Section C

Crater frequencies and morphologies

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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:

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

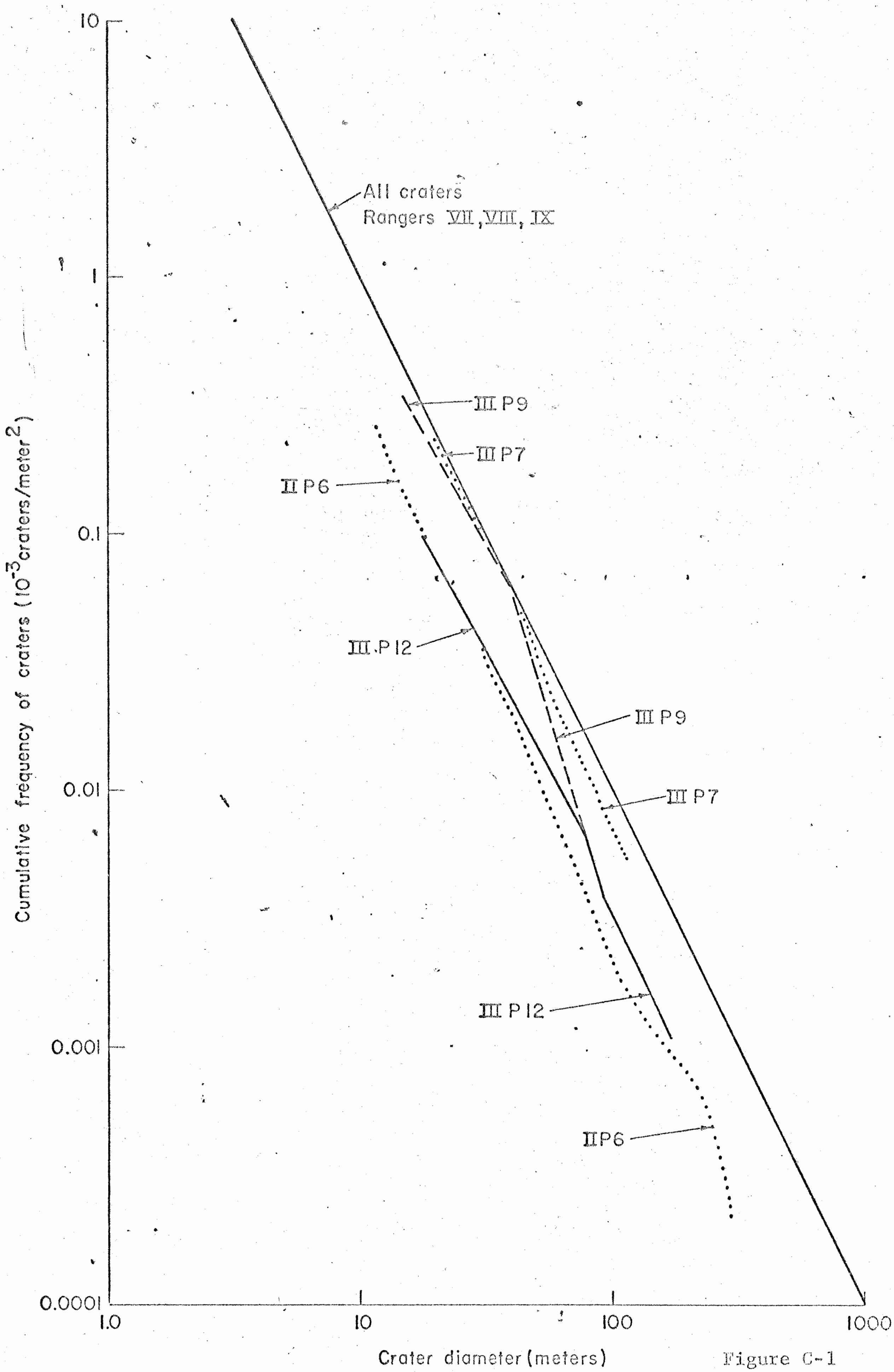
where: N is the cumulative number of craters per square meter,

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.

