Distribution of Blocks on the Lunar Surface

Section E--Increased Travel Distance Due to Craters and Other Obstacles on the Moon

by

H. J. Moore

Section C

Crater frequencies and morphologies

by H. J. Moore

Introduction

This section has been prepared in response to a request for an appraisal of trafficability of the lunar surface for Lunar Roving Vehicles. In the report much of the data presented should help to form an integrated model of the lunar surface. Such an integrated model has not been formed at this time, however. An integrated model for the lunar surface can be formed by combining data on the frequency distributions of craters of various morphologies with the data on crater morphologies and frequency distributions of blocks in and around craters (see Section D). Data in the section do permit an evaluation of normal conditions to be expected from crater frequencies.

In so far as data permit, they are considered in terms of rough (western) maria, smooth (eastern) maria, and uplands. This is done by considering (1) frequency distributions of craters, and (2) morphologies of craters.

Crater frequencies

The topographies of lunar surfaces are characterized by craters of various sizes with various states of preservation. Ideally, the surfaces can be grouped into two types: (1) the young surface where the frequency distribution directly reflects the rate of crater production and (2) the "steady-state" surface which is the result of the combined effects of of crater production and erosion-infilling produced by extensive cratering (Moore, 1964). Crater frequencies can be approximately expressed by equations of the form:

$$N = kD^n \tag{1}$$

where: N is the cumulative frequency of craters,

k is a constant,

D is the crater diameter,

n is an exponent.

For the young surface n is near -3 and for the "steady-state" surface n is near -2. A mature surface would be described by two equations where n = -2 would apply to the smaller size craters and n = -3 would apply to the larger size craters. The equation for the "steady-state" surface:

$$N \approx 10^{-1}D^{-2} \tag{2}$$

where: N is the cumulative number of craters per square meter,

D is the diameter of the craters in meters,

applies to all craters less than a certain size on a surface which has reached that state and the "steady-state" attains for the smaller craters first and extends to larger and larger craters with time. The morphologies of craters for the two idealized surfaces differ. Craters on the young surface are typically, but not entirely, fresh and uneroded. For the "steady-state" surface, craters range from fresh, well preserved craters to those so eroded and filled that they are barely discernible.

As nature would have it, lunar surfaces are typically a mixture of the two types of surfaces or even more complex because of various events. Some frequency distributions are shown in figure C-1 where the counts for Rangers VII, VIII, and IX (Trask, 1966) represent the "steady state" frequency distribution. The counts for II P-6 and III P-12 were taken from Lunar Orbiter screening reports (Screening Group, 1967a, 1967b) and current data suggests they may be low by a factor near 2. Their form is correct, however. In spite of complications, a few generalizations can be made: (1) the "steady-state" frequency distribution describes all surfaces for craters a few meters across and less (Shoemaker et al, 1966, 1967a, 1967b, 1968a, 1968b), most mare surfaces for craters 40 to 100 meters across and less, and for some surfaces, such as the floor of Alphonsus, for craters a few kilometers across and less (Trask, 1966), (2) locally frequency distributions may be significantly less than the "steady-state" distribution such as on steep slopes, (3) most mare and terra have the same frequency of craters in the 10 to 50 meter range, except on steep slopes, (4) rough mare has a significant frequency (10^{-5} craters/meter^2) of subdued craters 80-400 meters across while those of the same size in the smooth maria are less (4×10^{-6} craters/meter^2), and (5) for mare craters larger than 1 km the slope of the frequency distribution curve is steep ($n = -3$).

Recent data have shown that the form of frequency distributions of fresh appearing craters are similar to those for the "steady-state" (Moore and Trask, unpublished data). Crater frequencies of fresh craters made by 5 different observers using Lunar Orbiter photographs (fig. C-2) indicate that the frequency distribution of such craters can be described by:

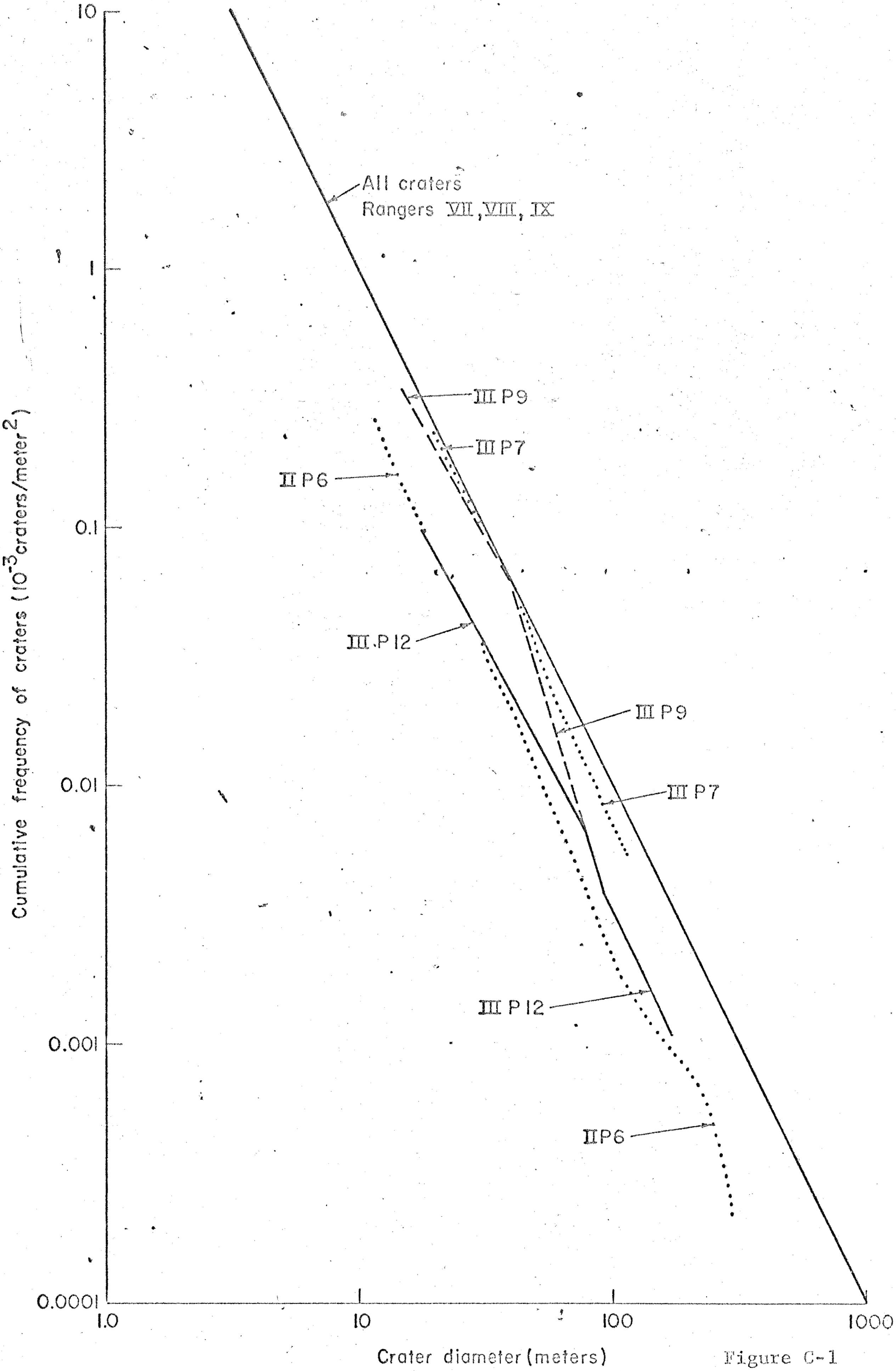
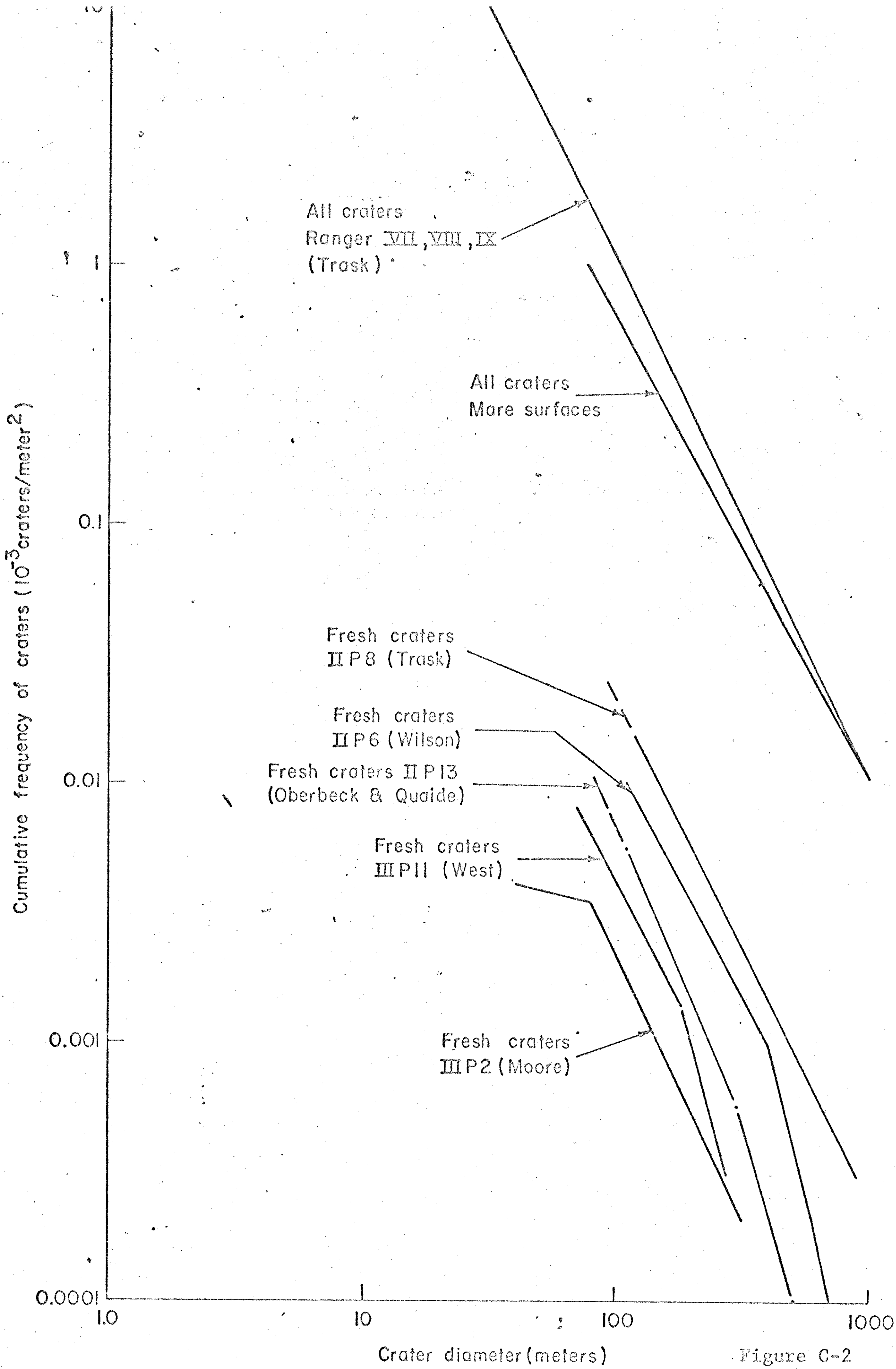

All craters
Rangers VII, VIII, IX
III P9
III P7
II P6
III P12
III P9
III P7
III P12
II P6
10
1
0.1
0.01
0.001
0.0001
1.0
10
100
1000
Cumulative frequency of craters (10^{-3} craters/meter^2)
Crater diameter (meters)

Figure C-1



All craters
Ranger VII, VIII, IX
(Trask)
All craters
Mare surfaces
Fresh craters
II P8 (Trask)
Fresh craters
II P6 (Wilson)
Fresh craters II P13
(Oberbeck & Quaide)
Fresh craters
III P11 (West)
Fresh craters
III P2 (Moore)
Cumulative frequency of craters (10^{-3} craters/meter^2)
1
0.1
0.01
0.001
0.0001
1.0
10
100
1000
Crater diameter (meters)

Figure C-2

$$N = kD^{-2} \tag{3}$$

where: k ranged from 2.1×10^{-6} to 2.0×10^{-5} for the various observers. Although the observers did not agree on the definition of a fresh crater, they did agree on the form of the equation for their distribution. Their work was done as part of studies designed to estimate the thickness of the lunar epilith. Equation (3) is also in agreement with earlier data on fresh (eumorphic) craters shown in Ranger photographs (Trask, 1966).

Equations 2 and 3 are important ingredients for this section since they imply "steady-state" frequency distributions exist not only for all craters but also for craters with given morphologies. Frequency distributions of craters of various morphologies can be estimated by combining the foregoing data in equations 2 and 3 with a theory which postulates that crater life-times are proportional to their original depth and hence diameter (Moore, 1964). In the theory, craters ranging from fresh craters to those so eroded and filled that they are barely discernible leads to equation 2. If crater life-times (t) are proportional to theie diameters according to:

$$t = \frac{10^9}{10^2} D, \tag{4}$$

where: D is in meters, then the variations of frequency of morphologies for each size can be estimated. For craters whose relief has been reduced by a factor of 1/2 or less:

$$N \approx 5 \times 10^{-2} D^{-2}. \tag{5}$$

For those with 3/4 or more of their original relief preserved:

$$N = 2.5 \times 10^{-2} D^{-2} \quad (6)$$

and for those with 31/32 of their original relief or more:

$$N = 3.1 \times 10^{-3} D^{-2}. \quad (7)$$

These distributions are shown in figure C-3 where crater morphologies have been named. Fresh craters have 31/32 or more of their original relief. Young craters have between 31/32 and 3/4 of their original relief. Mature craters have between 3/4 and 1/2 of their original relief. Old craters have 1/2 to almost none of their original relief. It can be seen from figure 3 that 1/2 of the craters of a given size are old, 1/4 of them mature, and 1/4 of the young to fresh.

The foregoing frequencies distributuions can be generalized as follows (see also fig. C-4):

A. Rough mare:

$$N = 10^{-1} D^{-2} \quad (D < 100m)$$

$$N = 10\ D^{-3} \quad (D > 100\ m)$$ 1/

B. Smooth mare:

$$N = 10^{-1}\ D^{-2} \quad (D < 40\ m)$$

$$N = 10^{0.602}\ D^{-3} \quad (100m > D > 40m)$$

$$N \approx 10^{-2.038}\ D^{-1.68} \quad (200m > 100m)$$ 1/

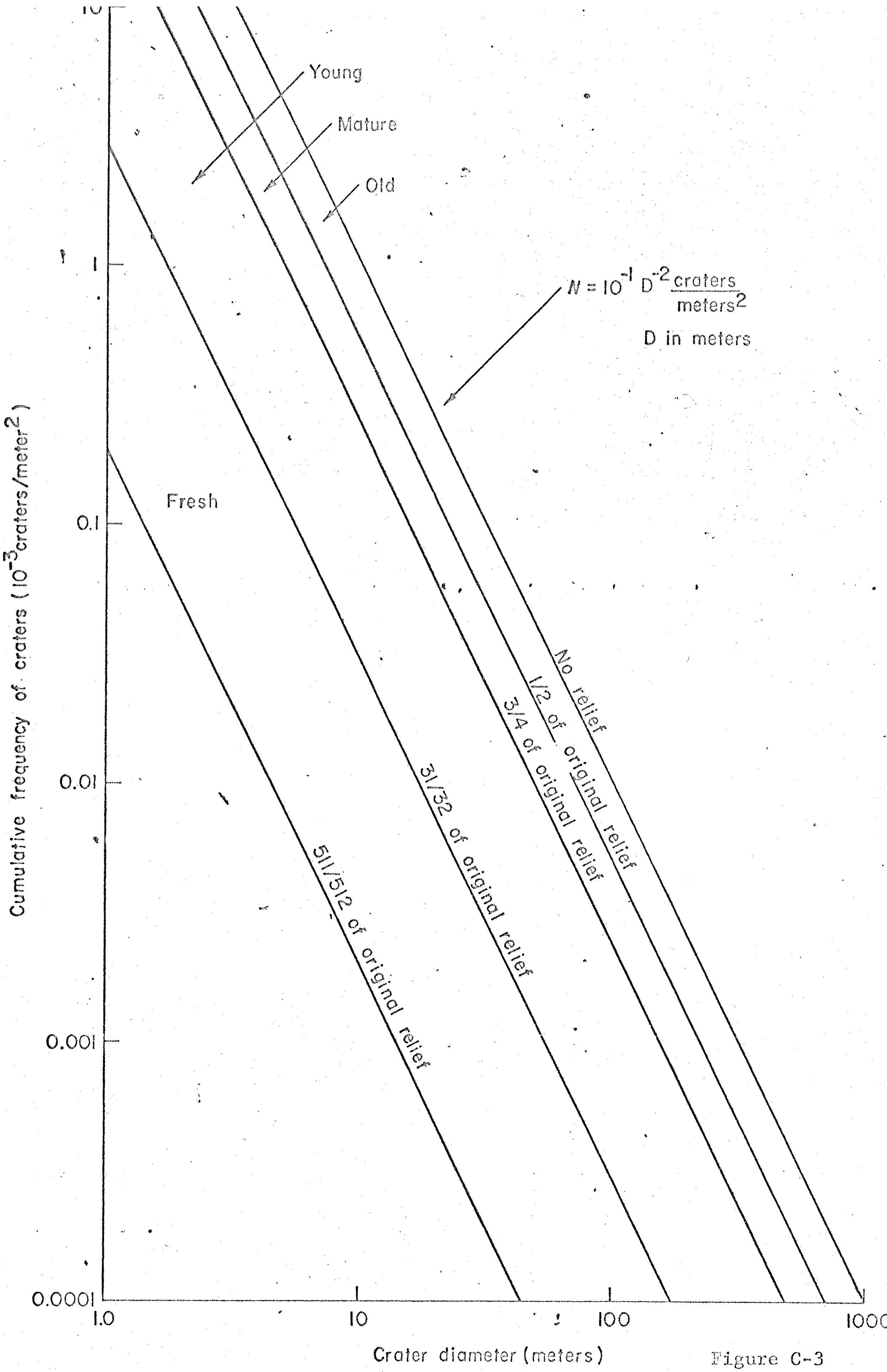
$$N = 10\ D^{-3} \quad (D > 200m).$$

C. Some uplands:

$$N = 10^{-1}\ D^{-2} \quad (D < 1000\ m)$$

$$N = 10^{2}\ D^{-3} \quad (D > 1000\ m)$$

1/ Craters near 80-400 meters on maria are largely subdued in morphology but their walls are often blocky.


Young
Mature
Old
$N = 10^{-1} D^{-2} \frac{\text{craters}}{\text{meters}^2}$
D in meters
Fresh
No relief
1/2 of original relief
3/4 of original relief
31/32 of original relief
511/512 of original relief
Cumulative frequency of craters (10^{-3} craters/meter^2)
10
1
0.1
0.01
0.001
0.0001
1.0
10
100
1000
Crater diameter (meters)
Figure C-3

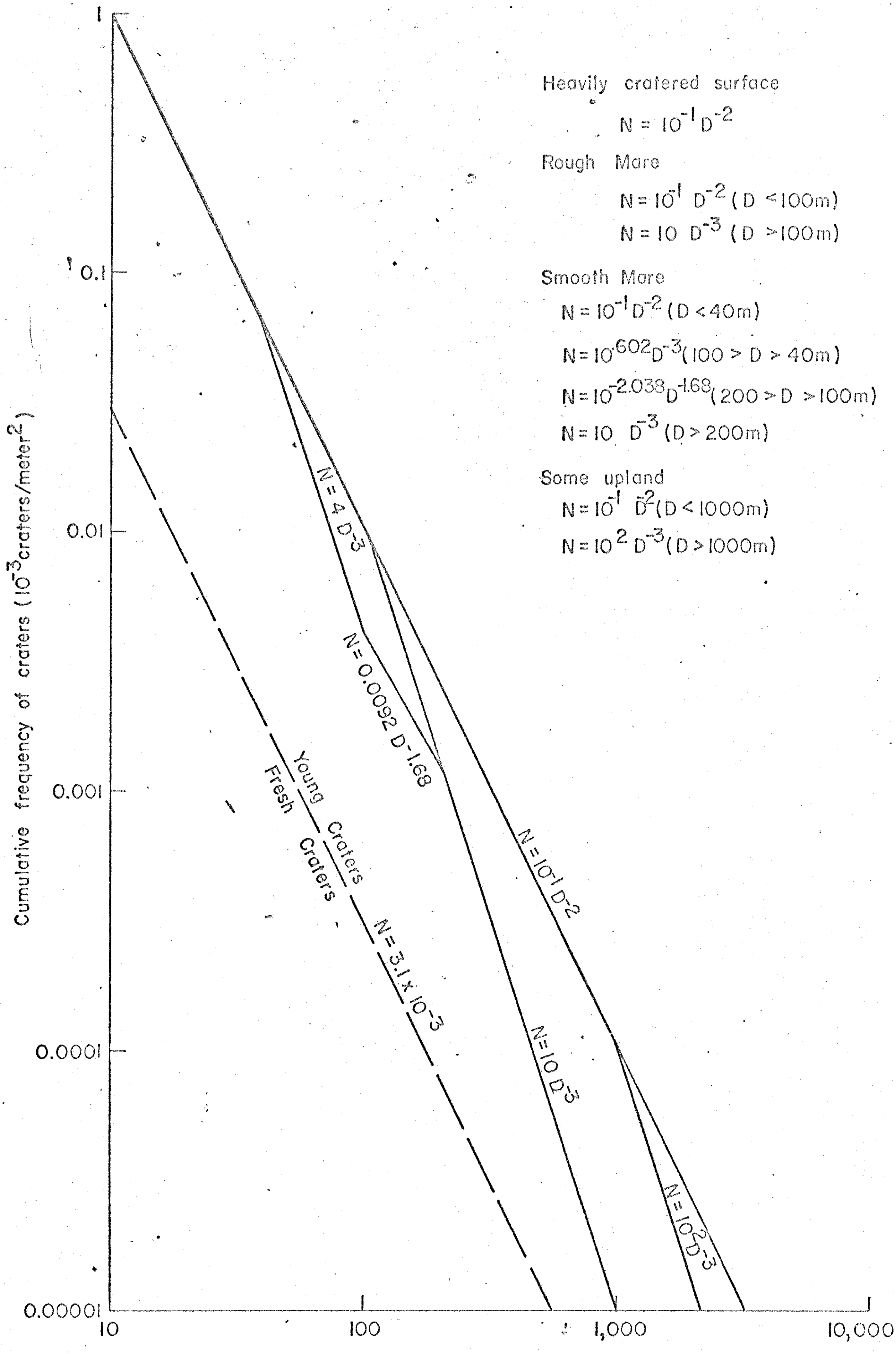

Heavily cratered surface
$N = 10^{-1} D^{-2}$
Rough Mare
$N = 10^{-1} D^{-2}$ (D < 100m)
$N = 10 D^{-3}$ (D > 100m)
Smooth Mare
$N = 10^{-1} D^{-2}$ (D < 40m)
$N = 10^{.602} D^{-3}$ (100 > D > 40m)
$N = 10^{-2.038} D^{-1.68}$ (200 > D > 100m)
$N = 10 D^{-3}$ (D > 200m)
Some upland
$N = 10^{-1} D^{-2}$ (D < 1000m)
$N = 10^{2} D^{-3}$ (D > 1000m)
$N = 4 D^{-3}$
$N = 0.0092 D^{-1.68}$
$N = 10^{-1} D^{-2}$
$N = 10 D^{-3}$
$N = 10^{2} D^{-3}$
Young Craters
Fresh Craters
$N = 3.1 \times 10^{-3}$
Cumulative frequency of craters (10^{-3} craters/meter^2)
1
0.1
0.01
0.001
0.0001
0.00001
10
100
1,000
10,000
Crater diameter (meters)

Figure C-4

D. Slopes $\approx$ 17 degrees and larger:

N is negligible.

