UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Distribution and relationships of 4-10 km diameter craters to global geologic units on Mars

by

Christopher D. Condit

Open-file report 77-421
1977

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Introduction

One of the major problems in planetary geology is the stratigraphic correlation of photogeologic-geomorphic units. Stratigraphic correlations, inferred from spacecraft images which afford little vertical control, are difficult to assign. One of the tools which has been applied to this problem is crater density data (that is, the number of craters per square unit area). Given the assumption the flux of impacting bodies has been reasonably constant since planetary accretion, geologists have counted the number of craters on a surface and inferred a different age for a more or less densely cratered surface. Using various size ranges of craters, this technique has been applied to small areas on Mars with reasonable success. This study extends the scope of such work to examine the global distribution of 4-10 km diameter craters and their relationship to planetwide geologic-geomorphic units.

In order to examine this relationship, the distribution of 4-10 km diameter craters on the surface of Mars between about ±65° lat., based on Mariner 9 images, has been digitized and displayed as a Mercator projection at 1:25,000,000 (1:25 M) scale. For the purpose of this study, the open file 1:25 M geologic map of Scott and Carr (1976) between ±65° lat. has also been digitized and displayed. The density of 4-10 km diameter craters (hereafter referred to as intermediate craters) for 23 of the equatorial geologic units has been compiled using a computer to compare the two digitized data sets. The age relationships among the 23 geologic units was examined by using the data generated by this comparison.

The objective of this paper is to present these data, and a description of the techniques used in obtaining them, in an effort to better define the stratigraphic relationships of these 23 geologic units on Mars. The digitized intermediate crater density data have been used previously by Soderblom and others (1974) in a paper which explains the justification for selecting a 4-10 km crater diameter size range whose densities are considered valid indicators of relative surface ages. A preliminary comparison of Viking I and Mariner 9 data has been made in order to substantiate the reliability of the planetwide Mariner 9 photographic coverage with respect to the density of intermediate craters.

Collection and digitization of intermediate craters

Crater densities were obtained from 1600 Mariner 9 MTVS (Mission Test and Video System) wide angle frames by using the reseau marks as sampling grids. These data were normalized to the density of craters per $10^6 km^2$ by establishing the altitude of each image and calculating the area within each reseau grid. These data were then compiled on 1:5 m scale photomosaics by averaging the normalized crater densities within the reseau grid into a more systematic array comprised of approximately 1.5° square grids (with 1.07° by 1.40° sides). When the 1:5 m arrays were mosaicked into a 1:25 M scale map, the composite array contained 122 lines (horizontal rows) of data (equivalent to 130° lat., or ±65° lat.) and 258 samples (vertical columns) of data (equivalent to 360° long.). Because of poor Mariner 9 images above 45°N lat., no crater density data were collected in this zone.