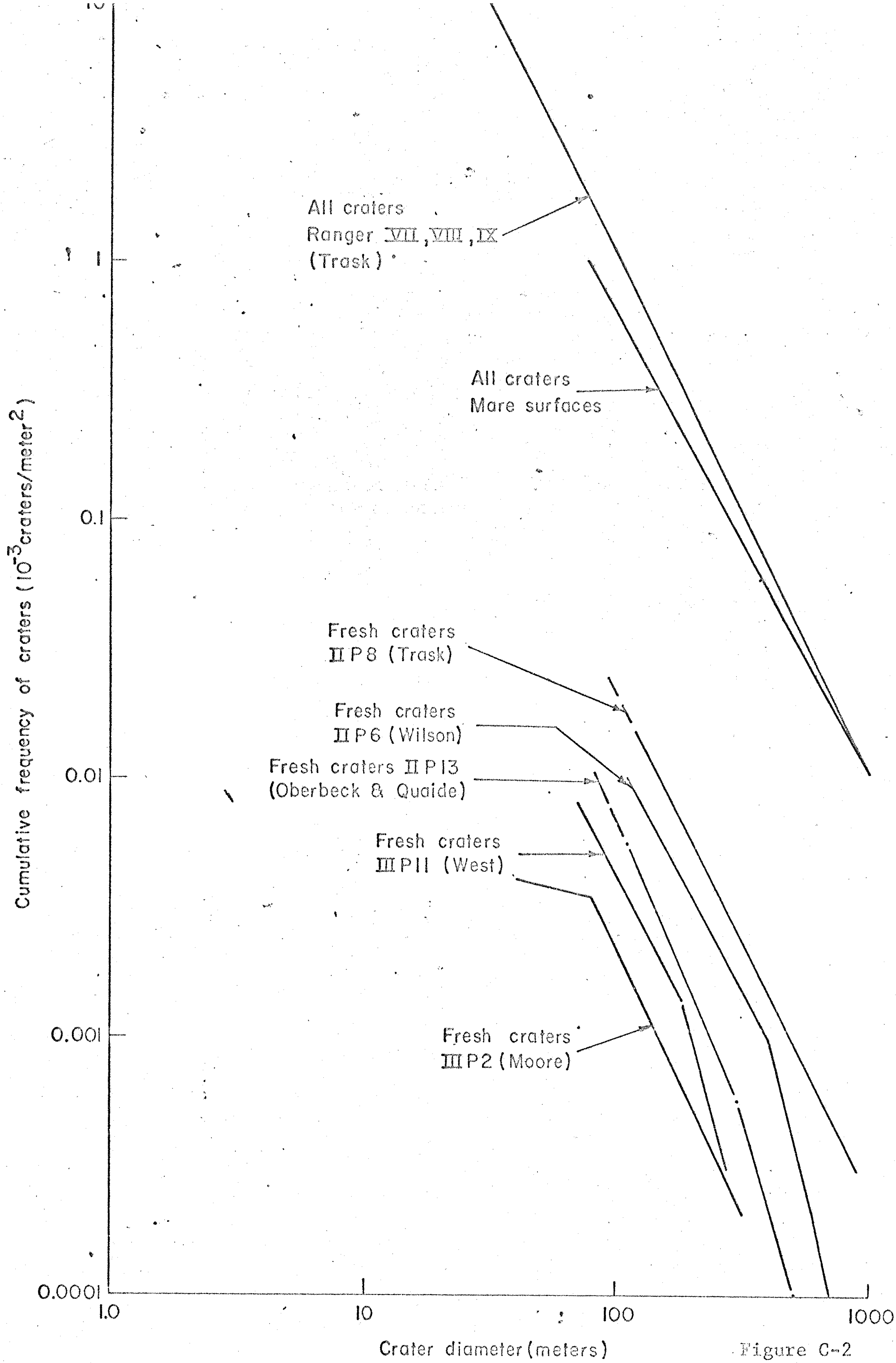
As nature would have it, lunar surfaces are typically a mixture of the two types of surfaces or even more complex because of various events. Some frequency distributions are shown in figure C-1 where the counts for Rangers VII, VIII, and IX (Trask, 1966) represent the "steady state" frequency distribution. 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:



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)
All craters
Rangers VII, VIII, IX