E. Heavily cratered surfaces

$$N = 10^{-1} D^{-2} \quad (D < 10{,}000m).$$

F. All craters on "steady state" surfaces (fresh, young, mature, and old craters):

$$N = 10^{-1} D^{-2}.$$

G. All craters on "steady state" surfaces that are fresh:

$$N = 3.1 \times 10^{-3} D^{-2}.$$

H. All craters on "steady state" surfaces that are fresh and young:

$$N = 2.5 \times 10^{-2} D^{-2}.$$

I. All craters on "steady state" surfaces that are fresh, young, and mature:

$$N = 5 \times 10^{-2} D^{-2},$$

where: N is the cumulative frequency of craters/meter^2

D is crater diameter in meters.

Before going to a description of crater morphologies, it is important to realize that the area covered by craters between equal logarithmic intervals is the same when the frequency distribution is of the form:

$$N = kD^{-2} \tag{1}$$

Thus craters between 100 and 200 meters can occupy as much area as those between 10 and 20 meters.

Morphologies of craters

As mentioned previously, craters of a given size can be classed into four types: (1) fresh, (2) young, (3) mature, and (4) old. Fresh craters are identified on the basis of their ejecta which are chacterized by the presence of blocks and secondary impact craters and, when they are small, by rays and bright halos. Morphologies and ejecta of these fresh craters vary with size especially in the maria where layering produces pronounced effects on the crater shapes (Quaide and Oberbeck, 1968). Such size effects are less pronounced in more uniform materials or when the crater depth is either smaller than or much larger than the thickness of the upper layer. For crater diameters that are less than 3.8 - 4.2 times the thickness of the layer, their shape is unaffected by the layer. Flat floored craters are produced when the diameter of the crater is between 3.8 - 4.2 and 8 - 10 times the thickness of the layer. Concentric structures are produced for large craters.

Although there are large local variations of thickness of the soil-like layer (epilith) on the mare, rough mare has a thinner regolith than smooth mare. Few data are available for the uplands so the presence of an epilith will be neglected. The median thickness for a rough mare of 3 - 4 meters was obtained for Lunar Orbiter site III P-12 (Quaide and Oberbeck, 1968) and 6 - 9 meters for II P-8 (Sinus Medii), a quasi-rough mare. In contrast Trask and Wilson (personal comm.) both obtain a median thickness near 5 meters for II P-8 (Sinus Medii). "Seat of the pants" estimates indicate a median thickness of 5 - 6 meters for II P-5 (a smooth mare). For this report, a median thickness of 3 meters will be used for rough mare and 6 for smooth (eastern) mare. Small fresh craters in rough mare then have diameters up to about 12 meters across and those of smooth mare have diameters up to about 24 meters. Studies of missile impact craters (Moore, unpublished data) and laboratory impact craters in sand (Gault, Quaide, Oberbeck and Moore, 1967), show that depth-to-diameter ratios of such craters are near 1/4 to 1/4.4 and rim height to diameter ratios are 6/100 to 2.2/100. Morphologies of such craters are taken to represent the morphologies of small fresh lunar craters. Small craters on the lunar surface which represent the boundary between young and mature craters have their relief reduced to 3/4, yielding depth-to-diameter-ratios between 1/5.3 and 1/5.9, and rim heights between 1.6/100 to 4.5/100. The boundary between mature and old small craters are represented by craters with depth-to-diameter ratios of 1/8.8 to 1/8 while rim height diamter ratios are 0.8/100 to 3/100. This morphological scheme is summarized in figure C-5.

Fresh craters on rough mare between 12 and 70 meters across are flattened and may have concentric structures within the craters. Variations in details of the craters are marked, but several examples of such craters are shown in figures C-6 and C-7. A somewhat flattened crater 13.2 meters across with a depth to diameter ratio of 1/4.9 is shown in figure C-6 along with a 72 meter crater which is both flattened (depth/diameter = 1/6.5) and has concentric structures. The shapes of these craters and most subsequent ones were obtained using shadow techniques and enlarged (≈ 36x) Lunar Orbiter photographs with scales near 0.45 mm/m. Rim heights were usually estimated using rim height-to-diameter ratios of 2.2/100. Craters measuring near 200 meters across (fig. C-7) on rough mare with depth-to-diamter ratios near 1/6.2 normally have well developed internal concentric structures.

Figure C-7 includes a profile of a crater near 130 meters across

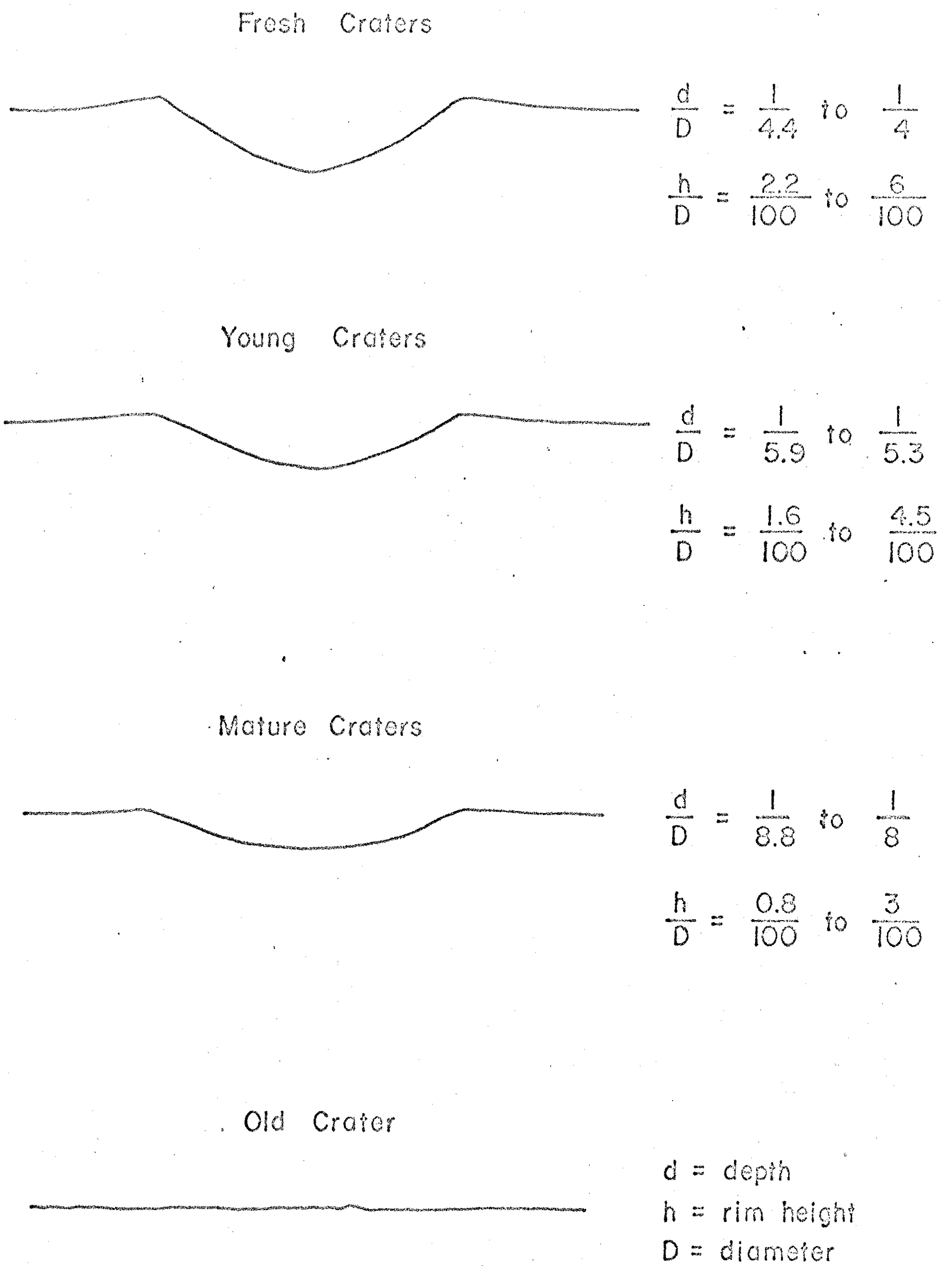

Fresh Craters
$\frac{d}{D} = \frac{1}{4.4}$ to $\frac{1}{4}$
$\frac{h}{D} = \frac{2.2}{100}$ to $\frac{6}{100}$
Young Craters
$\frac{d}{D} = \frac{1}{5.9}$ to $\frac{1}{5.3}$
$\frac{h}{D} = \frac{1.6}{100}$ to $\frac{4.5}{100}$
Mature Craters
$\frac{d}{D} = \frac{1}{8.8}$ to $\frac{1}{8}$
$\frac{h}{D} = \frac{0.8}{100}$ to $\frac{3}{100}$
Old Crater
d = depth
h = rim height
D = diameter

Figure C-5

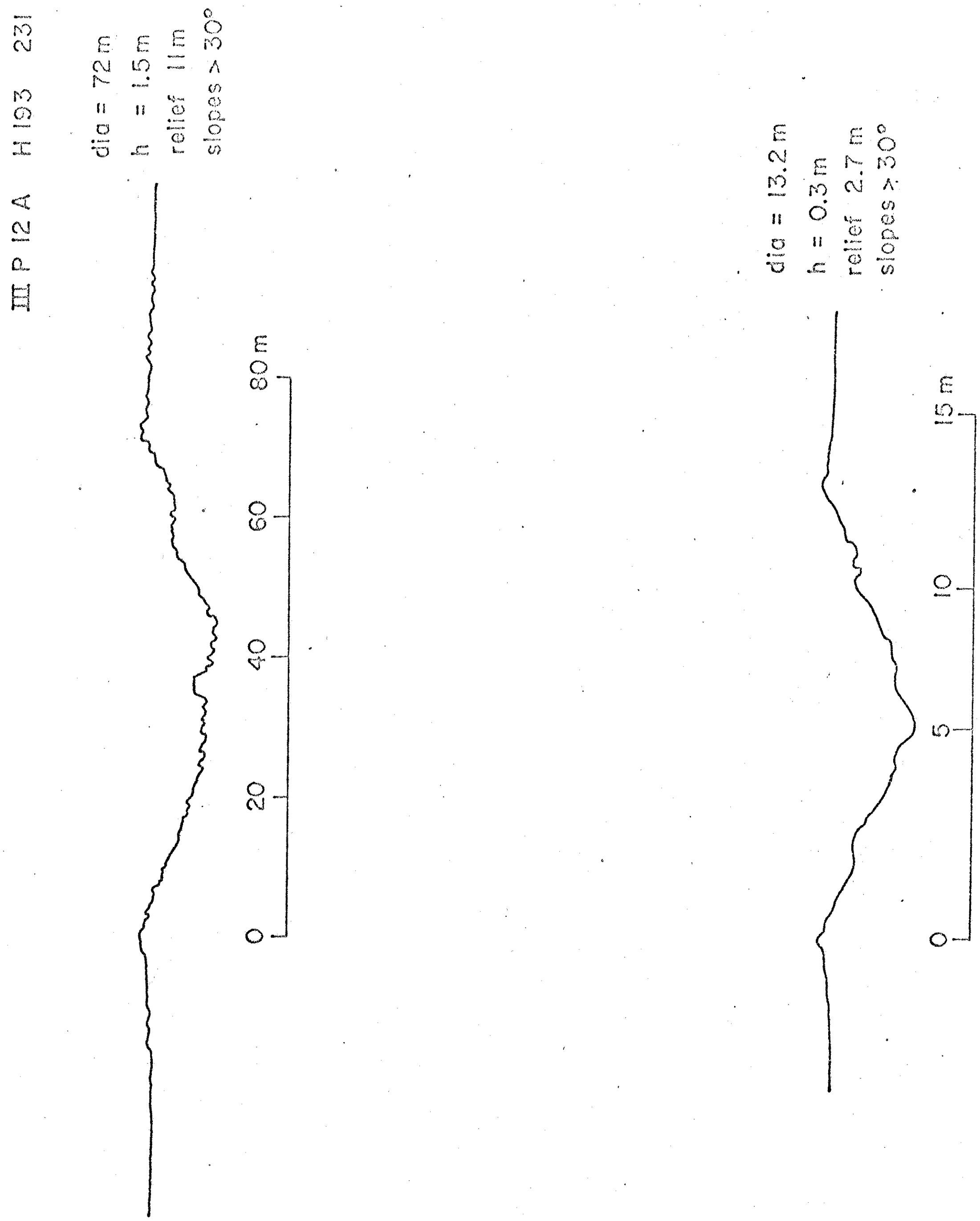

III P 12 A H 193 231
dia = 72 m
h = 1.5 m
relief 11 m
slopes > 30°
0
20
40
60
80 m
dia = 13.2 m
h = 0.3 m
relief 2.7 m
slopes > 30°
0
5
10
15 m

Figure C-6

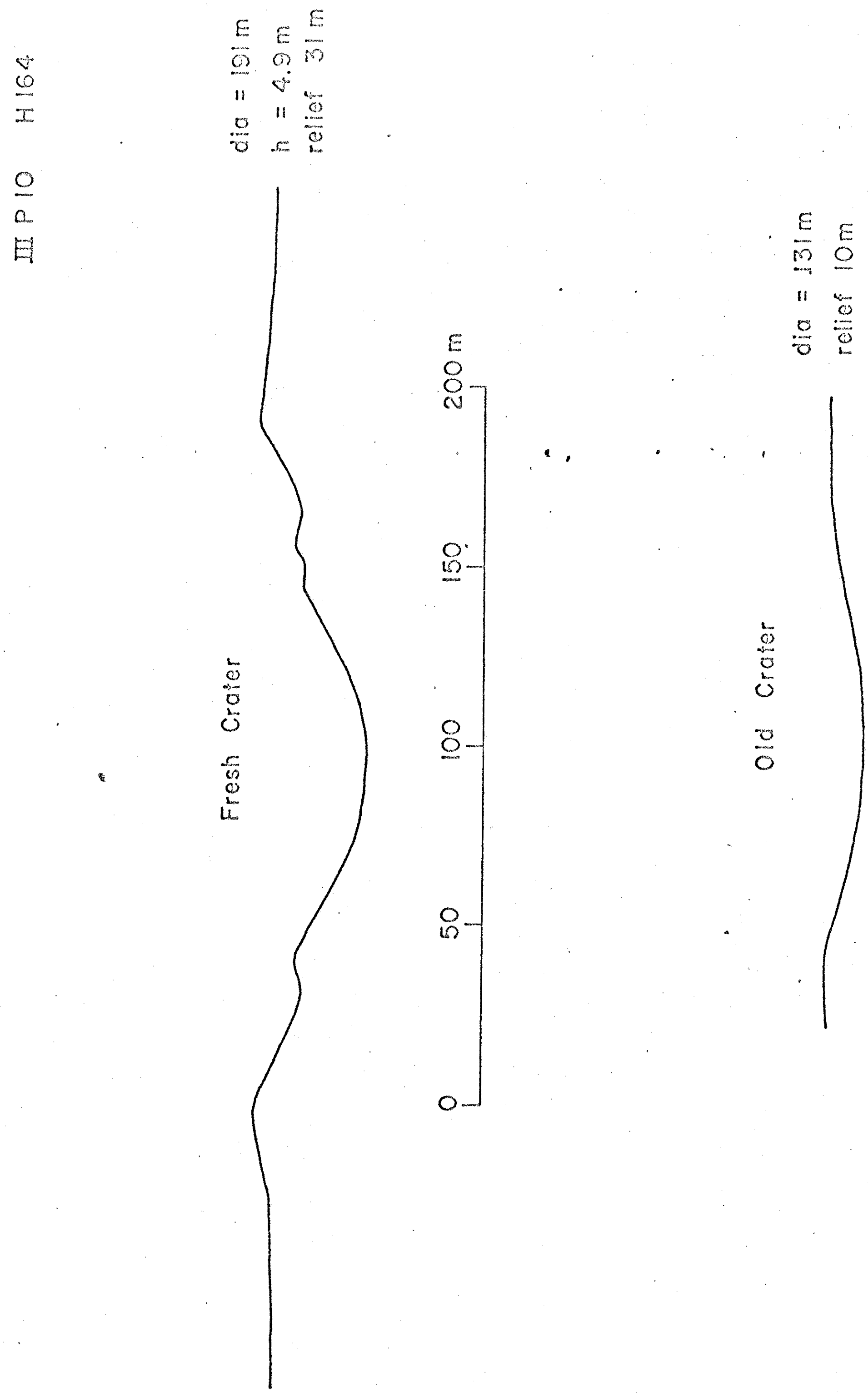
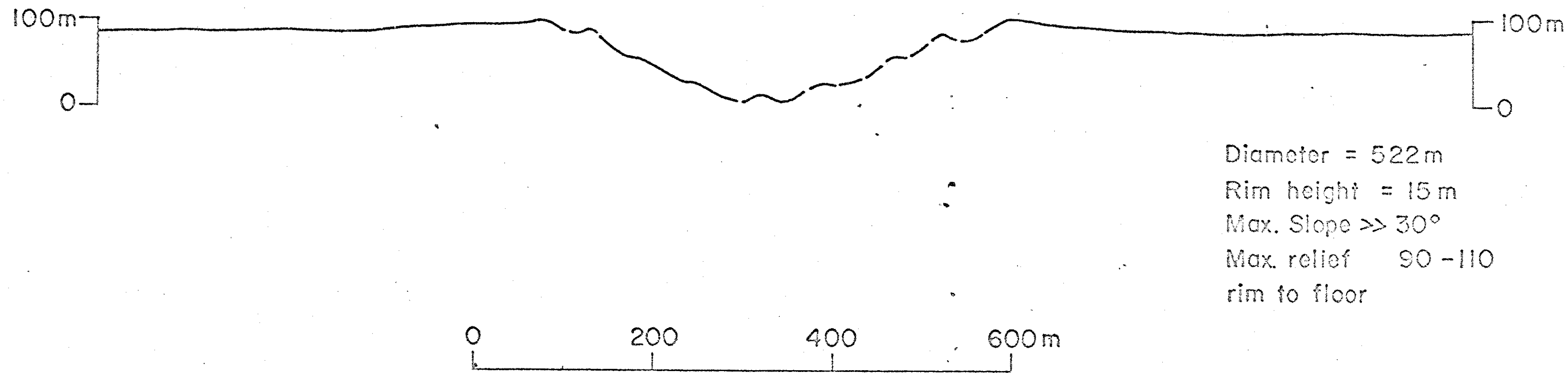

III P 10 H 164
dia = 191 m
h = 4.9 m
relief 31 m
Fresh Crater
200 m
150
100
50
0
dia = 131 m
relief 10m
Old Crater

Figure C-7

and a depth to diameter ratio near 1/13.1. Its depth-to-diameter ratio coupled with the assumption that the crater was originally like the accompanying 190 meter crater suggests it is an old crater but near the boundary between mature and old craters of this size. Depth to diameter ratios of larger fresh craters 500 meters across (fig. C-8) may be larger (1/5.2) than those of the smaller craters and internal structures are common.

For small craters on smooth mare the morphological scheme above would apply to craters with diameters up to 24 meters across because of the greater thickness of the epilith (taken as 6 meters). In addition, larger (24-70 m) crater profiles for smooth mare differ from those of the rough mare in that concentric structures do not appear until the craters are larger. Figure C-9 shows a 30 meter and 137 meter crater from site III P-9B. The depth to diameter ratio of the smaller crater obtained from shadow studies of 36x enlargements of Orbiter photographs is near 1/5.0 while that of the larger fresh crater is near 1/7.4. Concentric structures are weakly developed on the floor of the smaller crater and well developed on the larger crater. Fresh craters near 100 to 150 meters across in sites III P-6 and III P-5A have depth to diameter ratios of 1/8.2 to 1/7.5 and the floors are flattened to domical (figs. C-10 and C-11).