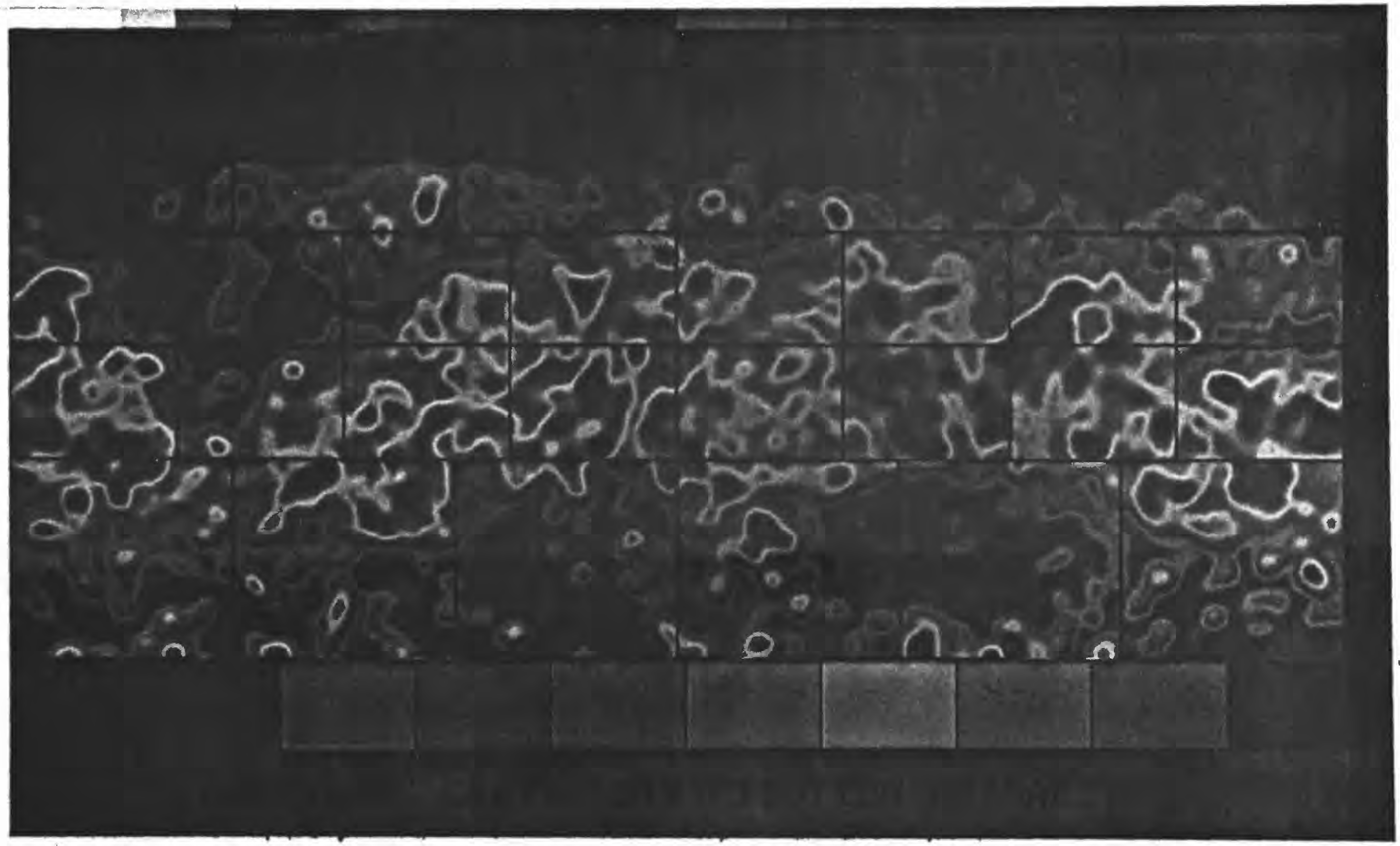

Figure 1. Digitized 4-10 km diameter crater density map of Mars between 65° north and south latitudes. 1:5 M quadrangle boundaries are outlined in black. Above about 45° north latitude (dashed line) no data were collected. Below about 40° south latitude data were collected but not used in this study. Color code at bottom shows least densely cratered surfaces in purple, most density cratered surfaces in red.

Within the final array the first 39 lines of data corresponding to this area from 65°N to 45°N lat. were compiled as zero crater density points, but were eliminated from this study. Thusly digitized (fig. 1) the data were in a format which could be compared to the digitized geologic map.

Digitization of 1:25 M geologic map

In 1976, D. H. Scott and M. H. Carr compiled a global geologic map of Mars at the 1:25 M scale, an effort which represents the synthesis and reinterpretation of the 1:5 M geologic map series based on Mariner 9 data. This open-file map (No. 76-753) was digitized by the author between ±65° lat., using a sample grid similar in format to that of the cratering data, containing 122 lines x 258 samples, or 31,476 data points. It should be pointed out that the digitized map differs slightly from the finalized version to be published in 1977. The three most marked differences are: 1) from 35°N - 35°S lat. near 100°W long. and near 38°N, 80°W, the fractured plains material has been deleted and incorporated into surrounding units, 2) at 20°S lat., 250°W long., the streaked plains material has been changed to ridged plains material, and 3) at 35°N lat., 255°W long., a patch of hilly and cratered material has been changed to cratered plateau material. Because of the small areal extent of the changes, it was thought unnecessary to change the digitized map to conform with the later version of the 1:25 m map.

Twenty-three different map units were recognized with the ±65° lat. zone. According to Soderblom and others (1974), intermediate crater densities are thought to be reliable indicators of relative age only in unmantled areas (roughly within the ±35° latitudes); debris mantles near the poles are thick enough to bury intermediate-size craters (fig. 2). For this reason, 16 of the 23 map units which occurred in areas north and south of the mantled zone were further subdivided, so that they could be excluded from the subsequent sorting process. An image of the entire digitized geologic map is shown in figure 3, with no subdivision of mantled geologic units.