III P9
III P7
II P6
III P12
III P9
III P7
III P12
II P6

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:

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

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

B. Smooth mare:

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

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

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

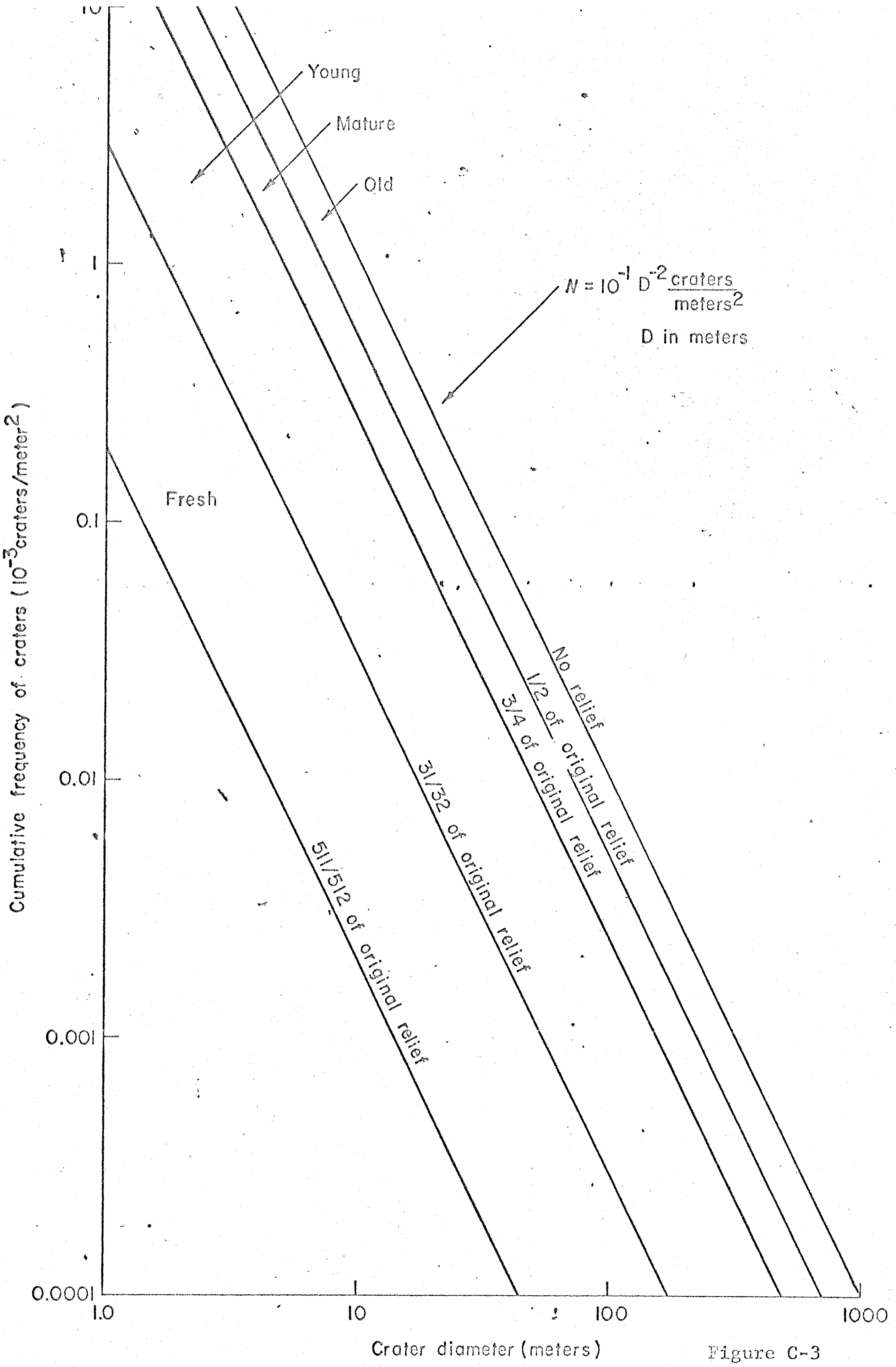
$$N = 10\, D^{-3} \quad (D > 200\text{m}).$$