Fresh craters for the uplands will be assumed to have depth to diameter ratios near 1/4.4 for all sizes to several hundred meters. Some justification for uniform crater shapes in the uplands is found for one upland crater which was 236 meters across (fig. C-12) and was estimated



Diameter = 522m
Rim height = 15 m
Max. Slope >> 30°
Max. relief 90 - 110
rim to floor

III P 12A	H189	628	8.6cm
I 3X	M200	227	27.9cm
Stereo pair I 3X	M184	190	

Figure C-8

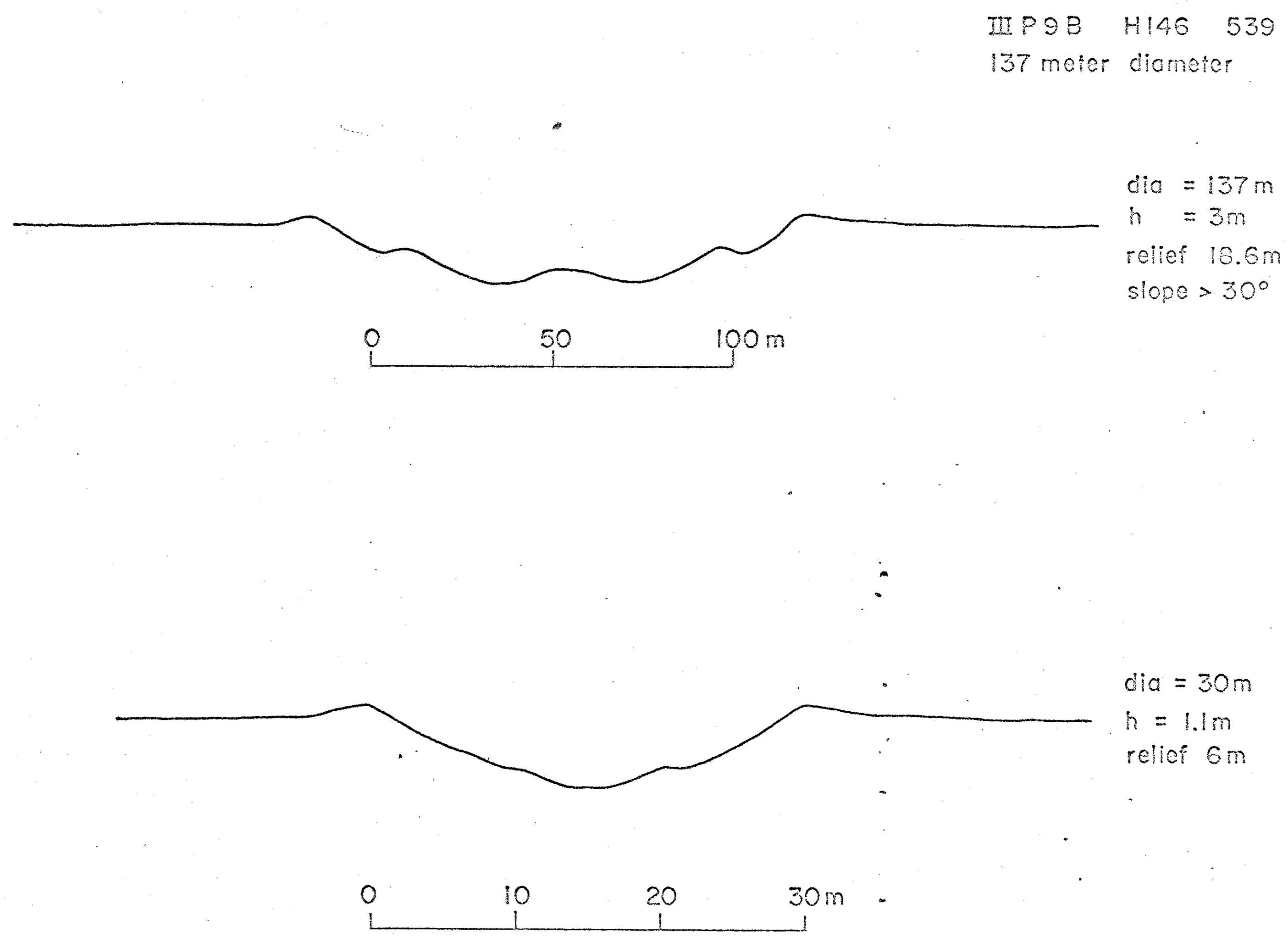

III P 9 B H146 539
137 meter diameter
dia = 137 m
h = 3m
relief 18.6m
slope > 30°
0 50 100 m
dia = 30 m
h = 1.1m
relief 6 m
0 10 20 30 m

Figure C-9

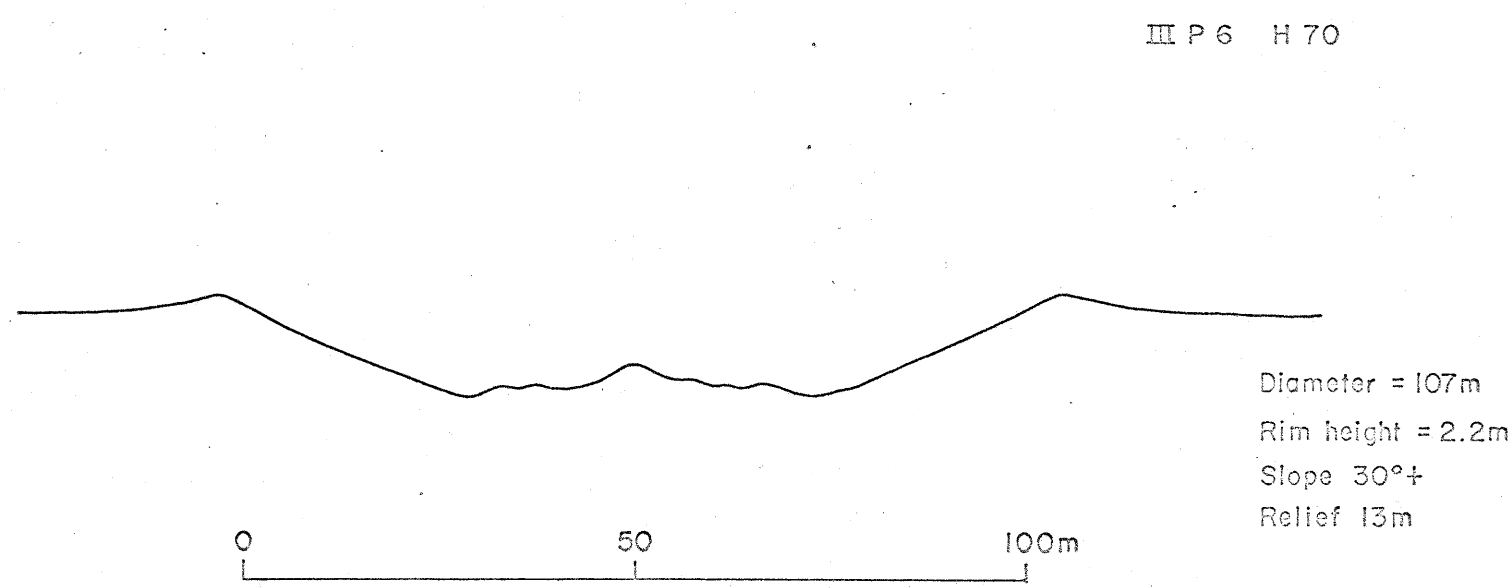

III P 6 H 70
Diameter = 107m
Rim height = 2.2m
Slope 30°+
Relief 13m
0
50
100m

Figure C-10

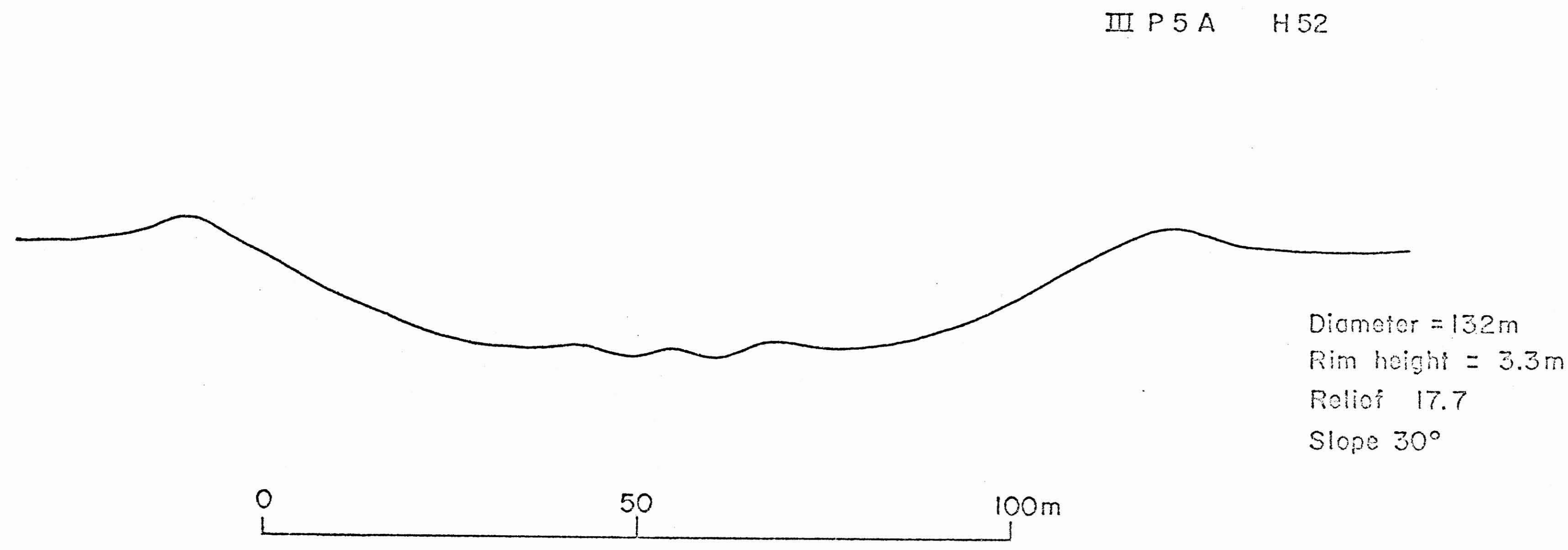

III P 5 A H 52
Diameter = 132m
Rim height = 3.3m
Relief 17.7
Slope 30°
0
50
100m

Figure C-11

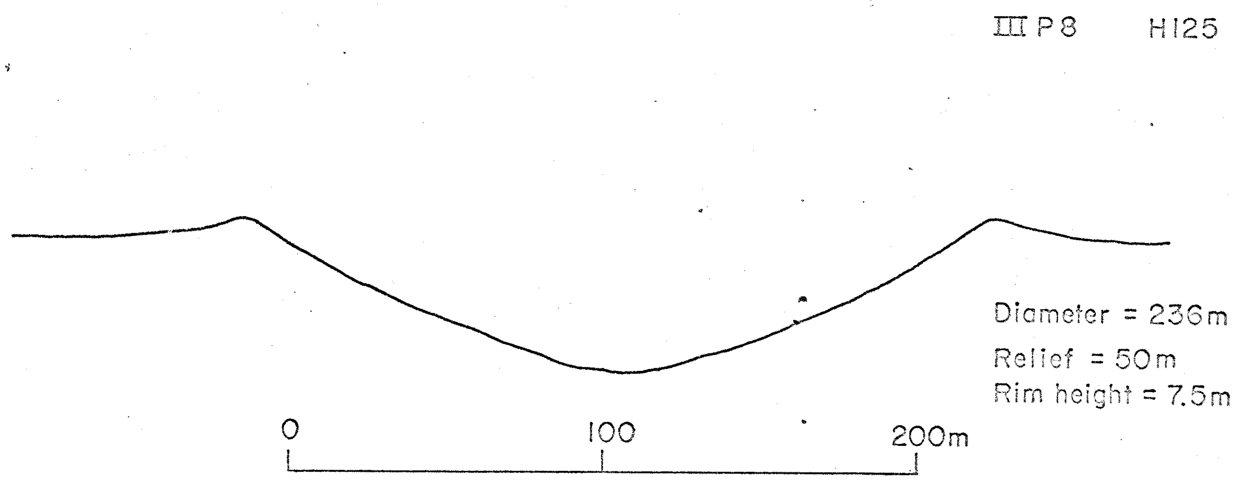

III P8 H125
Diameter = 236m
Relief = 50m
Rim height = 7.5m
0
100
200m

Figure C-12

by shadows to be 50 meters deep yielding a depth-to-diameter ratio of 1/4.7 which is near the 1/4 to 1/4.4 ratio of small craters.

Estimates of relief for young, mature, and old craters for both mare and upland craters in the 20 to 500 meter class can be estimated using the procedures outlined for the small craters but starting with the examples given above for the large craters. Some examples of young, mature, and old craters in the 200-400 meter sizes are given in figures C-13, C-14, C-15 where the original craters are taken to have depth-diameter ratios near 1/5.2. The young crater (fig. C-13) was measured using shadow techniques, which yields a depth-to-diamter ratio of 1/6.1 and a rim height-diameter ratio near 1.3/100. The mature crater in figure C-14 has a depth to diameter of 1/7.7 and the rim is guessed to be 0.8/100 or less. Surveyor III landed in an old crater (fig. C-15) which has a depth to diameter ratio of 1/18 (Shoemaker et al, 1966b); the rim height-diameter ratio is very small and probably less than 0.63/100.

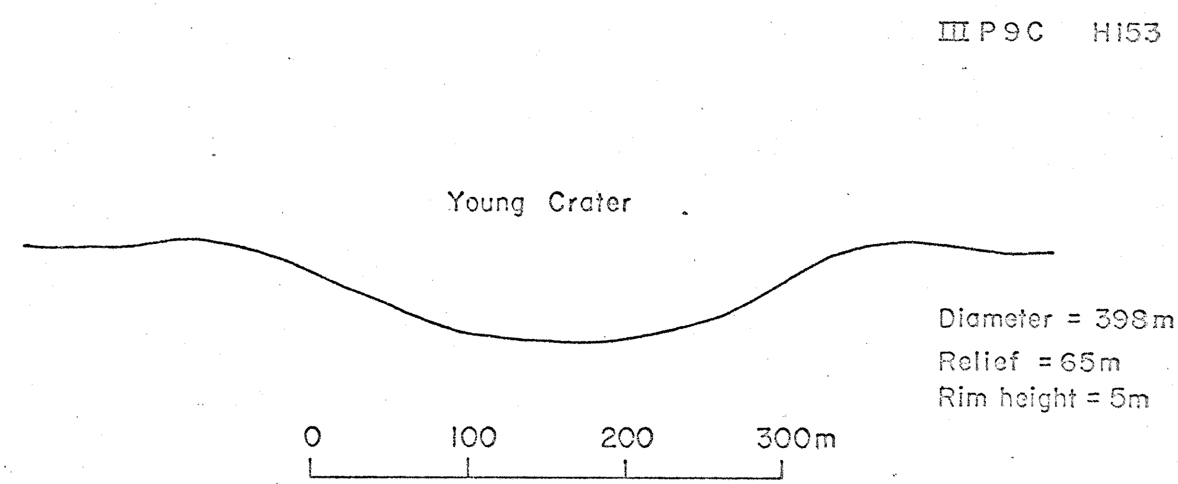

III P9C H153
Young Crater
Diameter = 398m
Relief = 65m
Rim height = 5m
0
100
200
300m

Figure C-13

III P 8 H 124

Mature Crater

Figure C-14

Surveyor III

Old Crater

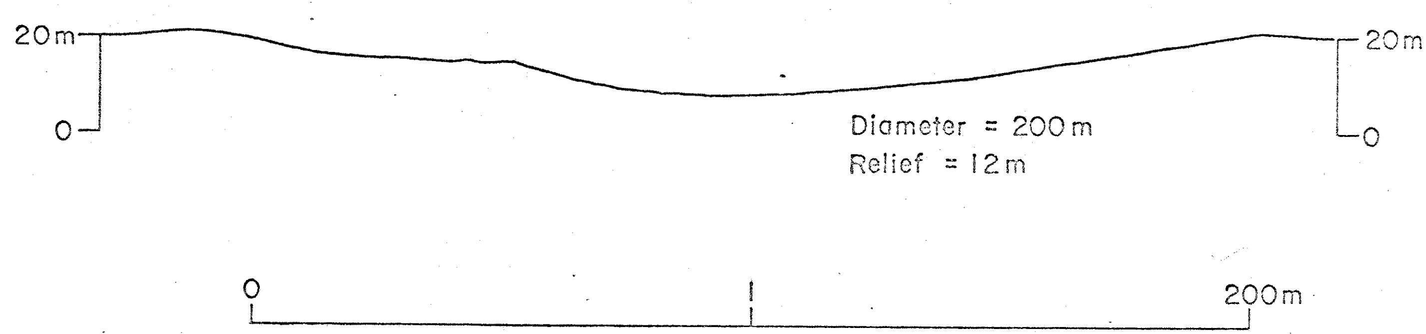


Figure C-15

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Gault, D. E., Quaide, W. L., Oberbeck, V. R., and Moore, H. J., 1966, Luna 9 photographs: evidence for a fragmental surface layer: Science, v. 153, no. 3739, p. 985-988.

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Section D

Distribution of blocks on the lunar surface

by H. J. Moore

Introduction

Although blocks large enough to constitute hazards to lunar roving vehicles are generally rare, they are found locally in concentrations large enough to seriously affect the success of a mission. Such concentrations of blocks are found in and around fresh craters, on the interiors of large subdued craters, in isolated block fields not related to craters, rille walls and other steep slopes and scarps. Examples of block frequencies for these features will be discussed below along with those for average mare.

It should be pointed out before proceeding that much work needs to be done in interpreting block frequencies in terms of vehicle mobility and that some of the interpretations below may be optimistic.

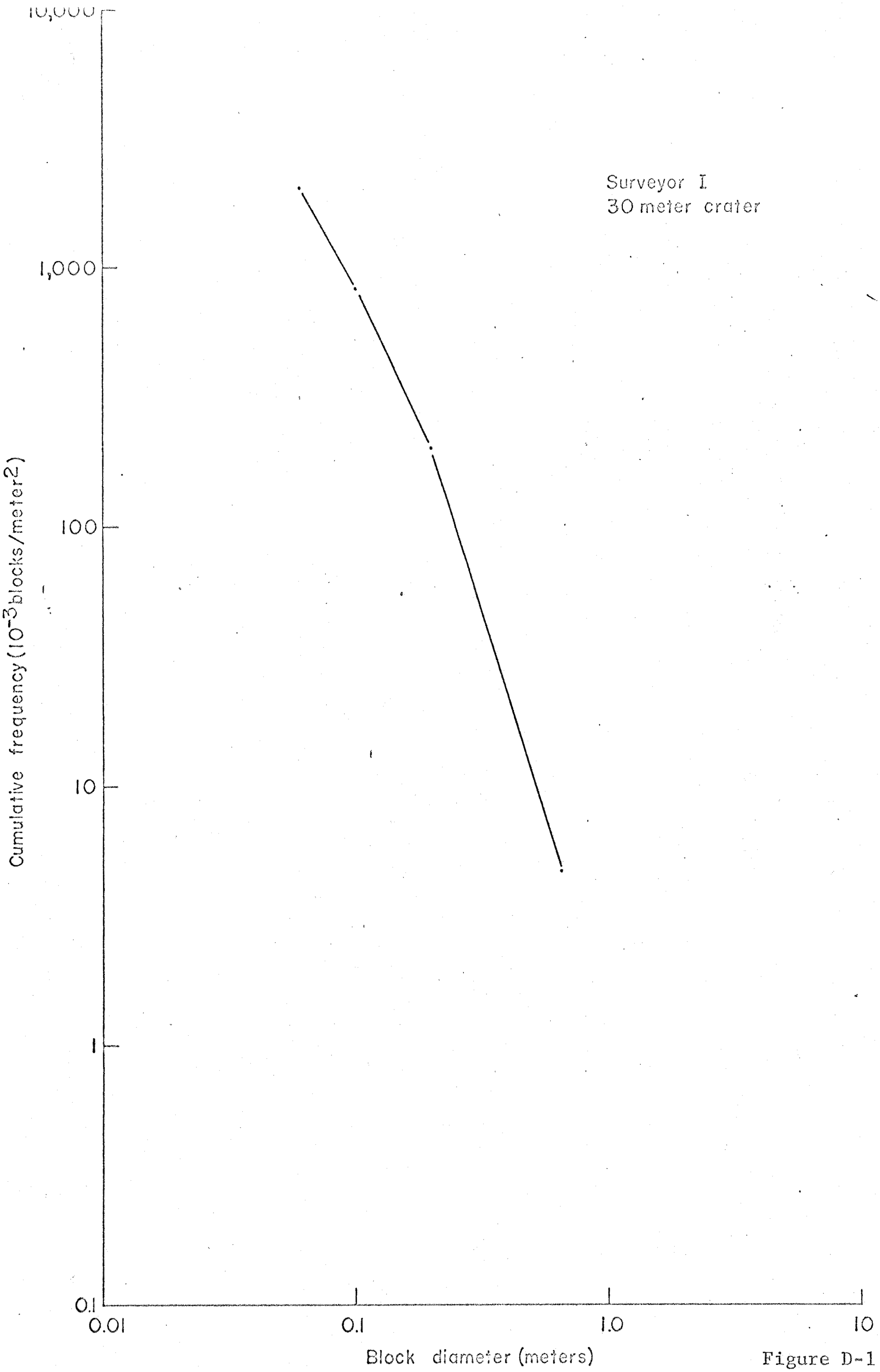
Frequency distribution of blocks around craters

Like crater morphology, the frequency of blocks around fresh craters varies with locale. Craters with abundant blocks characterize rough mare and contrast markedly with craters on smooth mare. Quasi-rough mare, such as Sinus Medii, may have craters with block frequencies between those of the rough and smooth mare. Insufficient data for the uplands are available, but current data suggest block frequencies around the craters are between those of the rough and smooth maria and large concentrations of blocks are found around small craters at the apices of upland hills. Thus large frequencies of blocks should be expected to occur around fresh craters in any terrain.