Technique for separating crater densities of geologic units

Because the geologic and crater density data sets were compiled in identical formats, such that each point in one array corresponds to a discrete point of similar areal extent in the other, the two data sets can be compared. In this comparison, the unit designation in the geologic data set is used as a "look-up" table. This table assigns the crater density value found in the corresponding location to a discrete computer file for each of the 23 geologic units. By averaging the crater density values accumulated in each file, an "average" crater density value for a geologic unit was computed (see summary of technique in fig. 4). Before the sorting process was applied, each point in both data sets was expanded to 9 points in order to aid in the visual interpretation of the data.

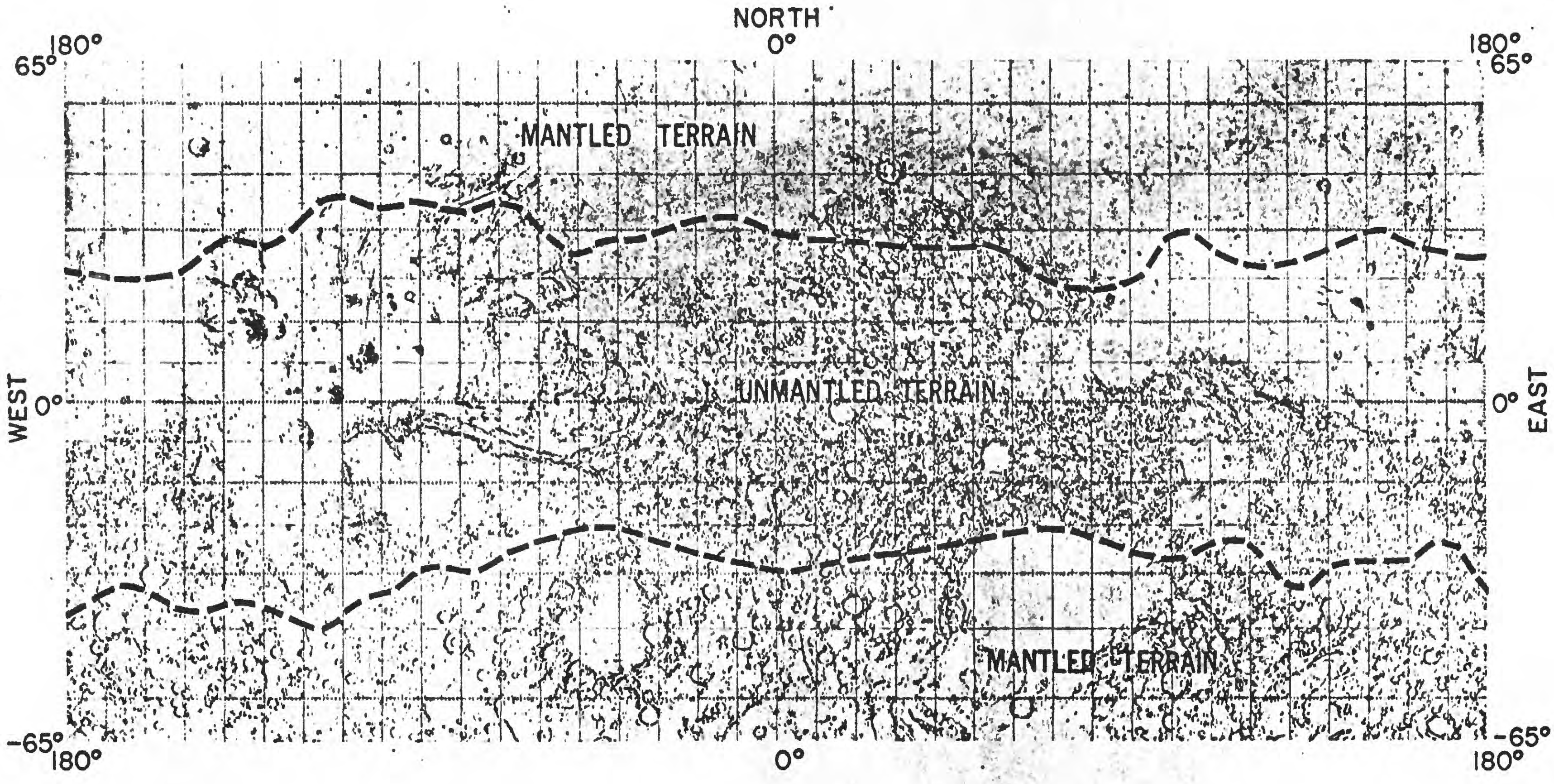

Figure 2. Distribution of thick Martian mantles (from Soderblom et al., 1973). No crater density data were considered in this study north and south of this boundary.