C. Some uplands:

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

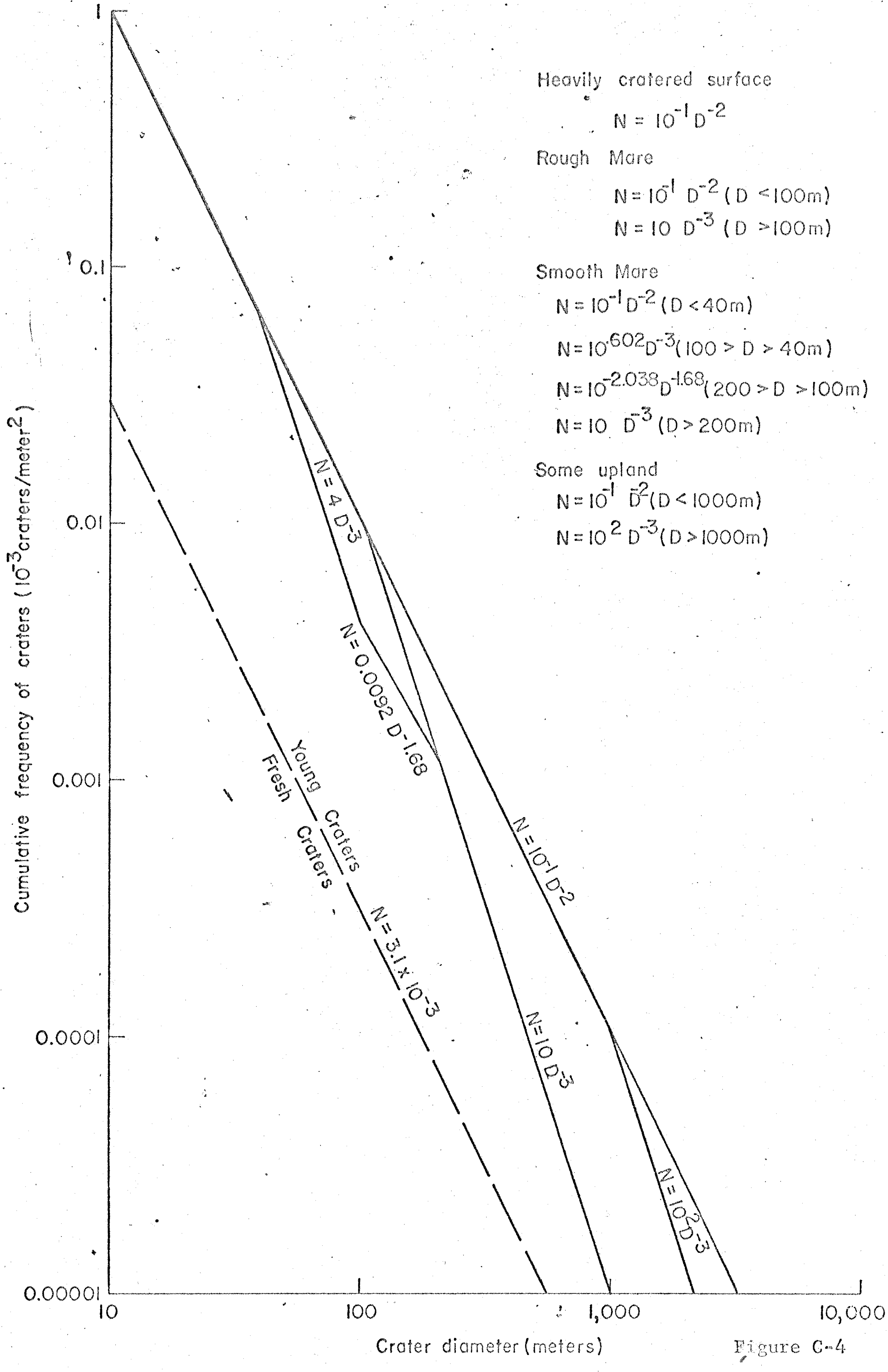
$$N = 10^{2}\, D^{-3} \quad (D > 1000\text{ m})$$

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})
Crater diameter (meters)
10
1
0.1
0.01
0.001
0.0001
1.0
10
100
1000

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 x 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 ($\approx$ 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