During the studies, it was also shown that the frequencies of blocks per unit area usually decrease with distance from the crater. The photographic images of the ejecta and craters were divided into rings of crater radii from the center to the rim (o-r), from the rim to one crater radius beyond the rim (r-2r), and so forth to a ring at one and one-half to two diameters (4r-5r) in order to estimate the outward changes. The results of such changes are listed and shown in figures and tables which follow.

Rough mare.--Block frequencies around craters are not only a function of locale and distance from the rim but also size. Such changes are clearly illustrated by rough mare craters. The near-rim flank of the 30 meter crater east of Surveyor I (Elliot Morris and H. J. Moore, unpubl. data) has blocks up to 0.64 meters on the rim (fig. D-1 and Table D-1). The rim and flanks are not particularly rough and less than 1/2 percent of the area is covered by blocks large enough ($\approx$ .5m) to be considered hazardous (fig. D-1 and Table D-1a). In contrast, counts on 36x enlargements of Lunar Orbiter photographs of a larger crater about 72.3 meters across show that frequencies of blocks larger than 1.2 meters on its near rim (r-2r) reach 6.0×10^{-3} blocks/meter^2 and higher; and 2.8 percent of the area is covered by such blocks (figs. D-2a, D-2b, and Table D-IIa, D-IIb). Although comparisons between the two counts are difficult because of resolution differences, it is clear that the 72.3 meter crater is blockier and more hazardous to roving vehicles.

Although block frequencies normally increase with size, this is not



10,000
1,000
100
10
1
0.1
Cumulative frequency (10^{-3} blocks/meter^2)
Surveyor I
30 meter crater
0.01
0.1
1.0
10
Block diameter (meters)

Figure D-1

Table D-Ia

Surveyor I 30 meter crater

Cumulative frequency in blocks/meter^2

Block size meters	r - 2r
0.64	4.7×10^{-3}
0.20	200×10^{-3}
0.10	820×10^{-3}
0.05	2000×10^{-3}

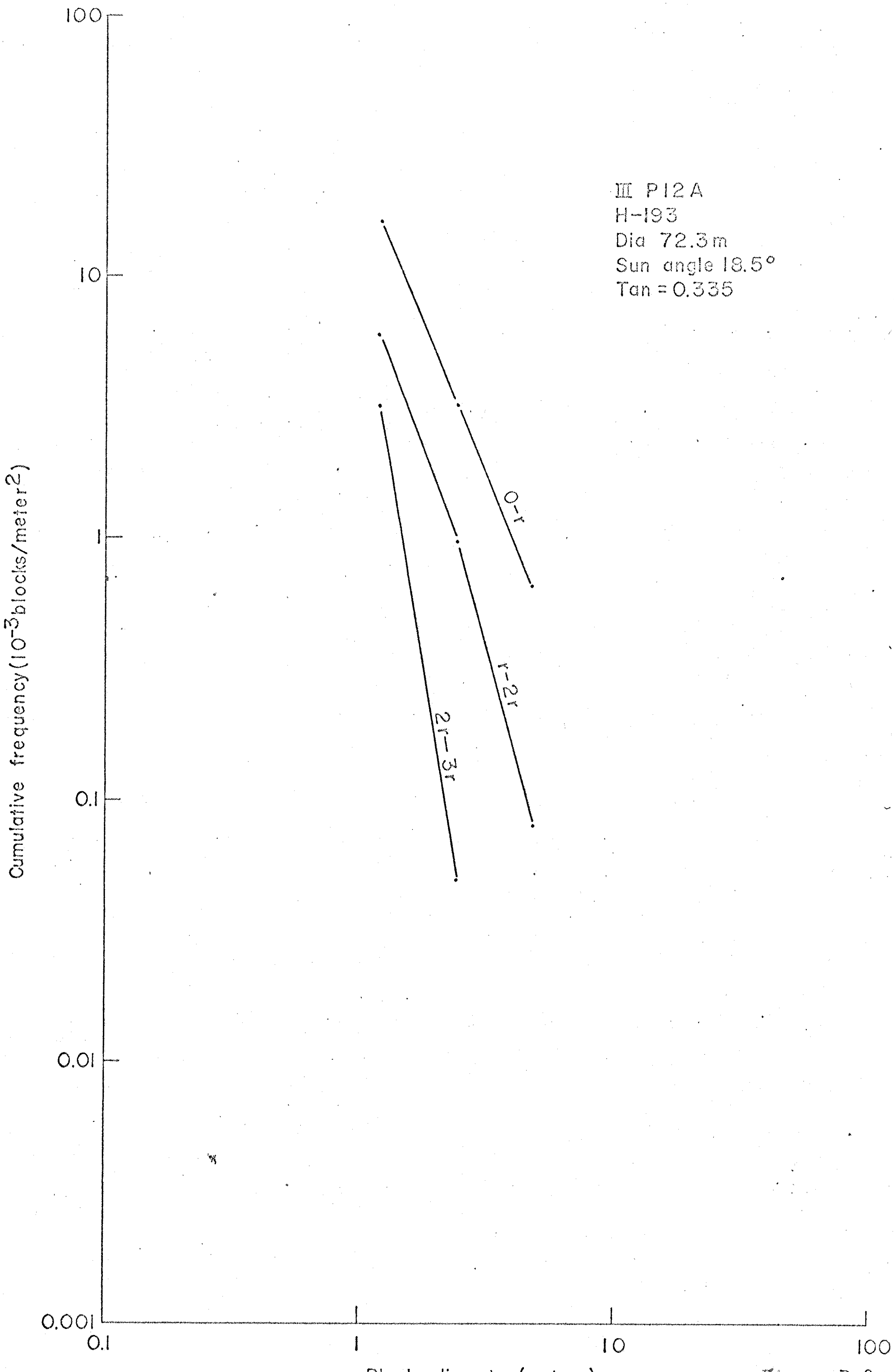
Table D-Ib

III P-12b.1 H 204 107.4 meter crater[1/]

Cumulative frequency of blocks/meter^2

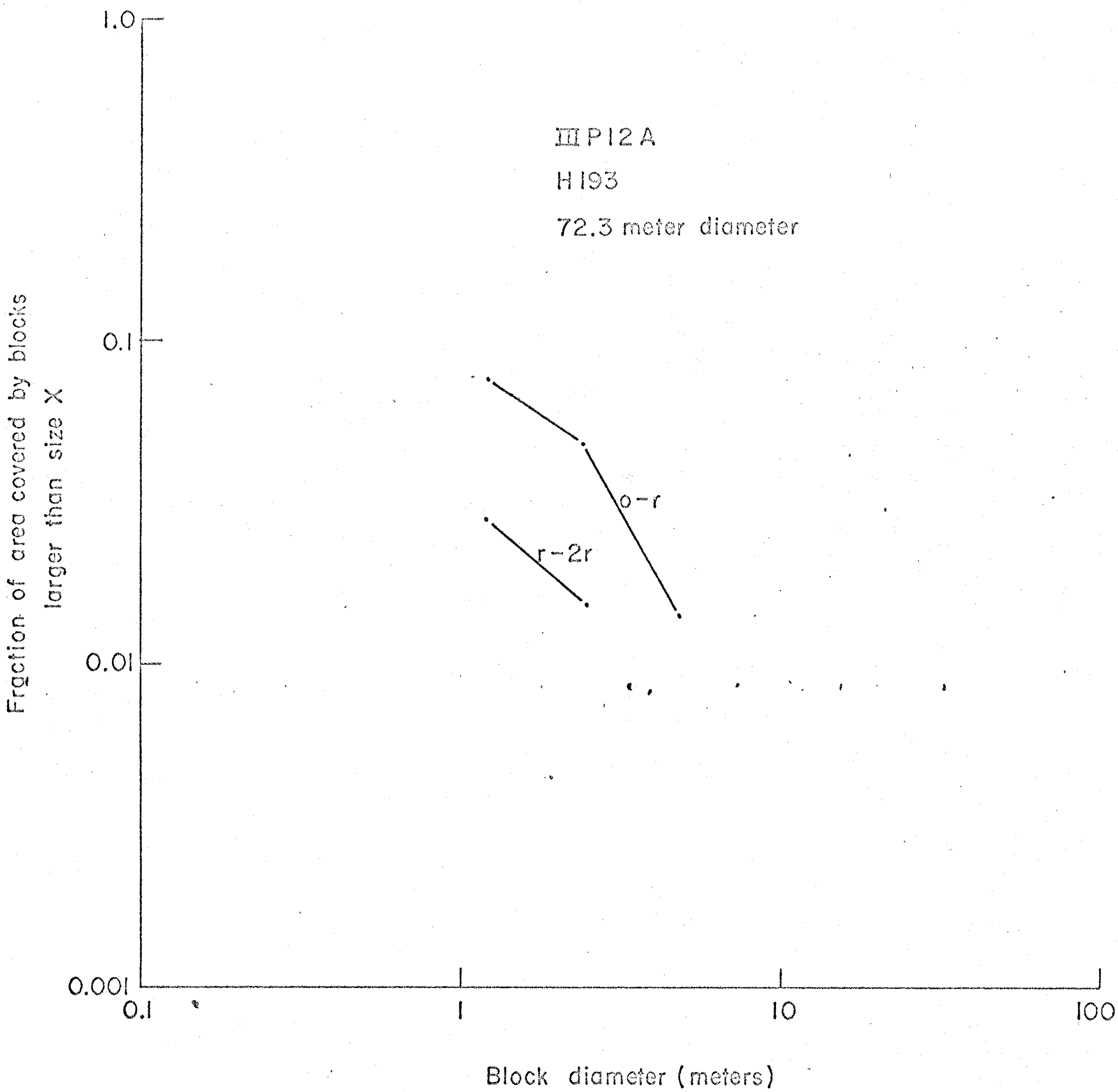
Block diameter (meters)	crater o - 4	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
4.8	--	--	--	--	--	--
2.4	2.0×10^{-3}	0.30×10^{-3}	0.11×10^{-3}	0.042×10^{-3}	--	0.12×10^{-3}
1.2	7.4×10^{-3}	3.12×10^{-3}	1.02×10^{-3}	0.36×10^{-3}	0.24×10^{-3}	0.82×10^{-3}

1/ Sun angle 20.65°, tan = 0.376.



III P12A
H-193
Dia 72.3m
Sun angle 18.5°
Tan = 0.335
0-r
r-2r
2r-3r
100
10
1
0.1
0.01
0.001
0.1
1
10
100
Cumulative frequency (10^{-3} blocks/meter^2)
Block diameter (meters)

Figure D-2a



III P12A
H193
72.3 meter diameter
o-r
r-2r
1.0
0.1
0.01
0.001
Fraction of area covered by blocks larger than size X
0.1
1
10
100
Block diameter (meters)

Figure D-2b

Table D-IIa

III P-12A H 193 72.3 meter crater

Cumulative frequency of blocks/meters^2

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
7.2	--	--	--	--	--	--
4.8	0.65×10^{-3}	0.08×10^{-3}	--	--	--	0.01×10^{-3}
2.4	3.2×10^{-3}	0.97×10^{-3}	0.05×10^{-3}	--	--	0.04×10^{-3}
1.2	16.2×10^{-3}	6.0×10^{-3}	3.2×10^{-3}	1.7×10^{-3}	0.6×10^{-3}	2.02×10^{-3}

Table D-IIb

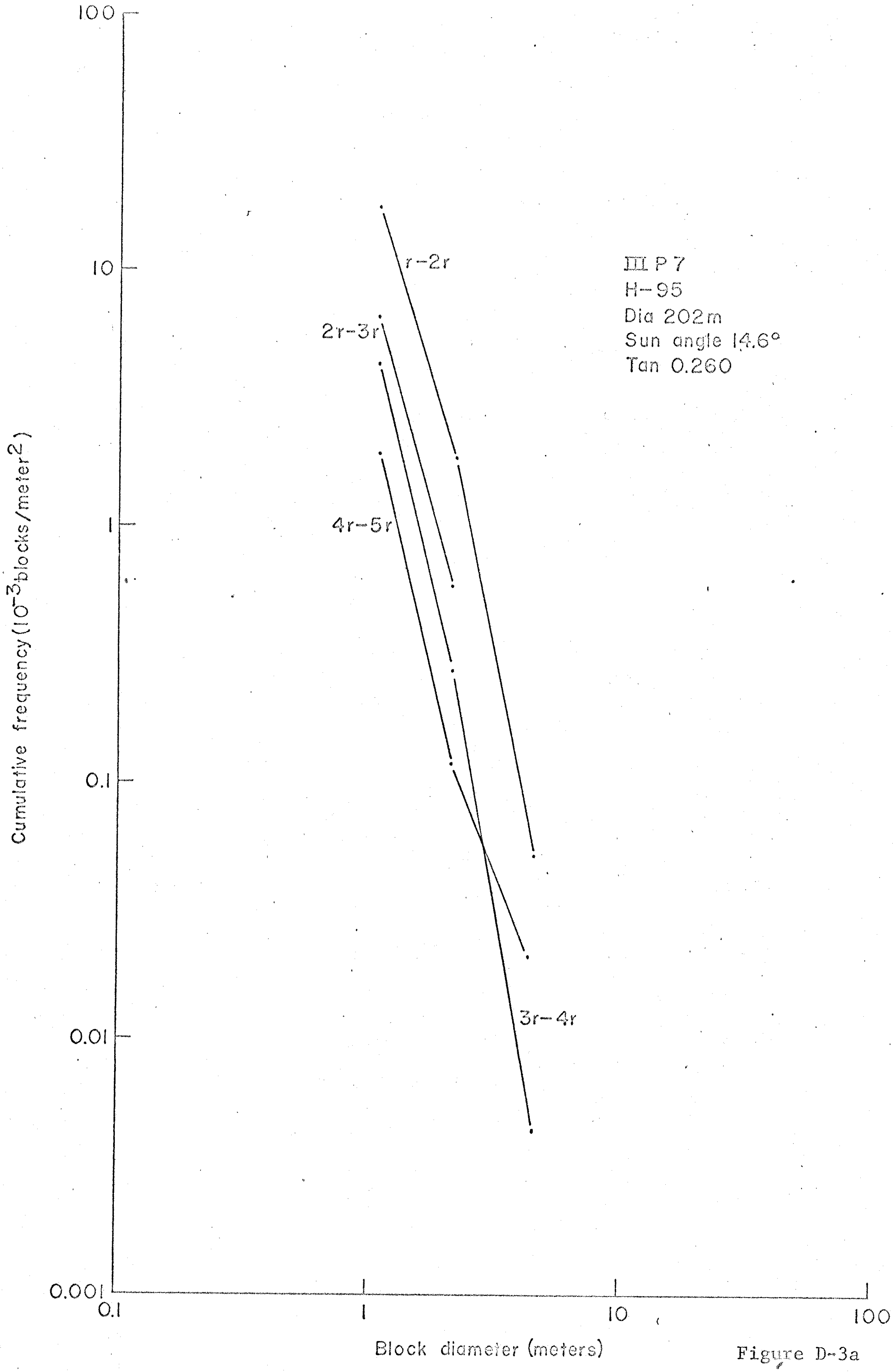
Fraction of area covered by blocks
larger than size x

Block diameter (meters)	crater 0 - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
7.2	--	--	--	--	--	--
4.8	0.014	--	--	--	--	--
2.4	0.042	0.015	--	--	--	0.003
1.2	0.076	0.028	0.006	--	--	0.004

always true. Table D-Ib represents such a crater where it can be seen that the block frequencies from r to 2r are less than those of the smaller 72.3 meter crater in Table D-IIa.

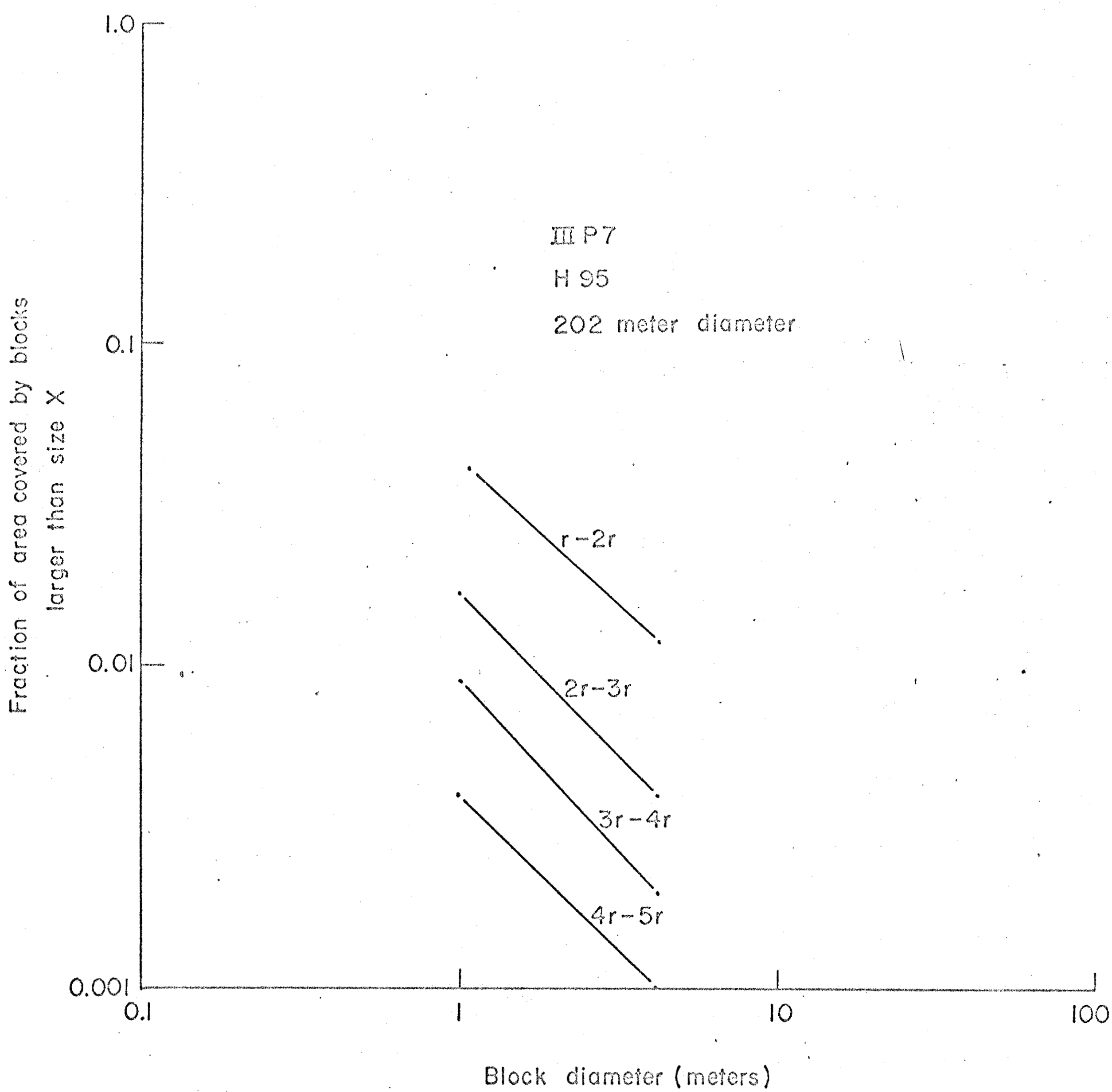
However with continuing increase in size, the general tendency for increase of block frequencies becomes clear. For craters near 200 meters across (figs. D-3a, D-3b, and Tables D-IIIa, D-IIIb) near rim (r-2r) frequencies of blocks larger than 1.06 meters reach 17.3×10^{-3} blocks/meter^2 and about 4.1 percent of the area is covered by such blocks. The crater in figures D-3a and D-3b is on a quasi-rough mare (Sinus Medii). Frequencies of blocks larger than 2.4 meters around larger craters near 380 and 500 meters across are as high as 2.9×10^{-3} blocks/meter^2 and between 5 and 6 percent of the area is covered by such blocks (figs. D-4a, D-4b, D-5a, D-5b, and Tables D-IVa, D-IVb, D-Va, and D-Vb). The counts for these two large craters were obtained on 14x enlargements so that the counts stop at about 2 meters but attempts to count the smaller blocks suggest their frequency increases rapidly to 1 meter with a slope of about -3 on the frequency curves. Thus frequencies near 20×10^{-3} blocks/meter^2 for blocks larger than 1 meter should be expected and about 10 percent of the area should be covered by such blocks.