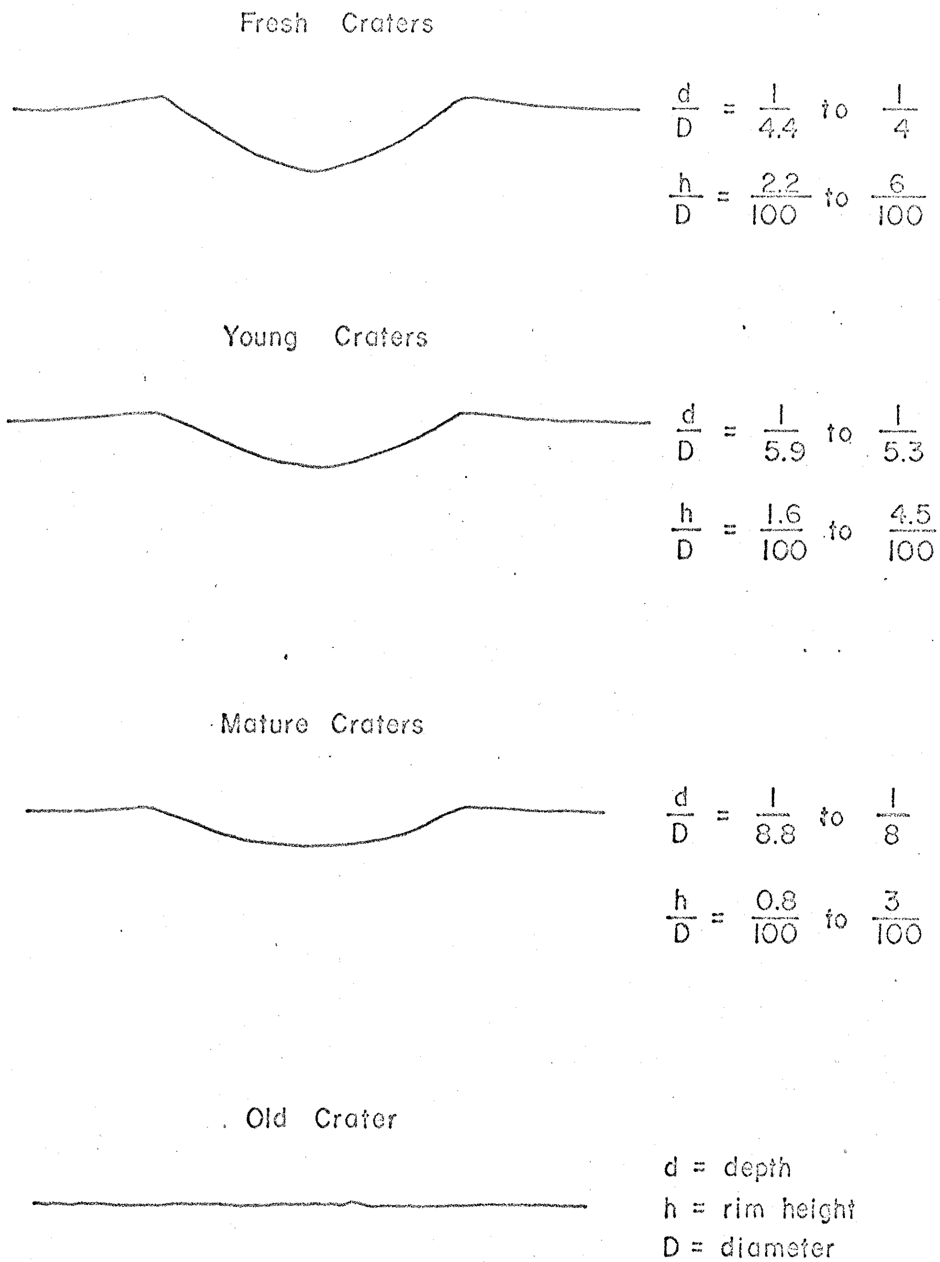
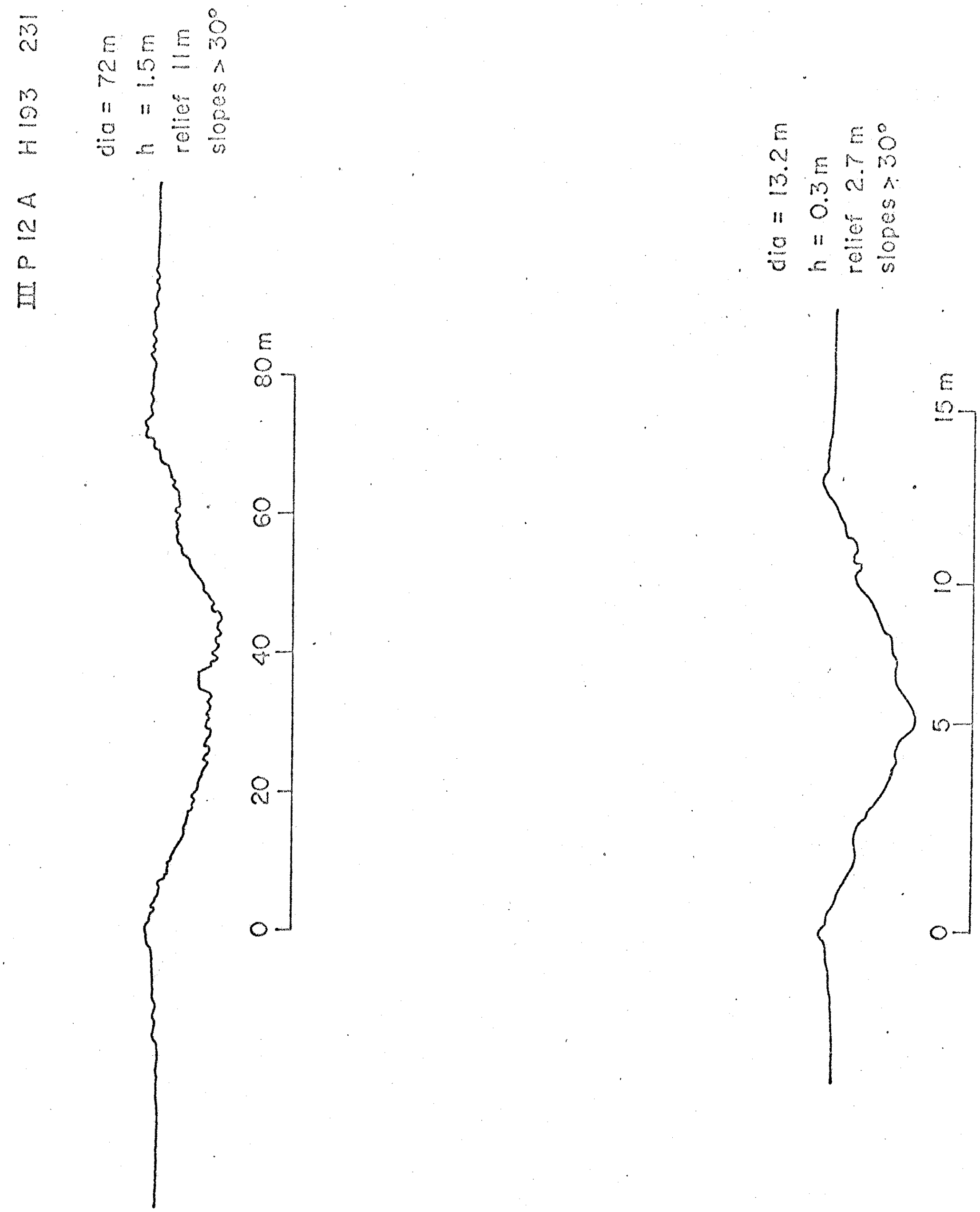

Fresh Craters
d/D = 1/4.4 to 1/4
h/D = 2.2/100 to 6/100
Young Craters
d/D = 1/5.9 to 1/5.3
h/D = 1.6/100 to 4.5/100
Mature Craters
d/D = 1/8.8 to 1/8
h/D = 0.8/100 to 3/100
Old Crater
d = depth
h = rim height
D = diameter

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

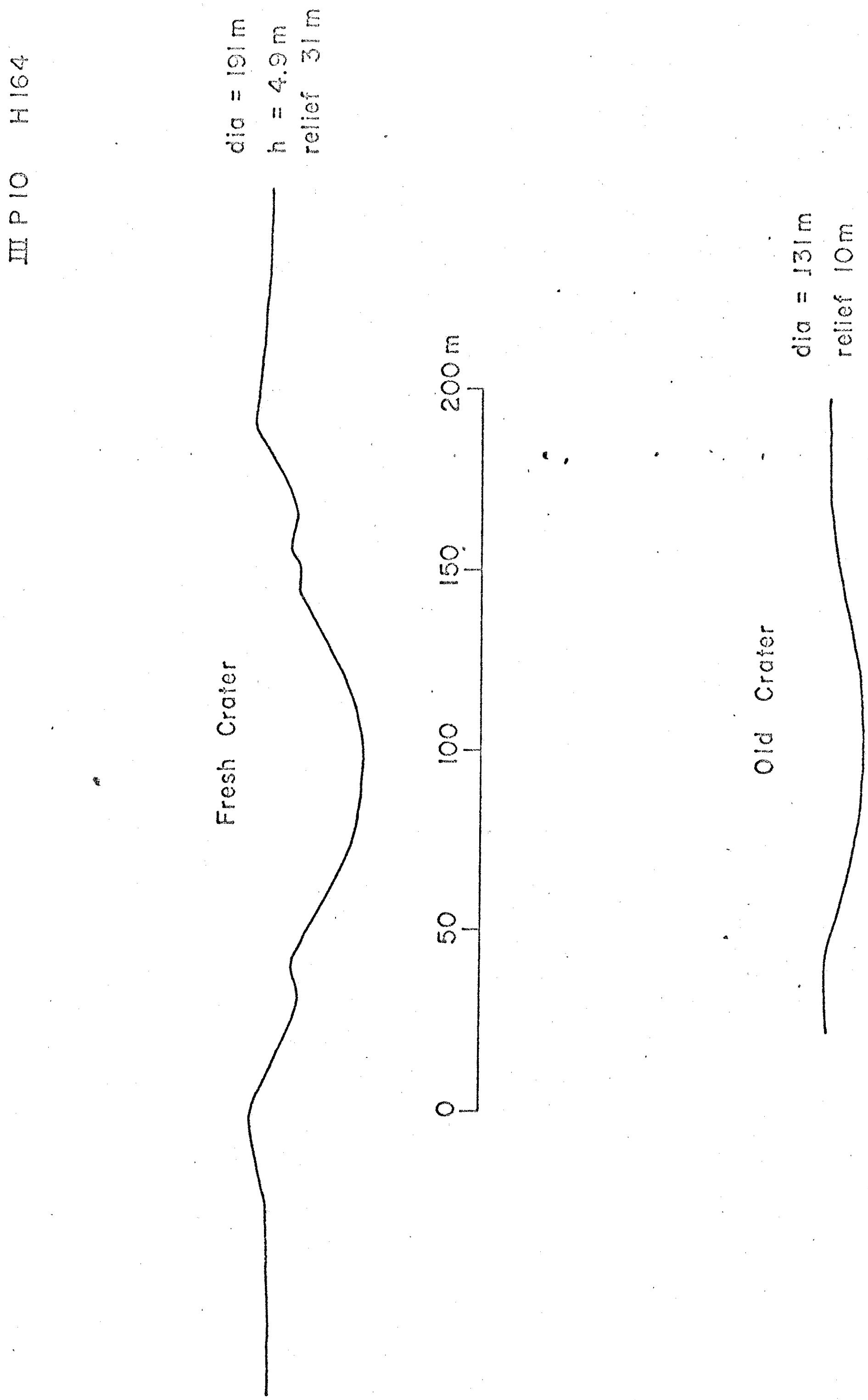
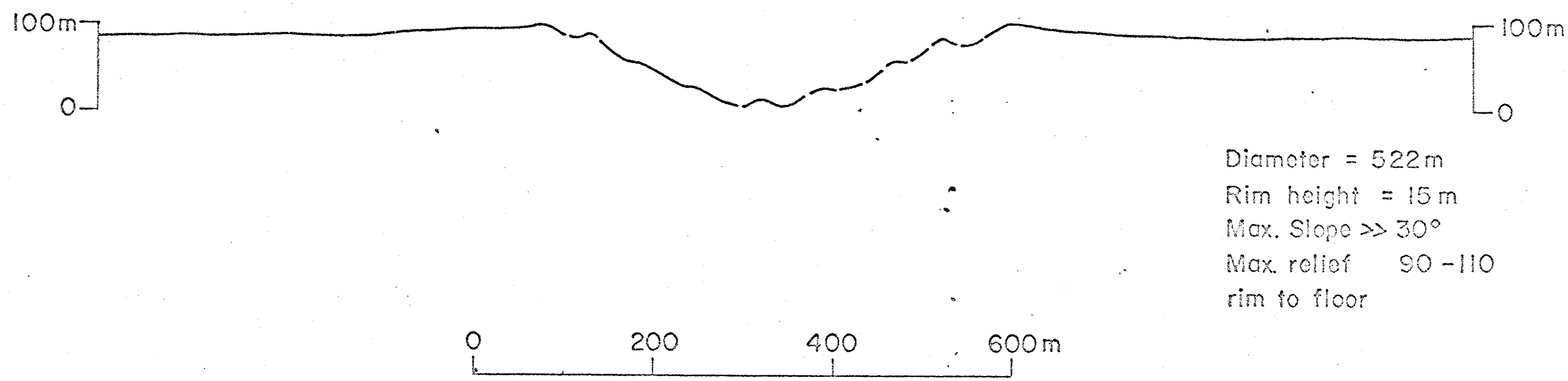