Smooth mare.--The low frequencies of blocks around craters on smooth mare contrast sharply with the high frequencies of those on the rough mare. The difference is so marked that it is difficult to find fresh craters with blocks around them, especially for craters near 70-100 meters across and less. For the smooth mare (figs. D-6a, D-6b, D-7 , D-8a, and D-8b, and Tables D-VIa, D-VIb, D-VII-a, D-VIIb, and D-VIIIa, and D-VIIIb),



100
10
1
0.1
0.01
0.001
0.1
1
10
100
Cumulative frequency (10^{-3} blocks/meter^2)
Block diameter (meters)
r-2r
2r-3r
4r-5r
3r-4r
III P 7
H-95
Dia 202m
Sun angle 14.6°
Tan 0.260

Figure D-3a



III P7
H 95
202 meter diameter
Fraction of area covered by blocks larger than size X
1.0
0.1
0.01
0.001
r-2r
2r-3r
3r-4r
4r-5r
0.1
1
10
100
Block diameter (meters)

Figure D-3b

Table D-IIIa

III P-7 H 95 202 meter diameter crater

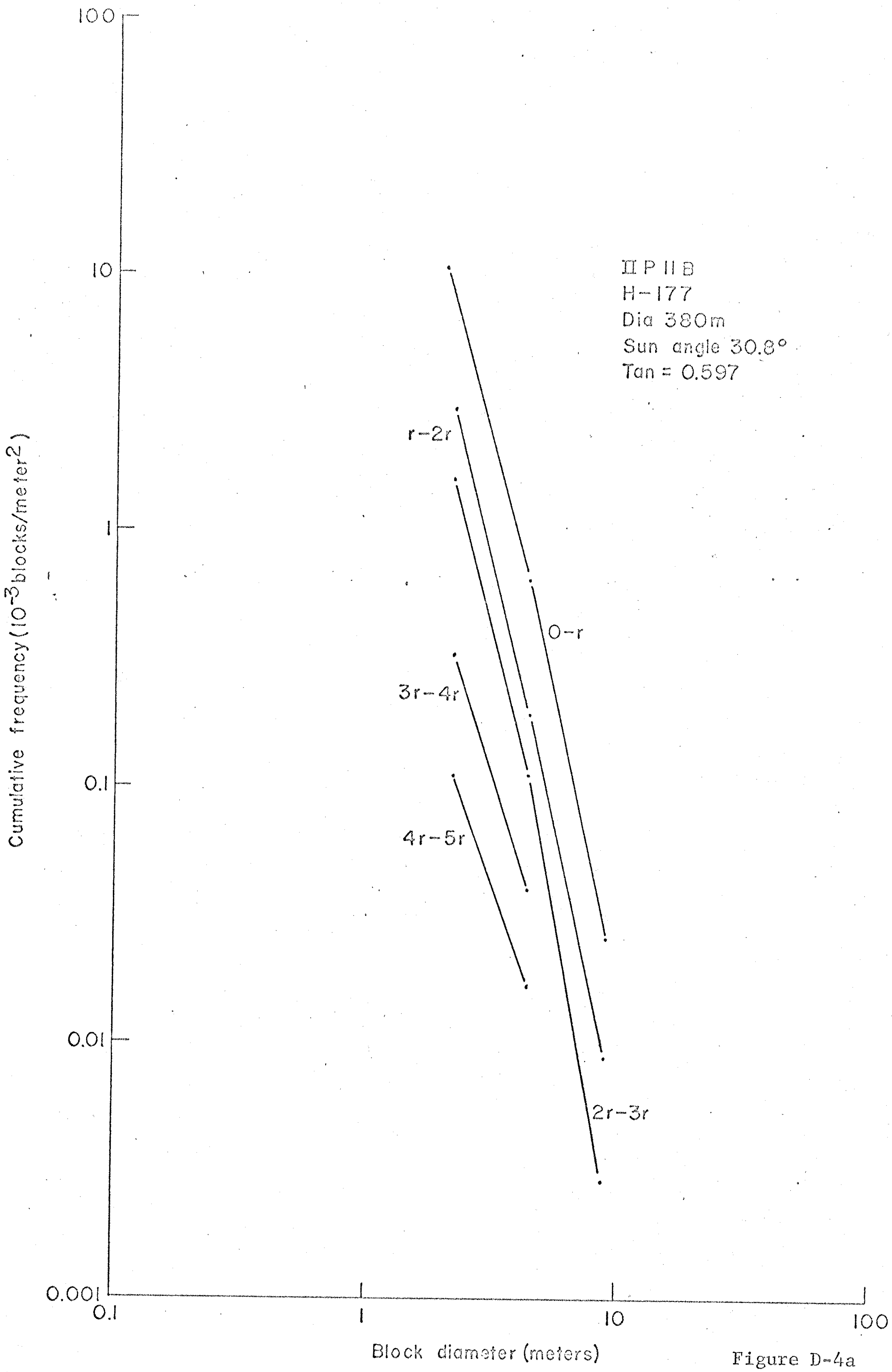
Cumulative frequency of blocks/meter^2

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
8.52		--	--	--	--	--
4.26		0.052×10^{-3}	--	0.0045×10^{-3}	0.021×10^{-3}	0.015×10^{-3}
2.13		1.81×10^{-3}	0.59×10^{-3}	0.273×10^{-3}	0.118×10^{-3}	0.47×10^{-3}
1.06		17.3×10^{-3}	7.53×10^{-3}	4.30×10^{-3}	1.93×10^{-3}	5.65×10^{-3}

Table D-IIIb

Fraction of area covered by blocks larger than size x

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
4.26		--	--	--	--	--
2.13		0.012	0.004	0.002	0.001	0.003
1.06		0.041	0.017	0.009	0.004	0.011



II P II B
H-177
Dia 380m
Sun angle 30.8°
Tan = 0.597
r-2r
0-r
3r-4r
4r-5r
2r-3r
Cumulative frequency (10^-3 blocks/meter^2)
100
10
1
0.1
0.01
0.001
0.1
1
10
100
Block diameter (meters)

Figure D-4a

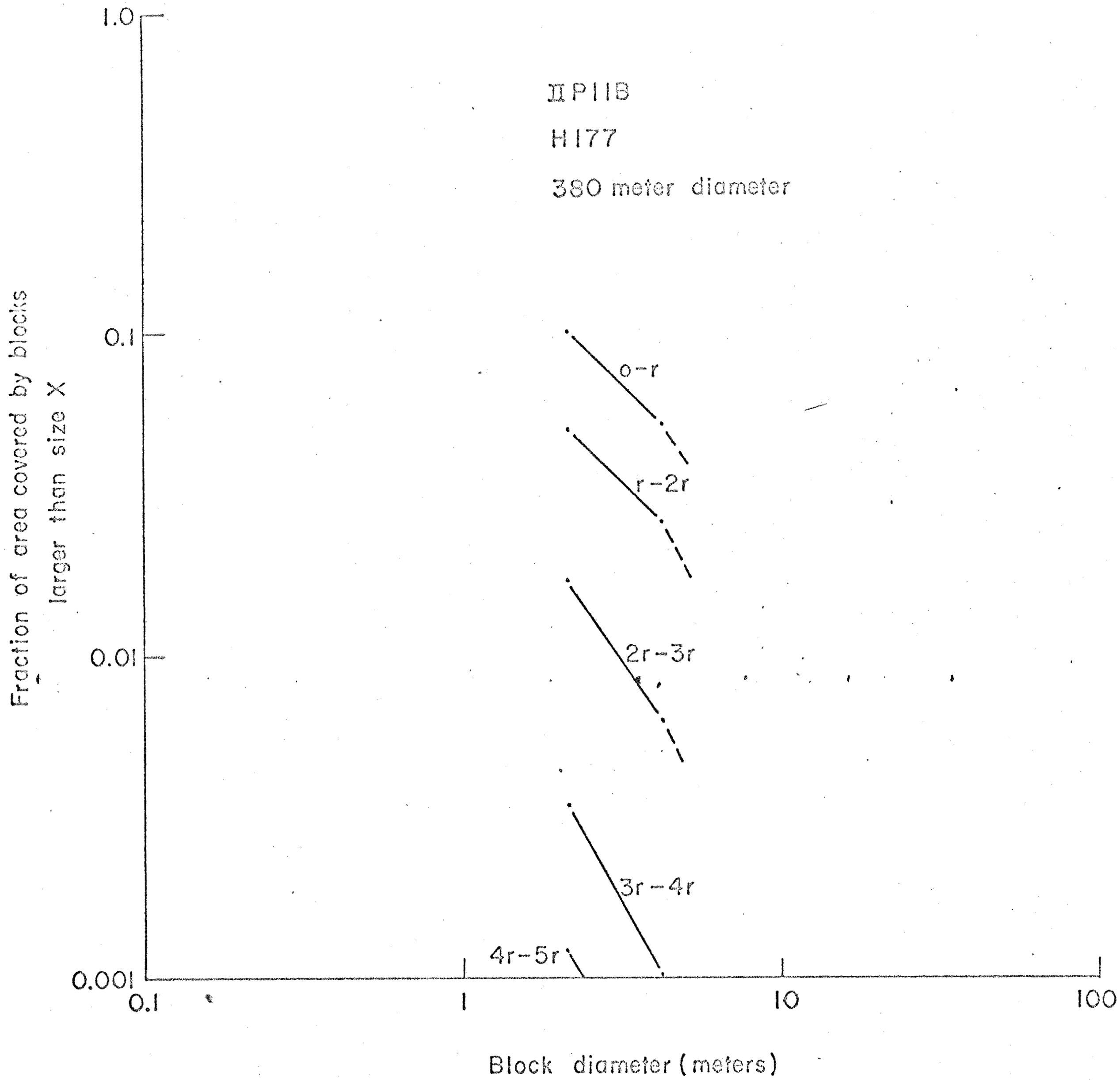

II P11B
H177
380 meter diameter
1.0
0.1
0.01
0.001
Fraction of area covered by blocks larger than size X
o-r
r-2r
2r-3r
3r-4r
4r-5r
0.1
1
10
100
Block diameter (meters)

Figure D-4b

Table D-IVa

II P-11b H 177 380 meter crater

Cumulative frequency of blocks/meter^2

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	5r - 6r	ejecta r - 6r
8.8	0.026×10^{-3}	0.007×10^{-3}	0.0029×10^{-3}	--	--	--	0.0009×10^{-3}
4.4	0.663×10^{-3}	0.191×10^{-3}	0.0108×10^{-3}	0.035×10^{-3}	0.017×10^{-3}	0.001×10^{-3}	0.039×10^{-3}
2.2	10.3×10^{-3}	2.96×10^{-3}	1.55×10^{-3}	0.33×10^{-3}	0.11×10^{-3}	0.0495×10^{-3}	0.519×10^{-3}

Table D-IVb

Fraction of area covered by blocks larger than size x

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	5r - 6r	ejecta r - 6r
8.8	--	--	--	--	--	--	--
4.4	0.050	0.025	0.006	0.001	0.0005	--	0.001
2.2	0.096	0.048	0.010	0.003	0.0013	≈ 0.0003	0.005

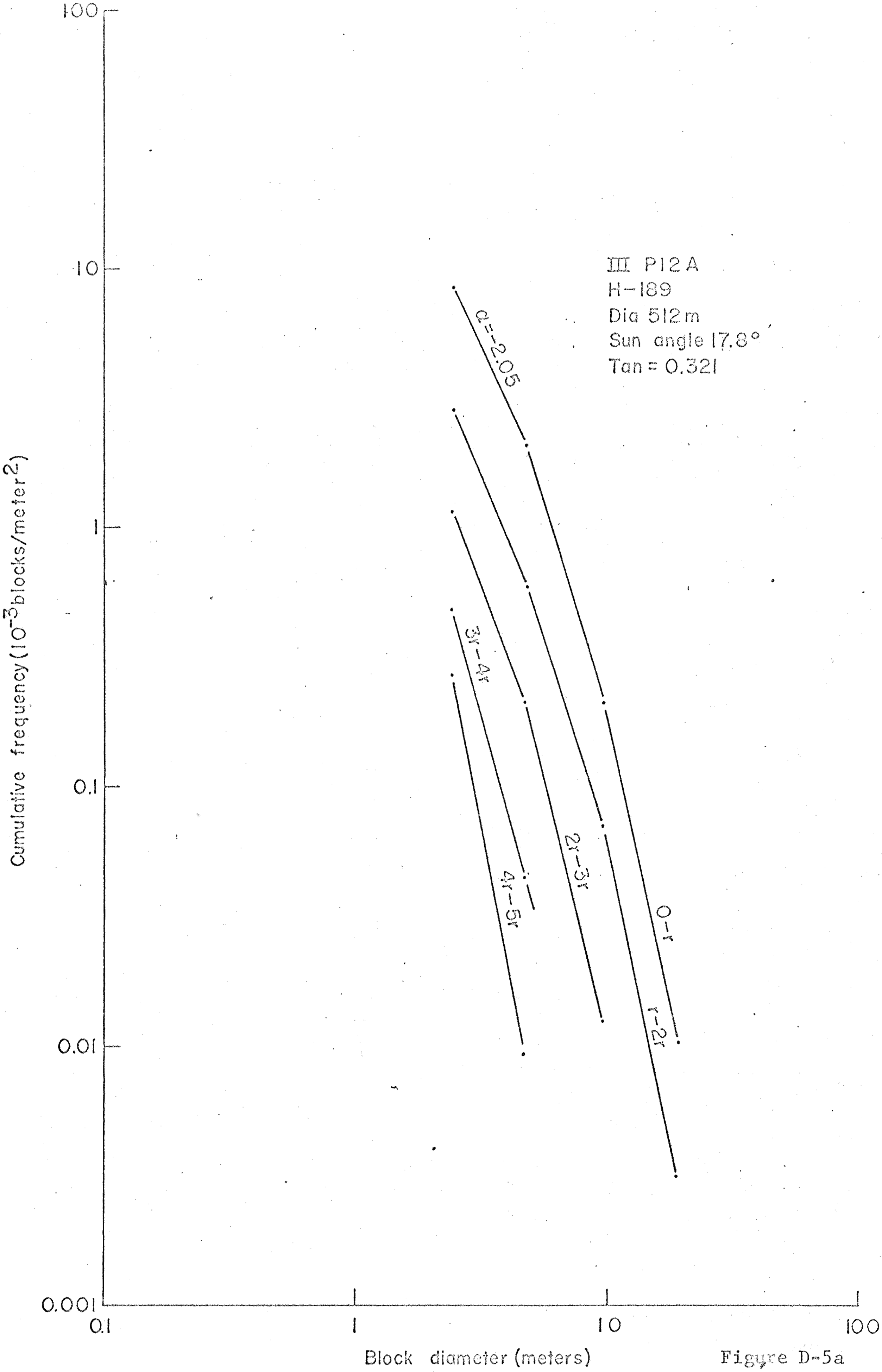

III P12A
H-189
Dia 512m
Sun angle 17.8°
Tan = 0.321
α=-2.05
0-r
r-2r
2r-3r
3r-4r
4r-5r
Cumulative frequency (10^-3 blocks/meter^2)
100
10
1
0.1
0.01
0.001
0.1
1
10
100
Block diameter (meters)

Figure D-5a

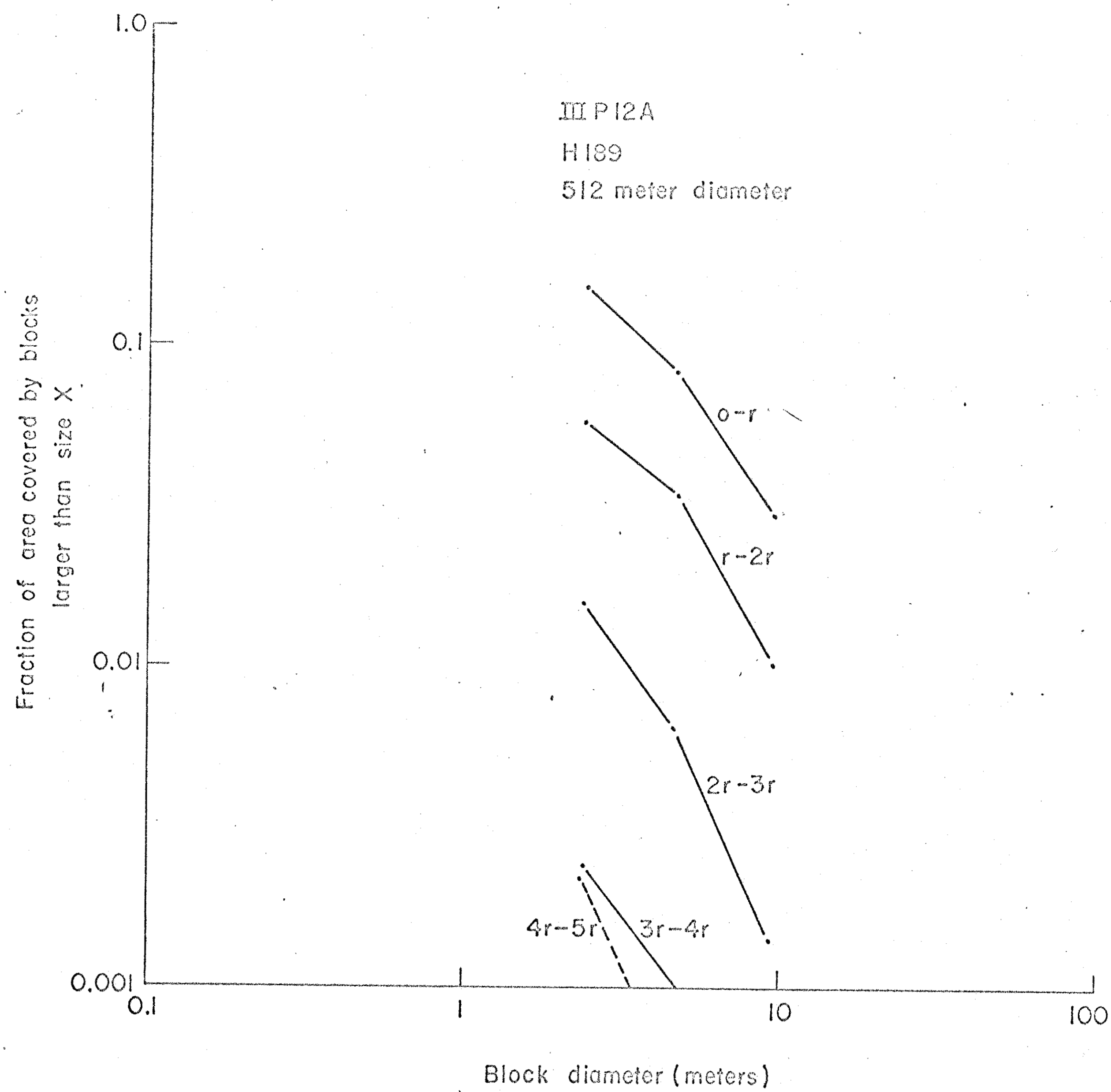

III P12A
H189
512 meter diameter
Fraction of area covered by blocks larger than size X
1.0
0.1
0.01
0.001
o-r
r-2r
2r-3r
4r-5r
3r-4r
0.1
1
10
100
Block diameter (meters)

Figure D-5b

Table D-Va

III P-12A H 189 512 meter diameter crater

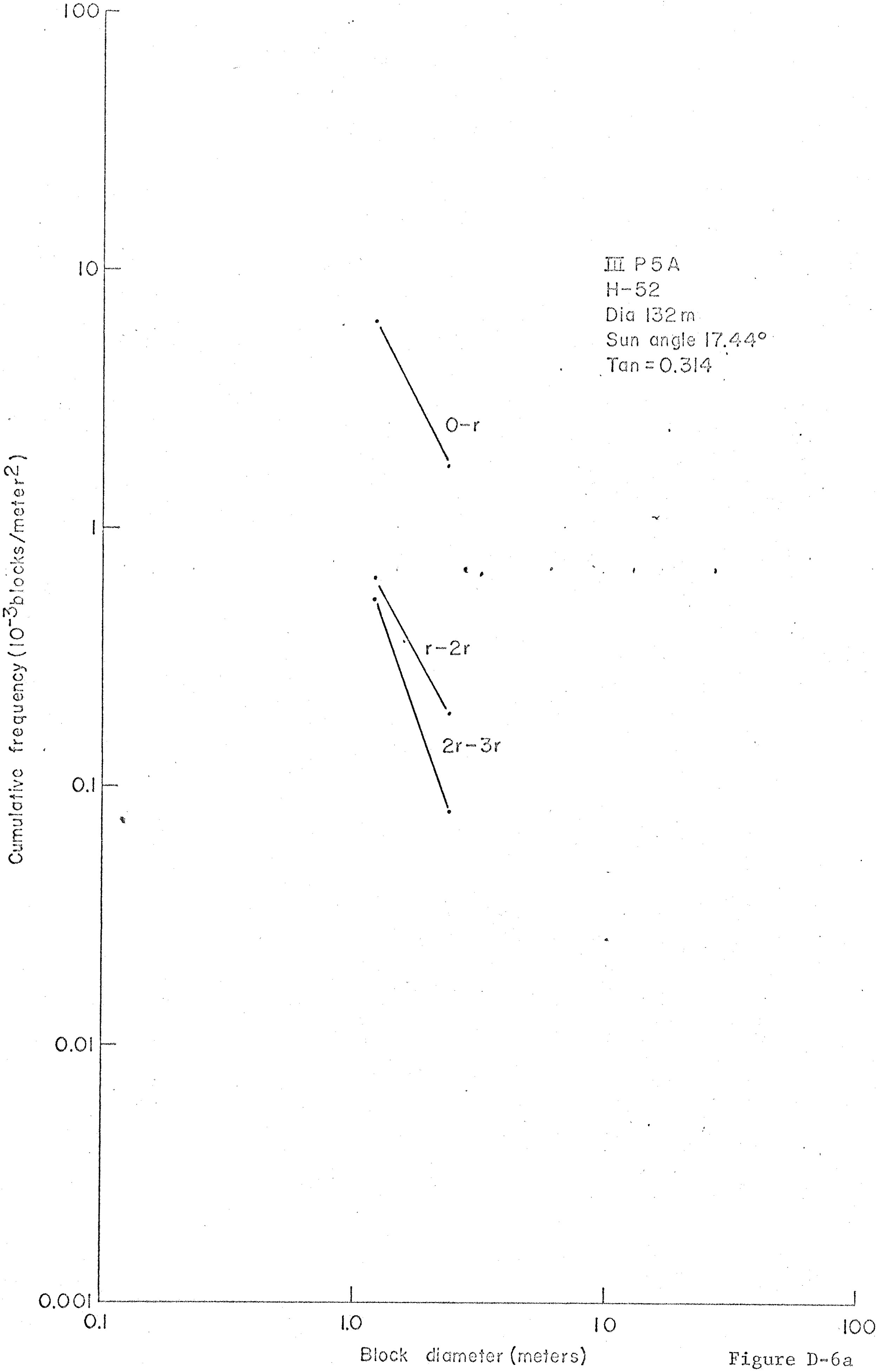
Cumulative frequency of blocks/meter^2

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
38	--	--	--	--	--	--
19	0.01×10^{-3}	0.003×10^{-3}	--	--	--	0.0004×10^{-3}
9.5	0.21×10^{-3}	0.07×10^{-3}	0.012×10^{-3}	--	--	0.011×10^{-3}
4.75	2.1×10^{-3}	0.69×10^{-3}	0.21×10^{-3}	0.044×10^{-3}	0.009×10^{-3}	0.15×10^{-3}
2.38	8.6×10^{-3}	2.9×10^{-3}	1.15×10^{-3}	0.48×10^{-3}	0.27×10^{-3}	0.83×10^{-3}

Table D-Vb

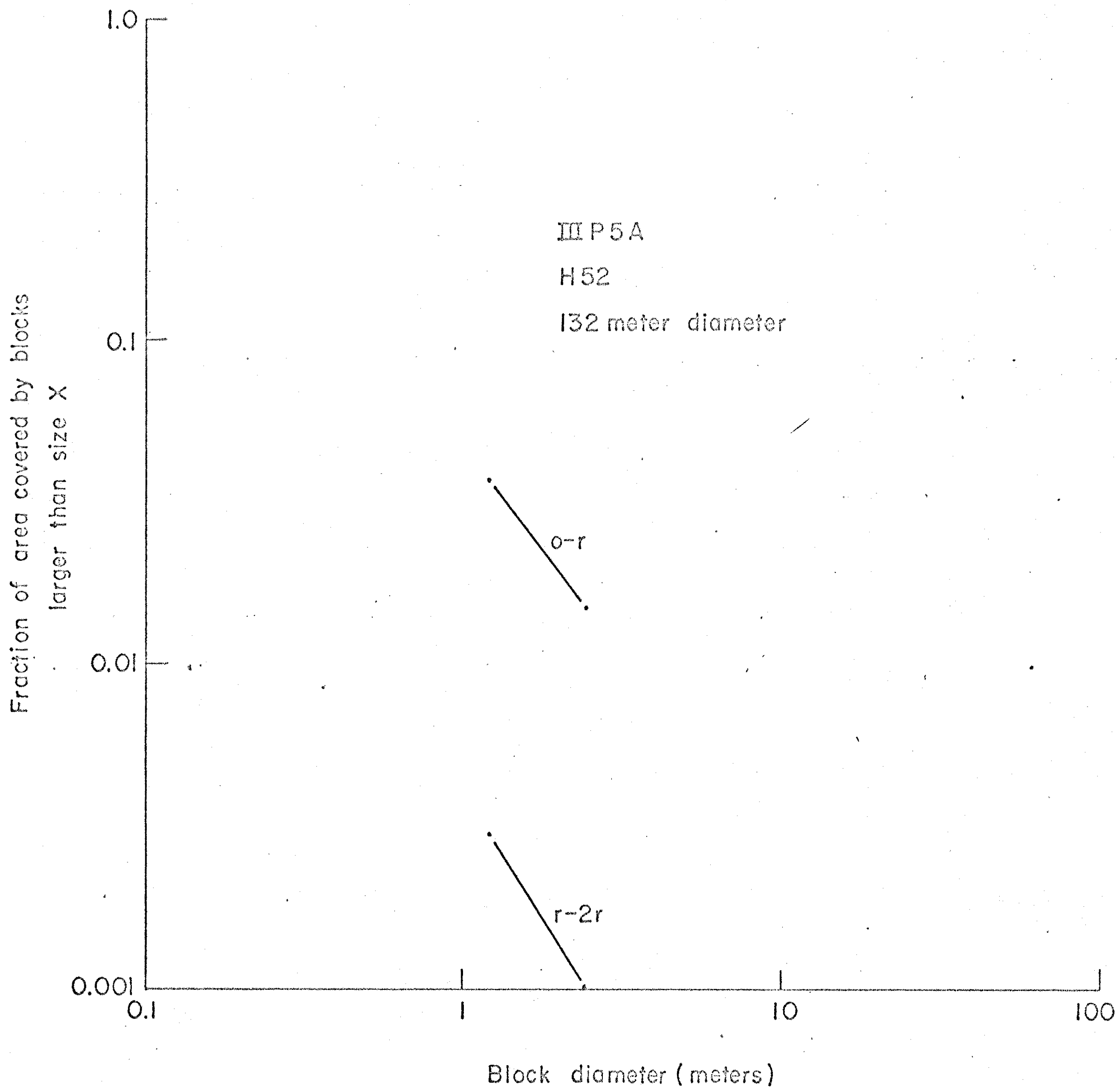
Fraction of area covered by blocks
larger than size x

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
19	--	--	--	--	--	--
9.5	0.029	0.01	0.0014	--	--	0.0014
4.75	0.101	0.034	0.0074	0.0007	--	0.0052
2.38	0.151	0.058	0.0154	0.0024	0.0022	0.0116



III P5A
H-52
Dia 132 m
Sun angle 17.44°
Tan = 0.314
0-r
r-2r
2r-3r
100
10
1
0.1
0.01
0.001
0.1
1.0
10
100
Cumulative frequency (10^-3 blocks/meter^2)
Block diameter (meters)

Figure D-6a



1.0
0.1
0.01
0.001
Fraction of area covered by blocks larger than size X
III P5A
H52
132 meter diameter
o-r
r-2r
0.1
1
10
100
Block diameter (meters)

Figure D-6b

Table D-VIa

III P-5A   H 52   132 meter diameter

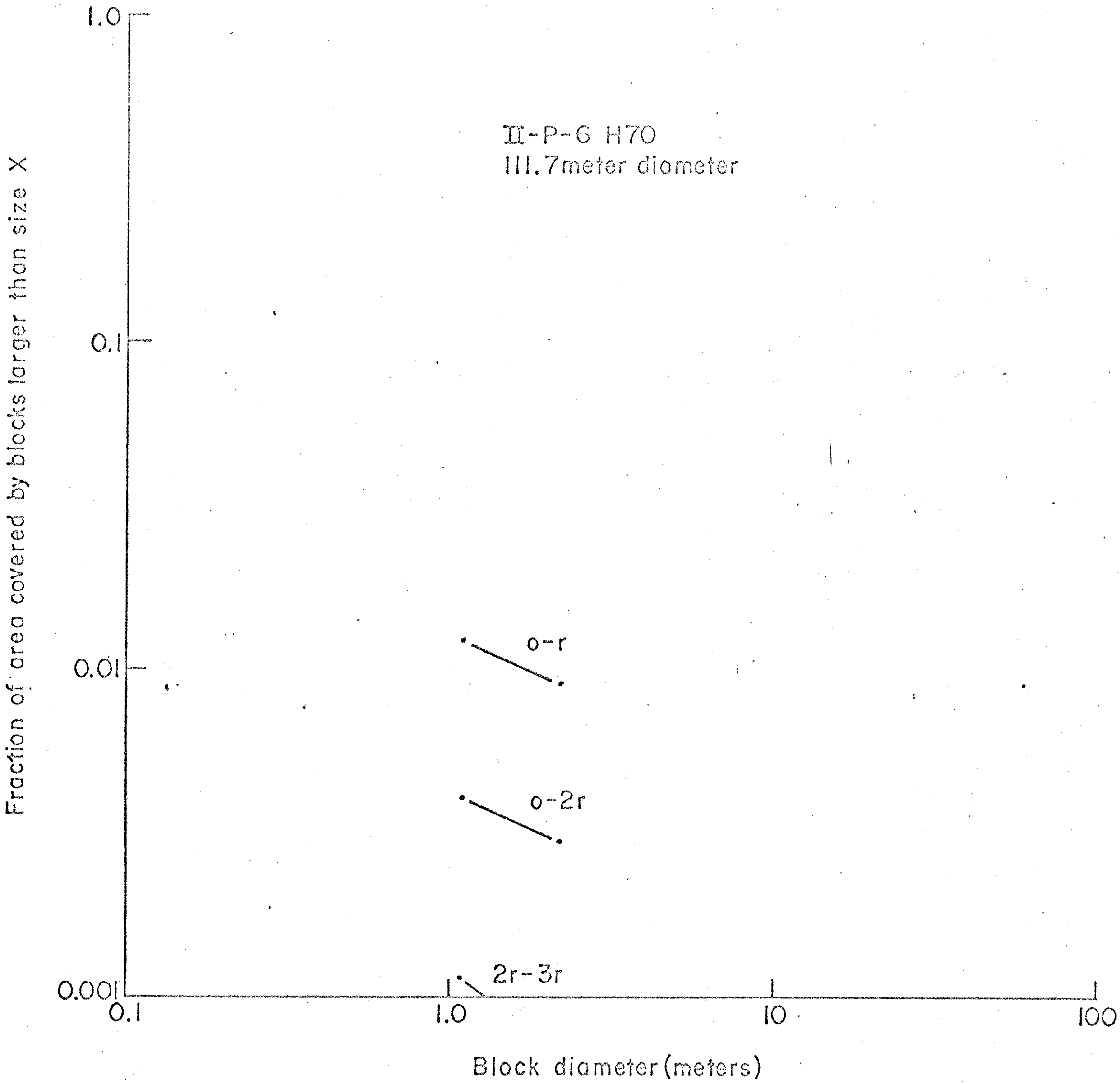
Cumulative frequency of blocks/meter^2

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
4.8	--	--	--	--	--	--
2.4	1.76×10^{-3}	0.196×10^{-3}	0.082×10^{-3}	--	--	0.0397×10^{-3}
1.2	6.38×10^{-3}	0.659×10^{-3}	0.539×10^{-3}	0.063×10^{-3}	0.049×10^{-3}	0.220×10^{-3}

Table D-VIb

Fraction of area covered by
blocks larger than size x

Block diameter (meters)	crater o - r	4 - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
4.8	--	--	--	--	--	--
2.4	0.015	0.001	--	--	--	0.0003
1.2	0.027	0.003	negligible	--	--	0.0008



II-P-6 H70
III.7meter diameter
1.0
0.1
0.01
0.001
Fraction of area covered by blocks larger than size X
o-r
o-2r
2r-3r
0.1
1.0
10
100
Block diameter(meters)

Figure D-7

Table D-VIIa

III P-6 H 70 111.7 meter diameter crater

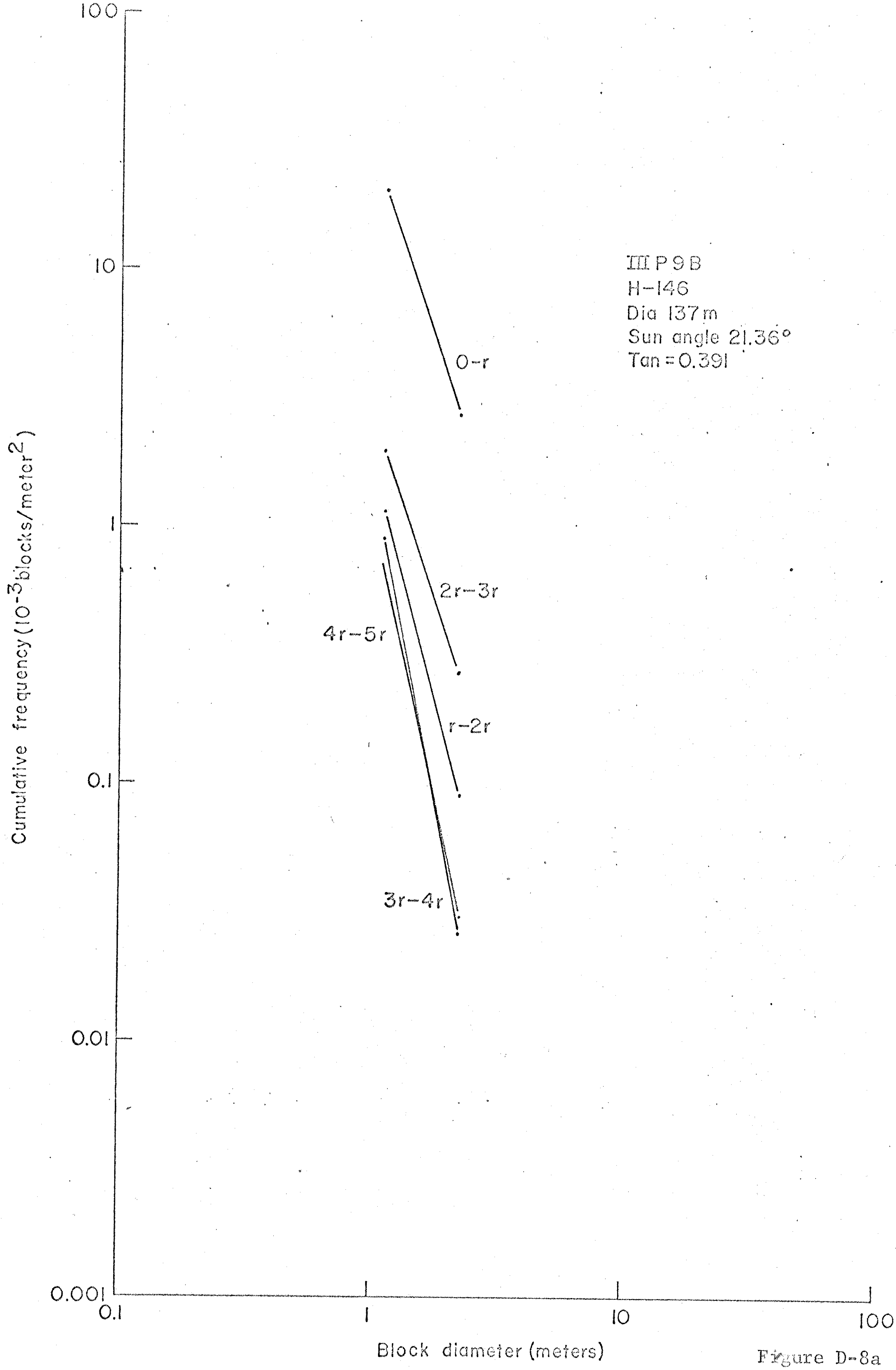
Cumulative frequency of blocks/meter^2

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
4.4	--	--	--	--	--	--
2.2	2.86×10^{-3}	0.952×10^{-3}	0.041×10^{-3}	0.058×10^{-3}	0.023×10^{-3}	0.153×10^{-3}
1.1	4.49×10^{-3}	1.50×10^{-3}	0.532×10^{-3}	0.292×10^{-3}	0.181×10^{-3}	0.451×10^{-3}

Table D-VIIb

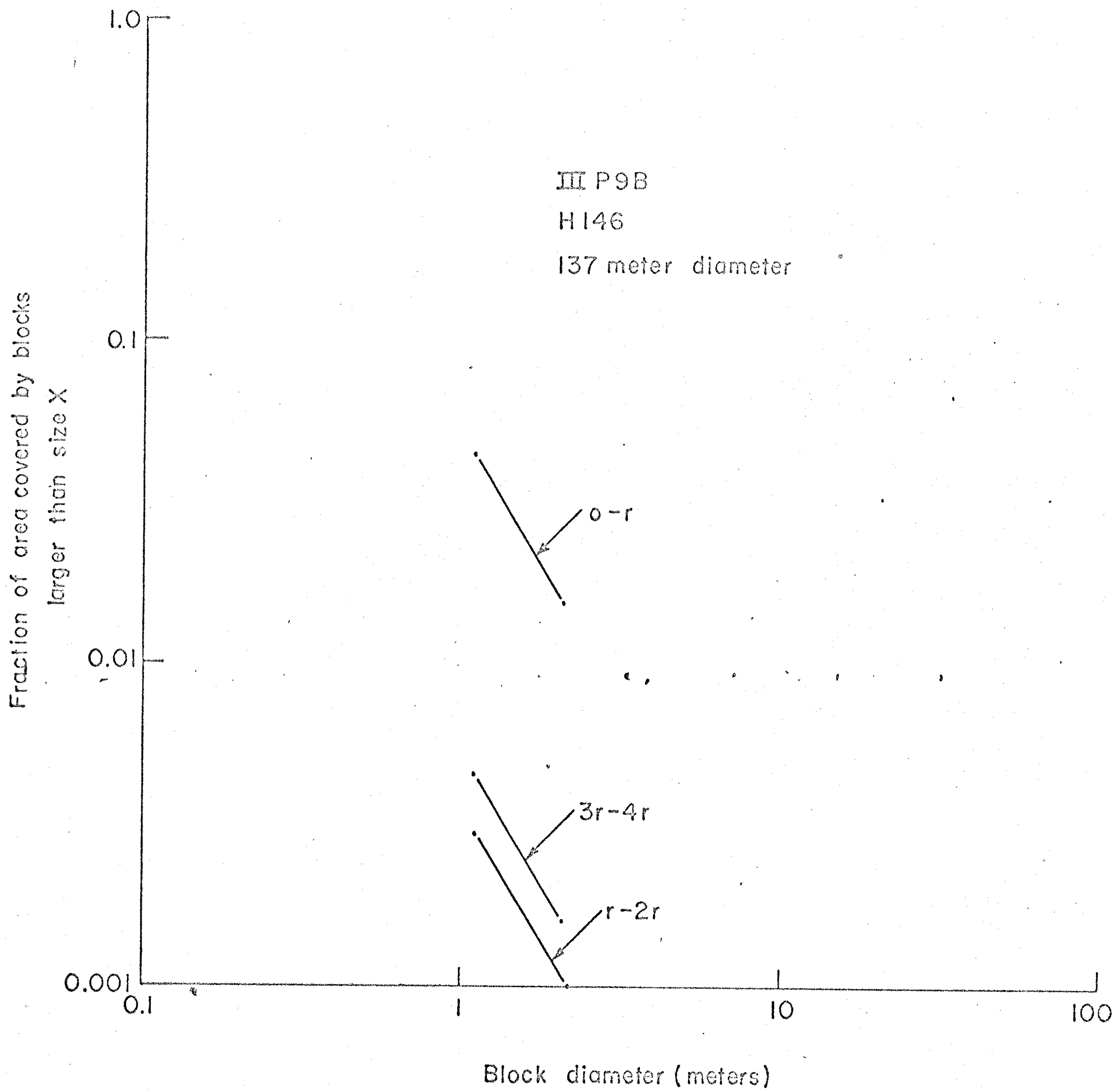
Fraction of area covered by blocks larger than size x

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
4.4	--	--	--	--	--	--
2.2	0.009	0.003	0.0004	--	--	0.0009
1.1	0.012	0.004	0.0009	--	--	0.0016



III P 9 B
H-146
Dia 137 m
Sun angle 21.36°
Tan = 0.391
0-r
2r-3r
4r-5r
r-2r
3r-4r
Cumulative frequency (10^-3 blocks/meter^2)
100
10
1
0.1
0.01
0.001
0.1
1
10
100
Block diameter (meters)

Figure D-8a



1.0
0.1
0.01
0.001
Fraction of area covered by blocks larger than size X
III P9B
H146
137 meter diameter
o-r
3r-4r
r-2r
0.1
1
10
100
Block diameter (meters)

Figure D-8b

Table D-VIIIa

III P-9B H 146 137 meter crater

Cumulative frequency of blocks/meter^2

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
4.32	--	--	--	--	--	--
2.16	2.72×10^{-3}	0.09×10^{-3}	0.27×10^{-3}	0.026×10^{-3}	0.03×10^{-3}	0.09×10^{-3}
1.08	20.1×10^{-3}	1.13×10^{-3}	1.94×10^{-3}	0.91×10^{-3}	0.75×10^{-3}	1.1×10^{-3}

Table D-VIIIb

Fraction of area covered by
blocks larger than size x

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
4.32	--	--	--	--	--	--
2.16	0.015	0.001	0.0016	--	--	0.0007
1.08	0.045	0.003	0.0046	0.001	0.0008	0.0027

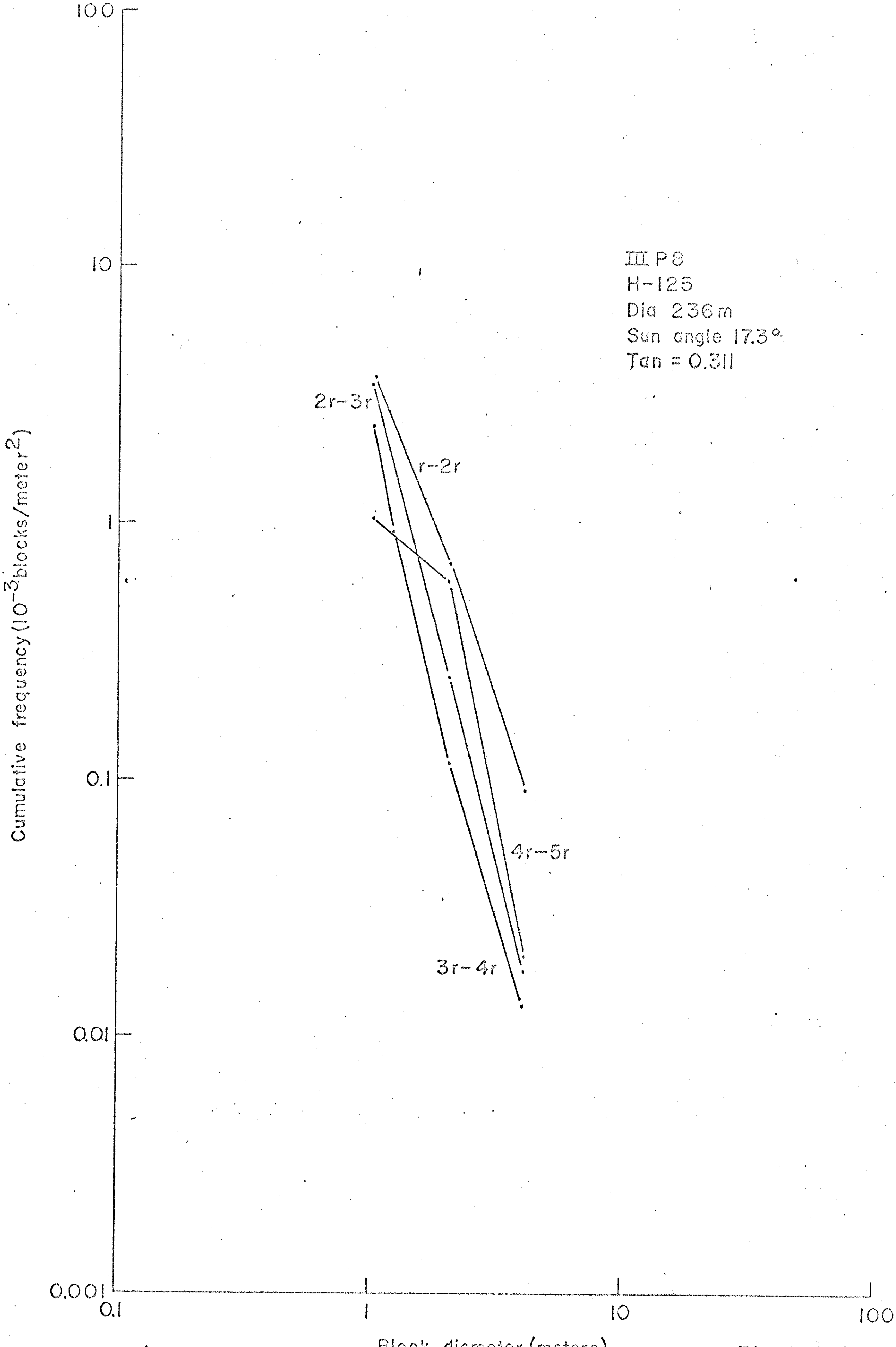
craters near 130 meters across have frequencies of blocks which reach 2×10^{-3} blocks/meter^2 for sizes larger than 1.1 meter and only about 0.3 percent of the area is covered by such blocks. These concentrations are less than those for similar and even smaller craters on rough mare.