III P10 H164
dia = 191 m
h = 4.9 m
relief 31 m
Fresh Crater
200 m
150
100
50
0
dia = 131 m
relief 10 m
Old Crater

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



III P 12 A H 189 628 8.6 cm
I 3 X M 200 227 27.9 cm
Stereo pair I 3 X M 184 190

Figure C-8

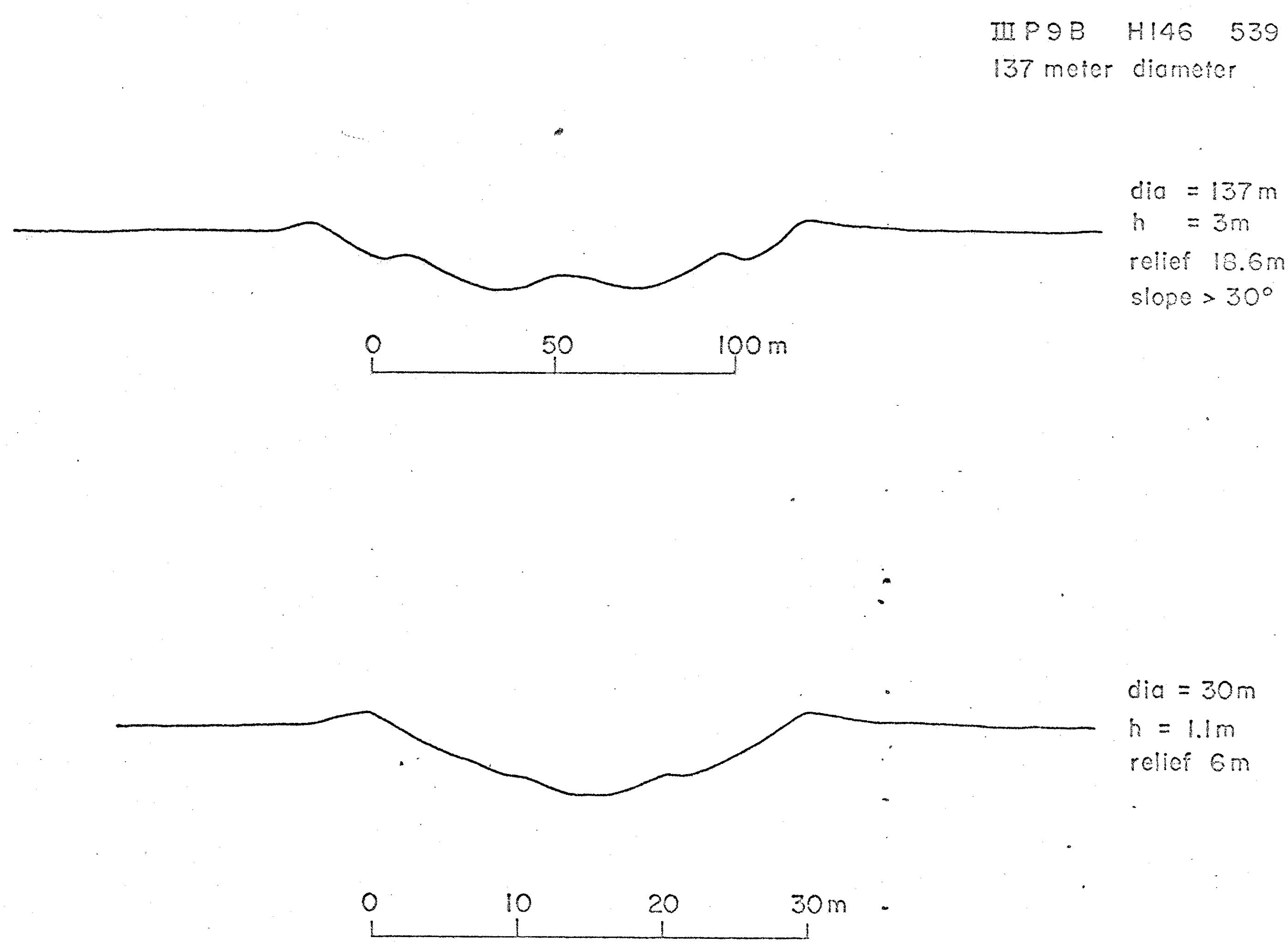
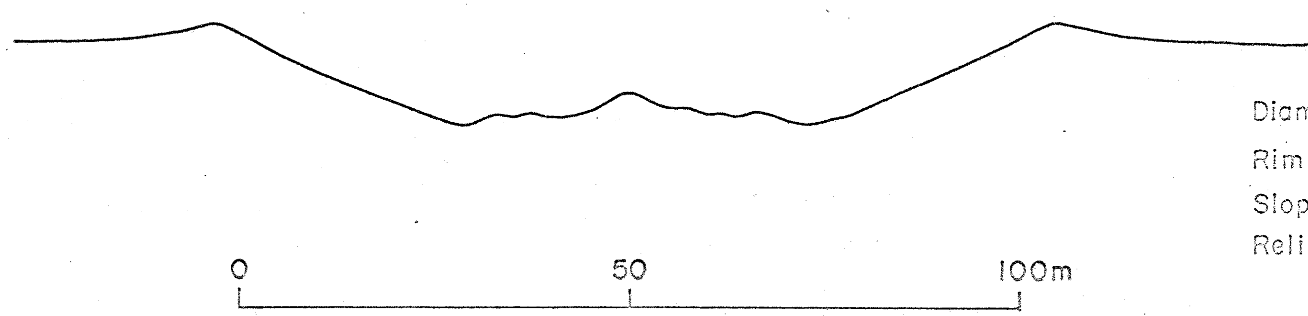

III P9B H146 539
137 meter diameter
dia = 137 m
h = 3m
relief 18.6m
slope > 30°
0
50
100 m
dia = 30m
h = 1.1m
relief 6m
0
10
20
30m