Low block frequencies around the craters in smooth mare partly reflects the thick epilith which is larger in the smooth than in the rough mare. These low block frequencies could arise from other factors as well, such differences in fracturing of the rocks.

Upland.--Block frequencies for one hummocky upland crater 200 meters across were obtained because only one 36x enlargement of Lunar Orbiter photograph of such a crater was available for the count. The frequencies obtained show, however, that significant numbers of blocks can occur around upland craters. The frequncies of blocks larger than one meter reach 3.7×10^{-3} blocks/meter^2 larger than one meter, and are intermediate between those of the rough and smooth maria. Inspection of other craters of comparable size on standard prints of Lunar Orbiter photographs show that blocks occur around other upland craters near 200 meters across and smaller. Some Orbiter photographs show small craters near 40 meters across at the apices of upland hills may have a profusion of blocks around them. The frequencies and data for the upland crater are shown in Tables D-IXa, D-IXb, and figures D-9a, and D-9b.

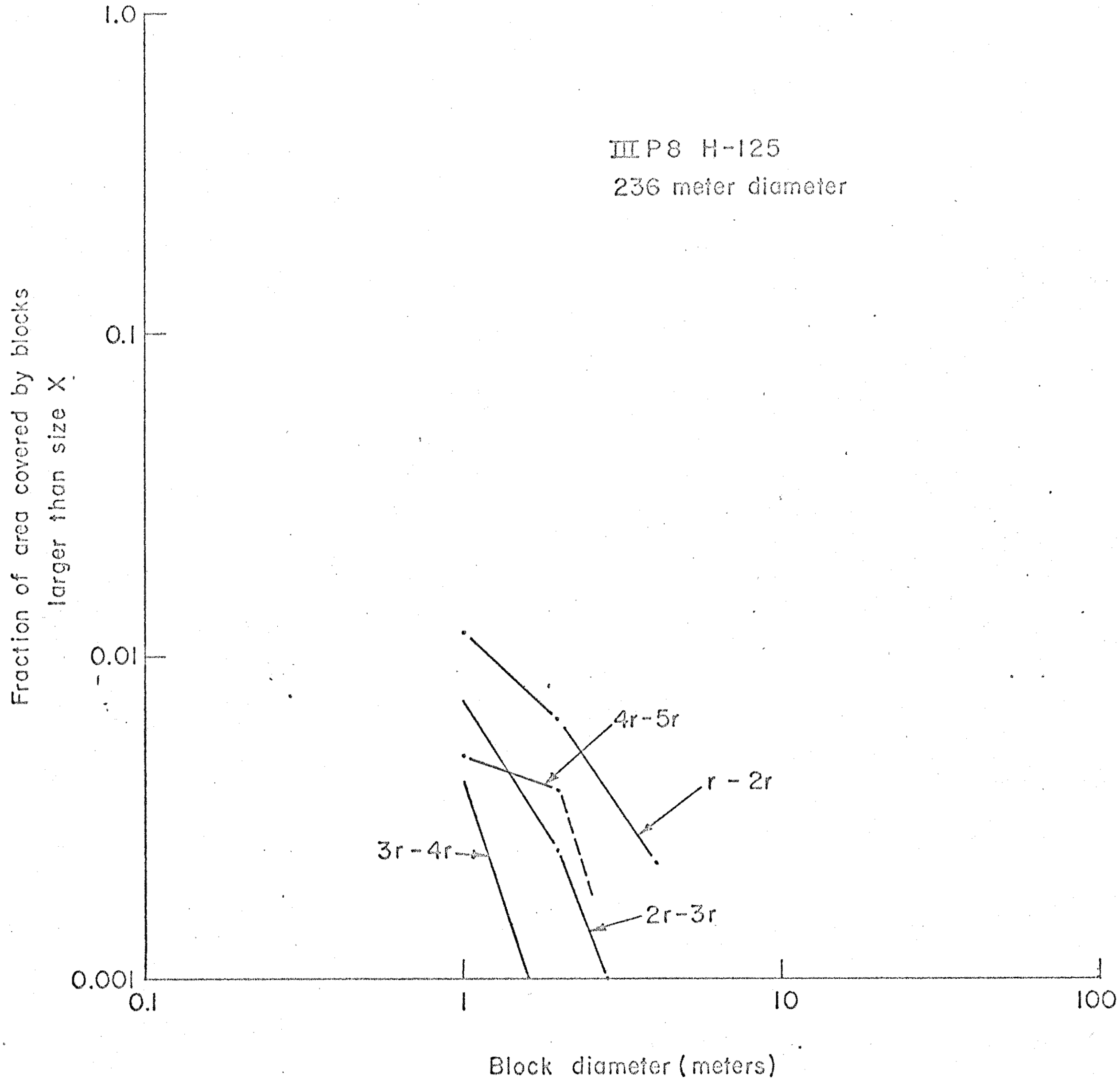
Interiors of large craters

As mentioned in the Section C, both rough and smooth mare have large subdued craters measuring near 80 to 400 meters across with frequencies



III P8
H-125
Dia 236m
Sun angle 17.3°
Tan = 0.311
2r-3r
r-2r
4r-5r
3r-4r
Cumulative frequency (10^{-3} blocks/meter^2)
100
10
1
0.1
0.01
0.001
0.1
1
10
100
Block diameter (meters)

Figure D-9a



1.0
0.1
0.01
0.001
III P8 H-125
236 meter diameter
Fraction of area covered by blocks larger than size X
4r-5r
r - 2r
3r - 4r
2r-3r
0.1
1
10
100
Block diameter (meters)

Figure D-9b

Table D-IXa

III P-8 H 125 236 meter crater

Cumulative frequency of blocks/meter^2

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
8		--	--	--	--	--
4		0.09×10^{-3}	0.018×10^{-3}	0.013×10^{-3}	0.02×10^{-3}	0.027×10^{-3}
2		0.697×10^{-3}	0.25×10^{-3}	0.117×10^{-3}	0.596×10^{-3}	0.224×10^{-3}
1		3.70×10^{-3}	3.51×10^{-3}	2.35×10^{-3}	1.07×10^{-3}	2.28×10^{-3}

Table D-IXb

Fraction of area covered by
blocks larger than size x

Block diameter (meters)	crater o - r	r - 2r	2r - 3r	3r - 4r	4r - 5r	ejecta r - 5r
		0.0023	0.0003	--	--	0.0007
		0.0064	0.0025	0.0006	0.0039	0.0020
		0.0119	0.0073	0.0041	0.0049	0.0057

of blocks on interior walls that are large enough to consider them potential hazards to lunar roving vehicles. Four such craters are considered here. One is used to show that it may be possible to enter such craters with planned traverses but unplanned traverses can result in disaster.

One crater in smooth mare measuring about 351 meters across was found to have concentrations of blocks on its rim, walls, and floor comparable to the concentration around some blocky craters in rough mare. The results are shown in Table D-X. Here again the blocks were counted in sectors using 36x enlargements of Lunar Orbiter photographs on which blocks and protuberances down to one meter and less can be measured.

In a manner similar to smaller craters, these large craters show morphological gradations (see Table D-XI, and D-XII) and may be quite smooth and free of blocks (Table D-XII). Normally the frequency of blocks on crater walls are higher than those on the floor.

One 215 meter crater (fig. D-9) was selected to illustrate what the difference between a planned traverse and a random traverse might be. This crater, which does not appear to fit into the morphological scheme described previously, has a depth to diameter ratio near 1/5.3, is rimless, and blocks are absent on the flanks. The upper crater walls are blocky and steep slopes arise from this. Using shadow techniques on a 36x enlargements of the Lunar Orbiter photographs, it was found that near-vertical slopes with local reliefs of 3 to 4 meters are present. One route (upper profile fig. D-9) would surely be disasterous for a roving vehicle because of numerous blocks with reliefs of 3 meters and

Table D-X

III P-5 H 46 351 meter crater

Cumulative frequency of blocks/meter^2

Block diameter (meters)	Floor o-½r	Lower wall ½r - 3/4r	Upper wall 3/4r - r	Rim r - 5/4r	o - 5/4r
8.96	--	--	--	--	--
4.48	0.09×10^{-3}	--	0.052×10^{-3}	0.033×10^{-3}	0.046×10^{-3}
2.24	0.9×10^{-3}	3.66×10^{-3}	4.9×10^{-3}	7.85×10^{-3}	2.54×10^{-3}
1.12	2.55×10^{-3}	12.9×10^{-3}	12.4×10^{-3}	15.7×10^{-3}	7.15×10^{-3}

Table D-XI

III P-9c H 153 398 meter crater

Cumulative frequency of blocks/meter^2

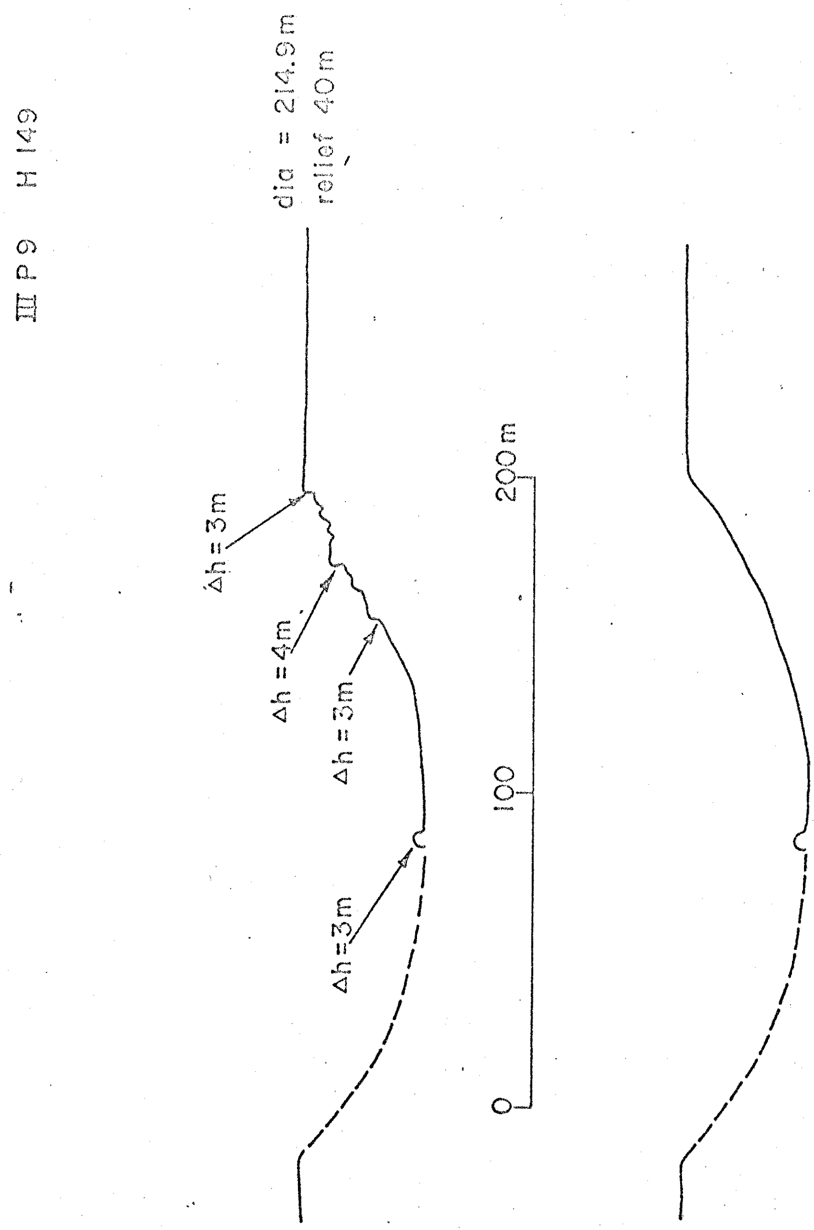
Block diameter (meters)	Floor $o - \frac{r}{2}$	Lower Wall $\frac{r}{2} - \frac{3}{4}r$	Upper Wall $\frac{3}{r}r - r$	Rim $r - \frac{4}{3}r$
8.85	--	--	--	--
4.42	0.258×10^{-3}	0.208×10^{-3}	0.509×10^{-3}	0.197×10^{-3}
2.21	0.969×10^{-3}	1.56×10^{-3}	2.47×10^{-3}	0.986×10^{-3}
1.1	2.00×10^{-3}	5.61×10^{-3}	7.28×10^{-3}	2.17×10^{-3}

Table D-XII

III P-8 H 124 426 meter crater

Cumulative frequency of blocks/meter^2

Block diameter (meters)	Crater Floor $o - \frac{r}{2}$	Crater Wall $\frac{r}{2} - r$	Crater rim $r - \frac{4}{3} r$
4	--	--	--
2	0	0.08×10^{-3}	0
1	0	1.68×10^{-3}	0.415×10^{-3}



III P9 H149
dia = 214.9 m
relief 40 m
Δh = 3m
Δh = 4m
Δh = 3m
Δh = 3m
0
100
200 m

Figure D-9

more. A second route (lower profile, fig. D-9) was free of blocks and would permit access for a roving vehicle.

Block field and talus slopes

Block fields and talus slopes present serious obstacles to roving vehicles and some of them may be impassable.

One block field (Lunar Orbiter frame H 26, site III P-2) was counted because of the availability of 36x enlargements of Lunar Orbiter photographs. For the block field a strip 46.87 meters by 656.2 meters was divided into 14 squares and counted. The results (see Table D-XIII) show large variations as the field is approached. Locally, there are no hazards and locally concentrations of blocks measuring between 9.44 and 1.18 meters reach 27.0×10^{-3} blocks/meter^2. This exceeds the concentrations of blocks in some blocky craters.

Talus slopes do not present the large concentrations of blocks seen in the block field above. Two counts on 150 x 750 meter and 150 x 900 meter strips down the walls of a rille in the Marius Hills using 36x Lunar Orbiter V photographs yield comparable results. Here, as in the block field, parts of the strips are relatively free of blocks. This occurs at both the flat bench at the top of the rille and on the floor of the rille. The largest concentration of blocks are found on the upper slopes of the rille. Surprisingly, it was found that blocks and protuberances less than 2.0 meters could be detected and measured on enlargements of Lunar Orbiter V photographs. The results of the counts are shown in Tables D-XIV and D-XV.

Table D-XIII

III P-2 H-26

Frequency of blocks/meter^2

Square designation along strip	9.44 4.72	4.72 2.36	2.36 1.18	Cumulative larger than 1.18 m.
A	$0.459x10^{-3}$	$0.918x10^{-3}$	0	$1.38x10^{-3}$
B	0	0	0	0
C	$0.459x10^{-3}$	0	0	$0.459x10^{-3}$
D	$0.918x10^{-3}$	$0.459x10^{-3}$	$0.459x10^{-3}$	$1.84x10^{-3}$
E	$0.459x10^{-3}$	$3.67x10^{-3}$	$2.29x10^{-3}$	$6.42x10^{-3}$
F	$0.459x10^{-3}$	$4.13x10^{-3}$	$5.05x10^{-3}$	$9.64x10^{-3}$
G	0	$5.05x10^{-3}$	$6.42x10^{-3}$	$11.47x10^{-3}$
H	0	$0.459x10^{-3}$	$5.51x10^{-3}$	$5.97x10^{-3}$
I	0	$7.34x10^{-3}$	$9.18x10^{-3}$	$16.5x10^{-3}$
J	$0.918x10^{-3}$	$11.9x10^{-3}$	$14.2x10^{-3}$	$27.0x10^{-3}$
K	$3.67x10^{-3}$	$7.80x10^{-3}$	$7.34x10^{-3}$	$18.8x10^{-3}$
L	$2.75x10^{-3}$	$5.97x10^{-3}$	$8.26x10^{-3}$	$17.0x10^{-3}$
M	$1.84x10^{-3}$	$5.97x10^{-3}$	$9.18x10^{-3}$	$17.0x10^{-3}$
N	$1.38x10^{-3}$	$6.42x10^{-3}$	$8.72x10^{-3}$	$16.5x10^{-3}$

Table D-XIV

V H-213 (434) Rille Wall

Cumulative frequency of blocks/meter^2

Block diameter (meters)	Top A	Upper Slope B	Middle Slope C	Lower Slope D	Near Floor E	Floor F	Whole Strip
20	--	--	--	--	--	--	--
10	0	0	0	0.088×10^{-3}	0	0	0.015×10^{-3}
5	0.044×10^{-3}	0.489×10^{-3}	0.352×10^{-3}	0.176×10^{-3}	0.222×10^{-3}	0.088×10^{-3}	0.230×10^{-3}
2.5	0.176×10^{-3}	2.85×10^{-3}	1.51×10^{-3}	1.11×10^{-3}	0.756×10^{-3}	0.222×10^{-3}	1.10×10^{-3}

Table D-XV

V H-213 (417) Rille wall

Cumulative frequency of blocks/meter^2

Block diameter (meters)	Top A	Upper Slope B	Middle Slope C	Lower Slope D	Floor E	Whole Strip
20	--	--	--	--	--	--
10	0	0	0.18×10^{-3}	0	0	0.035×10^{-3}
5	0	0.67×10^{-3}	2.13×10^{-3}	0.13×10^{-3}	0	0.59×10^{-3}
2.5	0	2.4×10^{-3}	4.75×10^{-3}	1.16×10^{-3}	0.09×10^{-3}	1.68×10^{-3}

Similar block frequencies were found for the walls of Schröter's Valley where cumulative frequencies of blocks down to 3 meters reaches 2.1×10^{-3} blocks/meter^2. Here the blocks seem fairly well distributed along the slope (see table D-XVI). Blocks for this slope were measured on 36x enlargements and measured in an area 183 x 1104 meters. They were counted in 6 squares. A second talus slope in Schröter's Valley was counted on 7.2x and 36x enlargements of Lunar Orbiter photographs. The counts correspond fairly well (compare Table D-XVII, column F and Table D-XVIII).

Crater block frequencies and intercrater areas

In order to place the frequencies of blocks around craters in some perspective it is necessary to discuss the intercrater areas represented by Surveyor I (rough mare), Surveyor V (smooth mare), and Surveyor VI (quasi-rough mare). Surveyor III is in an old age crater and Surveyor VII is on the flanks of a large fresh upland crater.

Surveyor results indicate differences between the rough and smooth mare which are in agreement with the block frequencies around craters. For example, the frequency of blocks larger than 10 cm are higher on rough mare (Surveyor I) than smooth mare (Surveyor V) and the quasi-rough mare (Surveyor VI) falls in between. The exponents on the frequency distributions also change systematically. Such differences are shown in the following equations (converted from equations furnished by E. C. Morris) which represent the frequency distributions for blocks less than a few tens of centimeters:

Table D-XVI

V H-205 Schröter's Valley

Cumulative frequency of blocks/meters^2

Block diameter (meters)	Top A	Upper Slope B	C	D	Lower Slope E	Floor F	Whole strip
24.4+	--	--	--	--	0.029×10^{-3}	--	0.005×10^{-3}
12.2	0	0	0	0	0.236×10^{-3}	0.029×10^{-3}	0.044×10^{-3}
6.1	0.56×10^{-3}	0.058×10^{-3}	0.029×10^{-3}	0.324×10^{-3}	0.560×10^{-3}	0.206×10^{-3}	0.290×10^{-3}
3.05	2.09×10^{-3}	1.59×10^{-3}	0.619×10^{-3}	1.42×10^{-3}	1.50×10^{-3}	0.796×10^{-3}	1.34×10^{-3}

Table D-XVII

V H-204 (235) 7.2x Schröter's Valley

Cumulative frequency of blocks/meter^2

Block diameter (meters)	Top A	Upper B	C	D	Lower Slope E	Near floor F
15	--	--	--	--	--	--
12.3	0.021×10^{-3}	0.031×10^{-3}	0	0.094×10^{-3}	0.052×10^{-3}	0.031×10^{-3}
6.1	0.031×10^{-3}	0.104×10^{-3}	0.073×10^{-3}	0.504×10^{-3}	0.483×10^{-3}	0.672×10^{-3}
3.0	0.084×10^{-3}	0.178×10^{-3}	0.168×10^{-3}	1.09×10^{-3}	1.14×10^{-3}	1.61×10^{-3}

Table D-XVIII

V H-204 (235) 33x Enlargement

Talus at base of slope

Block diameters (meters)	Cumulative frequency of blocks/meter^2
13.6	--
6.8	0.138×10^{-3}
3.4	1.65×10^{-3}

Surveyor I	$N = 2.39 \times 10^{-3} D^{-2.11}$
	$A = 4.59 \times 10^{-2} D^{-0.11}$
Surveyor III	$N = 6.9 \times 10^{-4} D^{-2.56}$
	$A = 3.16 \times 10^{-3} D^{-0.56}$
Surveyor V	$N = 1.4 \times 10^{-4} D^{-2.65}$
	$A = 5.7 \times 10^{-4} D^{-0.65}$
Surveyor VI	$N = 5.9 \times 10^{-4} D^{-2.51}$
	$A = 2.9 \times 10^{-3} D^{-0.51}$
Surveyor VII	$N = 2.74 \times 10^{-2} D^{-1.82}$
	$A_1 = 2.76 \times 10^{-1} D^{+0.18}$

where: N = cumulative blocks/meter^2

A = fraction of area covered by blocks larger than size x

A_1 = fraction of area covered by blocks smaller than size x

D = block diameter in meters.

There is no evidence that these block frequencies can be extrapolated upward to estimate frequencies of blocks larger than a few tens of centimeters. Studies of Lunar Orbiter III photographs of the Surveyor I site suggest that:

$$N = 0.002\ D^{-3}$$

is a reasonable estimate for frequencies of blocks larger than 1.0 meter (see fig. D-10). For the smooth mare, the frequencies are probably one order of magnitude less. Insufficient data are available for the Crater Tycho, but the following equation seems to be reasonable:

$$N = 0.027\ D^{-3}.$$

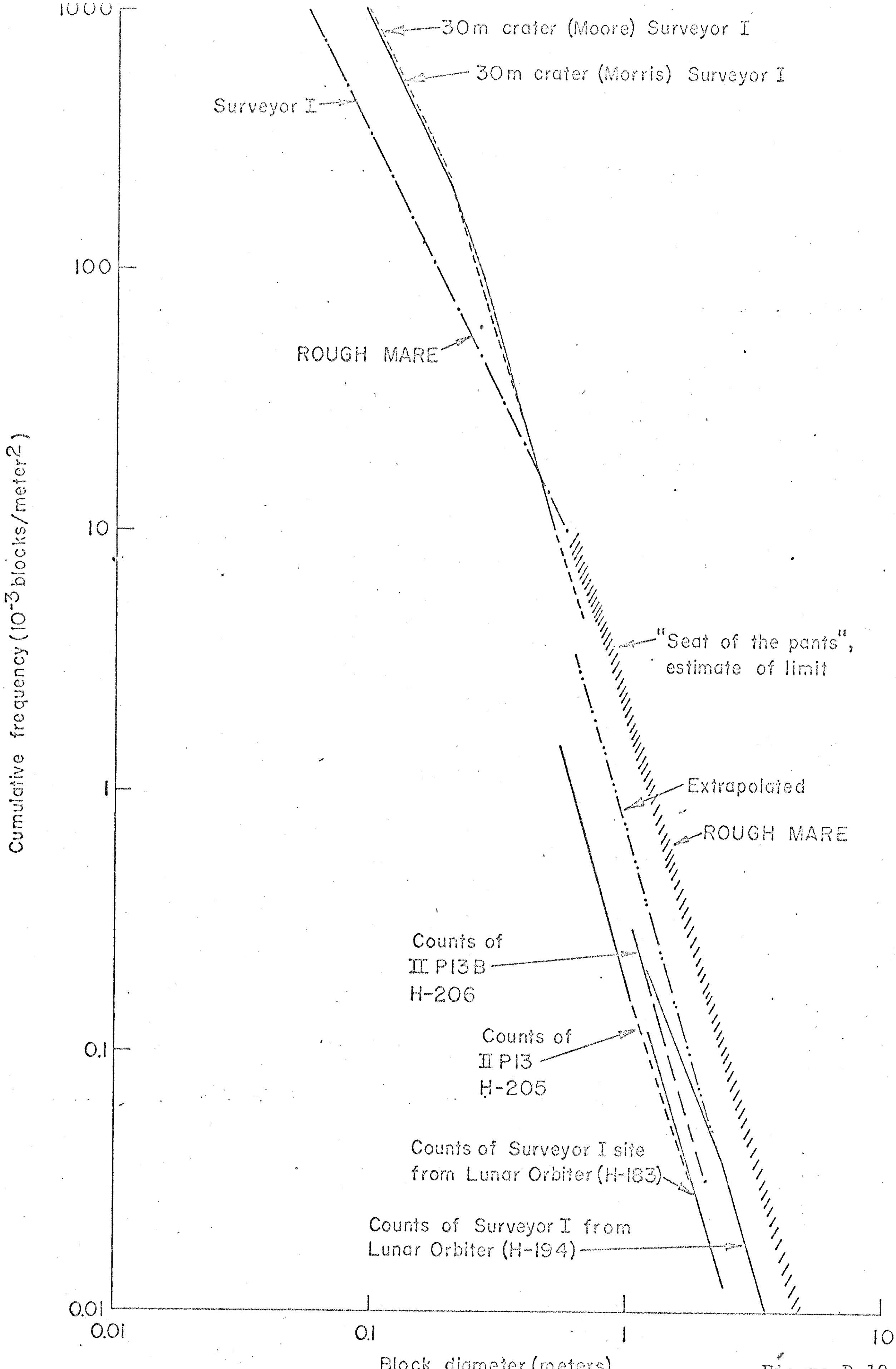

1000
100
10
1
0.1
0.01
Cumulative frequency (10^-3 blocks/meter^2)
0.01
0.1
1
10
Block diameter (meters)
30m crater (Moore) Surveyor I
30m crater (Morris) Surveyor I
Surveyor I
ROUGH MARE
"Seat of the pants", estimate of limit
Extrapolated
ROUGH MARE
Counts of II P13B H-206
Counts of II P13 H-205
Counts of Surveyor I site from Lunar Orbiter (H-183)
Counts of Surveyor I from Lunar Orbiter (H-194)

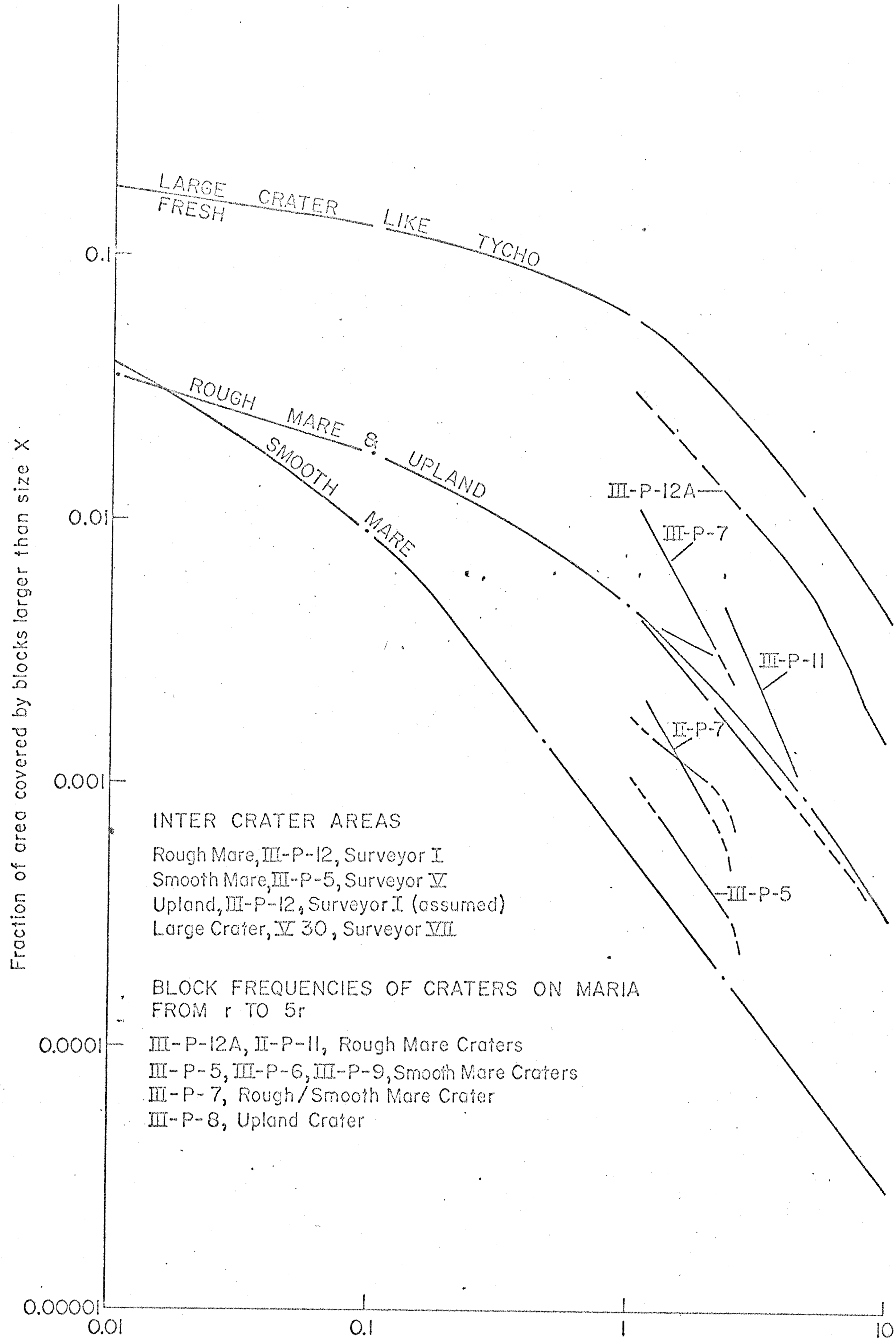
Figure D-10

Estimates of the fraction of area covered by blocks are shown in figure D-11 for Surveyors I, V, and VII along with those for blocks around fresh craters. Upland surfaces are assumed to have block frequencies identical with Surveyor I or rough mare.

In summary, frequencies of blocks around fresh lunar craters change with size, locale, and distance from the crater rim. Frequencies of blocks around rough mare craters between 72 and 500 meters are large enough so that at least 3 percent of the surface near the rims of craters 72 meters across will be covered by blocks that are hazardous to roving vehicles and for the larger crater at least as much as 10 percent of the surface will be covered by such hazards. The frequency of blocks and percentage area covered by hazardous blocks are highest within the craters where 30 percent or so of the surface may be covered by such blocks but only a percent or less of the surface is covered by hazardous blocks at distance of one and one-half crater diameter from the crater rim. Frequencies of blocks increase with the size of the crater. For small craters less than 12 - 24 meters across, there are normally no hazards but those 500 meters across will present problems to lunar roving vehicles. Frequencies of blocks are significantly smaller for craters on smooth mare than craters on rough mare.

Interiors of large craters, block fields, and talus slopes may present obstacles with concentrations comparable to or higher than those found around fresh craters in rough mare.

Finally, frequencies of blocks larger than one meter across are higher on rough mare than on smooth mare. The largest frequencies of



LARGE FRESH CRATER LIKE TYCHO
ROUGH MARE & UPLAND
SMOOTH MARE
III-P-12A
III-P-7
III-P-11
II-P-7
III-P-5
INTER CRATER AREAS
Rough Mare, III-P-12, Surveyor I
Smooth Mare, III-P-5, Surveyor V
Upland, III-P-12, Surveyor I (assumed)
Large Crater, V 30, Surveyor VII
BLOCK FREQUENCIES OF CRATERS ON MARIA FROM r TO 5r
III-P-12A, II-P-11, Rough Mare Craters
III-P-5, III-P-6, III-P-9, Smooth Mare Craters
III-P-7, Rough/Smooth Mare Crater
III-P-8, Upland Crater
Fraction of area covered by blocks larger than size X
0.1
0.01
0.001
0.0001
0.00001
0.01
0.1
1
10
Block diameter (meters)

Figure D-11

blocks are found around fresh craters on rough mare, in talus slopes, on walls of large subdued craters, in block fields, on some upland slopes and hills, and in and around very large craters such as Tycho and Aristarchus.

Section E

Increased travel distance due to craters and other obstacles on the Moon

by H. J. Moore

Introduction

Craters, blocks, scarps, and linear depressions present obstacles which must be crossed or by-passed by Lunar Roving Vehicles. Small craters and blocks with reliefs of 1/2 to 1 meter or less can be crossed. Craters and blocks with larger reliefs must be circumvented. Rilles or linear depressions can generally be crossed at some point along their length but there are little data on the frequency of occurrence of crossings. Thus, only craters and blocks will be considered below.

Method of analysis

Procedures for analyzing increased path lengths of vehicle travel required by the presence of obstacles have been discussed by Brooks (1958), Ulrich (1968), and Rozema (unpublished data). The analysis below is similar to those above but it differs in that the obstacles are described by a frequency distribution rather than by a discrete size, and the size of the vehicle is taken into account. No consideration is given to the vehicle turning radius which may have considerable importance when frequency of small obstacles is high.

Increased travel distance for one circular obstacle

The vehicle will encounter a circular obstacle over any interval dy with equal probability (see fig. E-1):

$$dy = \sin\theta \, d\theta \qquad (1)$$

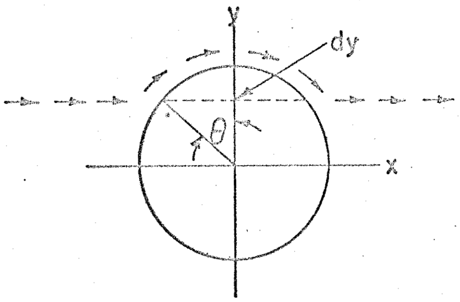


Figure E-1. Circular obstacle

It will travel an additional distance (p_1) of:

$$p_1 = 2\,(\theta - \sin\theta), \qquad (2)$$

and the mean additional distance traveled (p_2) is:

$$\bar{p}_2 = \frac{\int_0^{\frac{\pi}{2}} 2(\theta - \sin\theta)\sin\theta \, d\theta}{\int_0^{\frac{\pi}{2}} \sin\theta \, d\theta} = \frac{2(1 - \frac{\pi}{4})}{(1 - 0)} = 2(1 - \frac{\pi}{4}) \qquad (3)$$

The effective size of an obstacle is a function of the size of the obstacle (D) and the vehicle size (figure E-2) because the vehicle must clear the obstacle by half of its width (w). Then for obstacles with diameters D and vehicles with width w, the mean additional distance traveled per obstacle ($\bar{p}_3$) is:

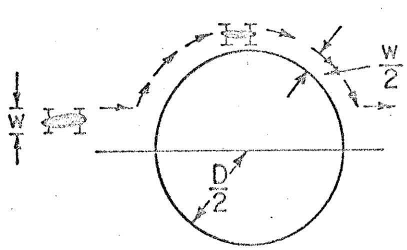


Figure E-2. Clearance

$$\bar{p}_3 = (D + w)(1 - \frac{\pi}{4}) \qquad (4)$$

in travel distance:

$$dP = \frac{\frac{\pi}{4}\left(1 - \frac{\pi}{4}\right)\left(D + w\right)d\ell}{(D + w)} \qquad (9)$$

Equation 9 may be restated:

$$dP = \frac{\pi}{4}\left(1 - \frac{\pi}{4}\right) nk \int_{D_1}^{D_2}\left(D^{n+1} + 2wD^{n} + w^{2}D^{n-1}\right) dD \qquad (10)$$

or

$$P = \frac{\pi}{4}\left(1 - \frac{\pi}{4}\right) nk \left[\frac{D^{n+2}}{n+2} + \frac{2wD^{n+1}}{n+1} + \frac{w^{2}D^{n}}{n}\right]_{D_1}^{D_2}$$

where:

$$n \neq -2,\ n \neq -1,\ \text{and}\ n \neq 0.$$

Solution of equation 10 for n = -2 gives:

$$P = \frac{\pi}{4}\left(1 - \frac{\pi}{4}\right)\left(-2k\right)\left[\ell nD + \frac{2wD^{-1}}{-1} + \frac{w^{2}D^{-2}}{-2}\right]_{D_1}^{D_2}. \qquad (11)$$

Solution of equation 10 for n = -1 gives:

$$P = \frac{\pi}{4}\left(1 - \frac{\pi}{4}\right)\left(-k\right)\left[D + 2w\ \ell nD + \frac{w^{2}D^{-1}}{-1}\right]_{D_1}^{D_2}. \qquad (12)$$

Because the path length increases, there must be corresponding increases in subsequent path lengths resulting from the initial increased path lengths. For example, the added path length (P), when taken as unity, is accompanied by an increase (P'):

$$P' = nk \frac{\pi}{4} (1 - \frac{\pi}{4}) \int_{D_1}^{D_2} \left(D^{n+1} + 2wD^n + w^2 D^{n-1} \right) dD \quad (13)$$

But P is a fraction the map length (M) so that:

$$PP' = P^2. \quad (14)$$

Then the traverse length (L) becomes the sum of the map length (M=1) and sum of all the increased path lengths:

$$L = 1 + P + P^2 + P^3 + \ldots + P^{n-1}, \quad (15)$$

or

$$L = \frac{1}{1-P}; \quad (16)$$

Criteron for impassability

In order to establish if a block field or a cluster of sharp craters is passable or impassable requires detailed examination of that field because statistical approaches do not necessarily yield such information. However, an estimate can be made from the foregoing equations. For a field of obstacles (D+w) that cover all the area, the area is clearly impassable. The vehicle might drive through if the area covered by obstacles (D+w) is less than 1.0. Thus the integral of equation 6 may be used to estimate passability:

$$A = \frac{\pi}{4} kn \int_{D_1}^{D_2} \left(D^{n+1} + 2wD^n + w^2 D^{n-1} \right) dD, \quad (17)$$

where:

$n \neq -2$, $n \neq -1$, and $n \neq 0$.

Solutions for equation 17 are similar to those for equation 10.

Examples of the use of equations 5, 10, 16 and the integral of equation 8 are given in tables E-I, E-II, and E-III.

References cited

Brooks, F. C., 1958, Effect of impenetrable obstacles on vehicle operational speed: Land Locomotion Research Branch of U.S. Army Ordnance Tank-Automotive Command Report #28, 11 p.

Rosiwal, August, 1898, Ueber geometrishe Gesteinsanalysen: Verhandlungen Geologischen Bundesanstalt (Reichsanstalt), p. 143-175.

Ulrich, G. E., 1968, Advanced Systems Traverse Research Project Report: U.S. Geol. Survey Interagency Report: Astrogeology 7, 59 p.

Table E-I. Examples of calculations for increased travel distances due to blocks.

	N_A 1/	D_2 & D_1 2/	P	L_B 3/	N_L 4/
Rough maria w = 2 meters	$0.002\ D^{-3}$	1 - 30	0.0043	1.0044	2.0
Smooth maria w = 2 meters	$0.0002D^{-3}$	1 - 30	0.0004	1.0004	0.2
Large fresh crater flank (crater diam. 80 km) w = 2 meters)	$0.027\ D^{-3}$	1 - 100	0.059	1.063	31.7
Block field w = 2 meters					
Section A	$0.100\ D^{-1.1}$	1 - 10	0.358*	1.558	178
Section B	$0.032D^{-1.08}$	1 - 2.36	0.040		22.6
	$0.336D^{-3.80}$	2.36-9.44	0.059		31.5
Section C	$0.012D^{-1.07}$	1-2.36	0.014		8.0
	$0.080D^{-3.32}$	2.36-9.44	0.022		11.7
Section D	$0.002D^{-0.415}$	1 - 2.36	0.001		0.7
	$0.002D^{-0.585}$	2.36-9.44	0.006		2.8

* Each section is 47 x 47 meters.

1/ N_A = number of craters per square meter.

2/ D, D_1, D_2 are crater diameters in meters.

3/ L, L_B, L_C = ratio of distance traveled to map length.

4/ N_L = number of obstacles encountered for each kilometer of distance traveled.

Table E-II. Examples of calculations for increased travel distances due to craters.

	N_A 1/	D_2 & D_1 2/	P	L_B 3/	N_L 4/
Rough maria w = 2 meters	$0.05\ D^{-2}$	2 - 200	0.119	1.136	38.8
Smooth maria w = 2 meters	$10.0\ D^{-3}$	200-10,000	0.026	1.026	0.3
	$0.05\ D^{-2}$	2 - 40	0.091	1.100	37.3
	$2.0\ D^{-3}$	40 - 60	0.009	1.009	0.8
	$0.033D^{-2}$	60 - 300	0.018	1.019	0.7
	$10.0\ D^{-3}$	300 -10,000	0.017	1.017	0.1
Large fresh crater flank (crater diam. 80 km) w = 2 meters	$0.1\ D^{-3}$	2 -10,000	0.059	1.063	29.4

1/ N_A = number of craters per square meter.

2/ D, D_1, D_2 are crater diameters in meters.

3/ L, L_B, L_C = ratio of distance traveled to map length

4/ N_L = number of obstacles encountered for each kilometer of distance traveled.