Figure C-9

III P 6 H 70



Diameter = 107m
Rim height = 2.2m
Slope 30°+
Relief 13m

Figure C-10

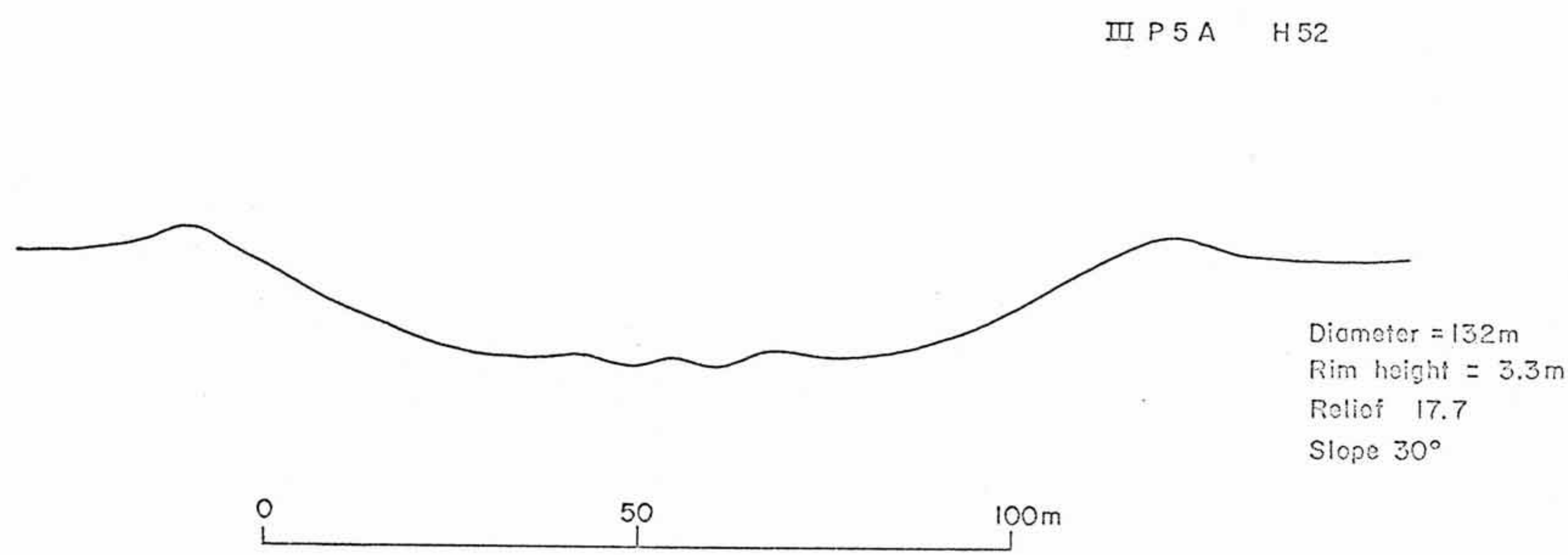

III P 5 A H 52
Diameter = 132m
Rim height = 3.3m
Relief 17.7
Slope 30°
0
50
100m

Figure C-11

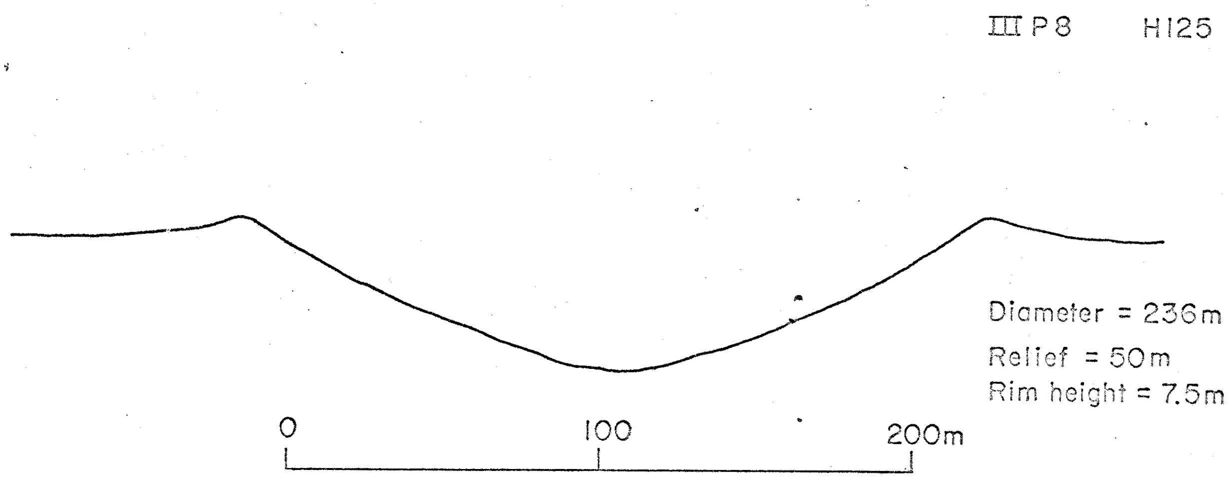

III P8 H125
Diameter = 236m
Relief = 50m
Rim height = 7.5m
0
100
200m

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

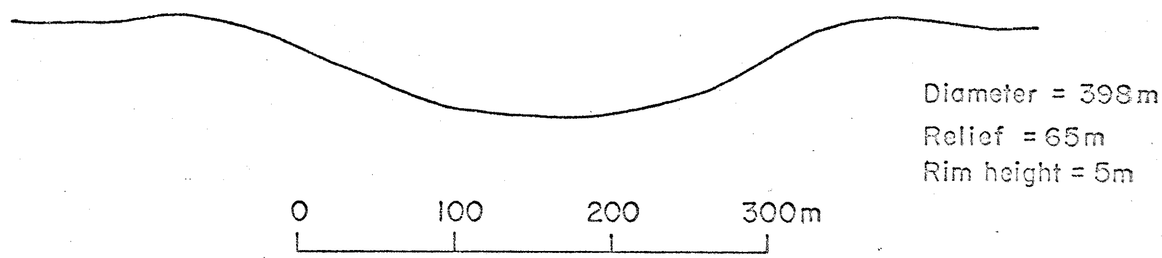


Figure C-13

III P 8 H 124

Figure C-14

Surveyor III

Old Crater

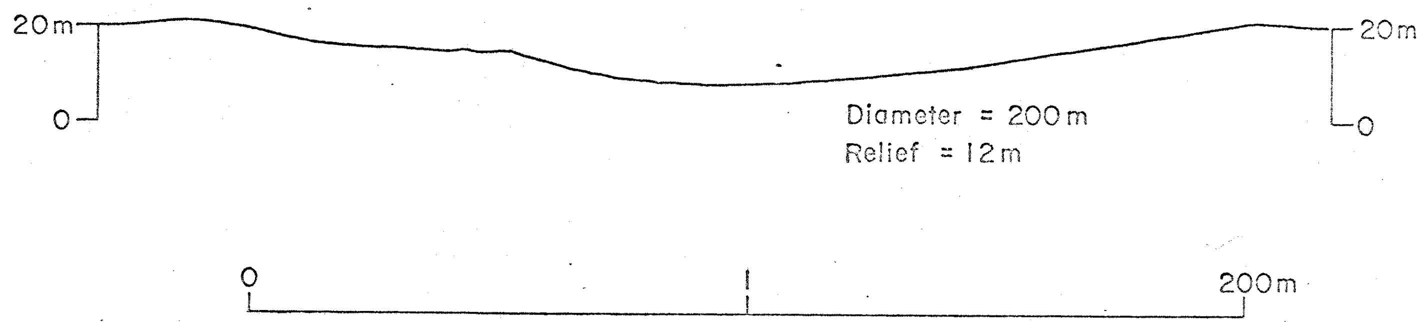


Figure C-15

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