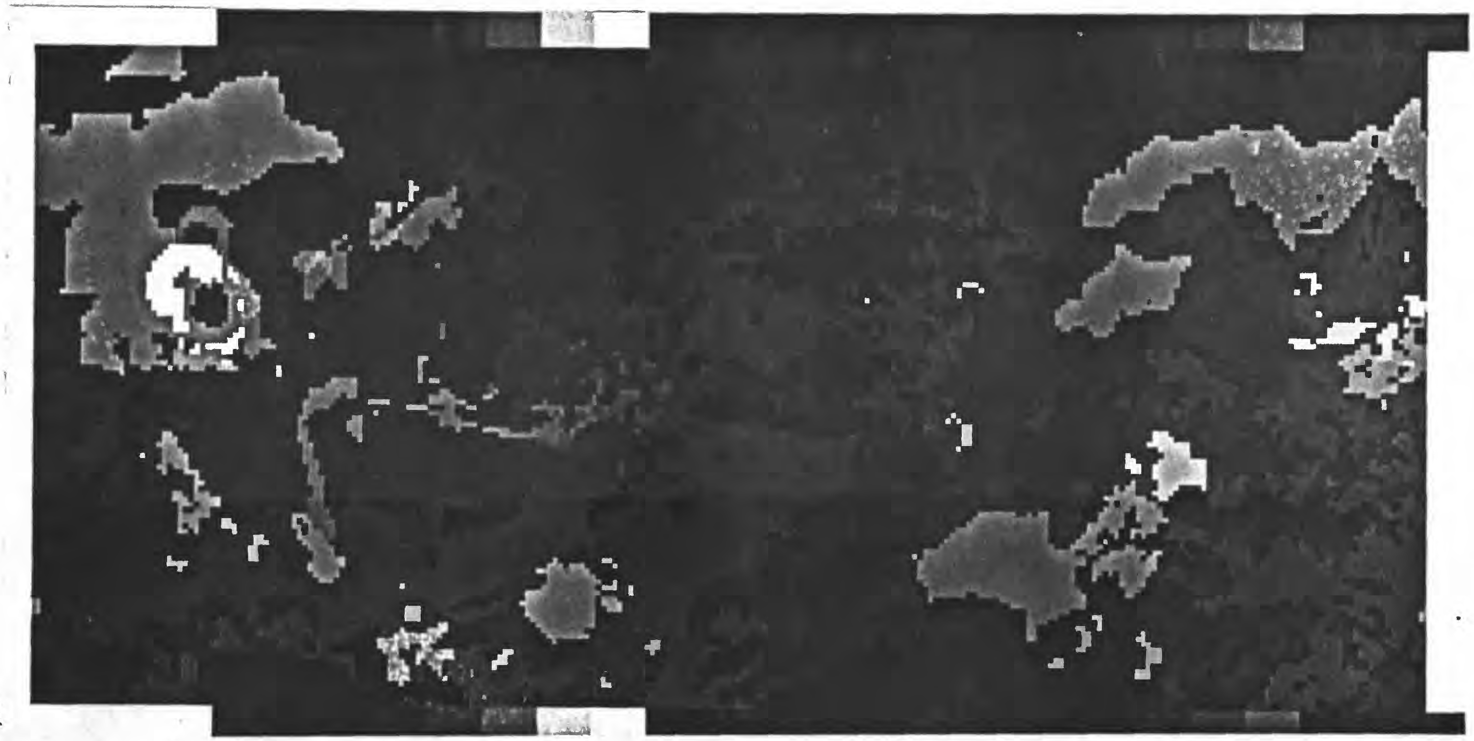

Figure 3. Digitized geologic map of Mars between 65° north and south latitudes. Twenty-three geologic units were digitized from the 1:25 M geologic map of Scott and Carr (1976).

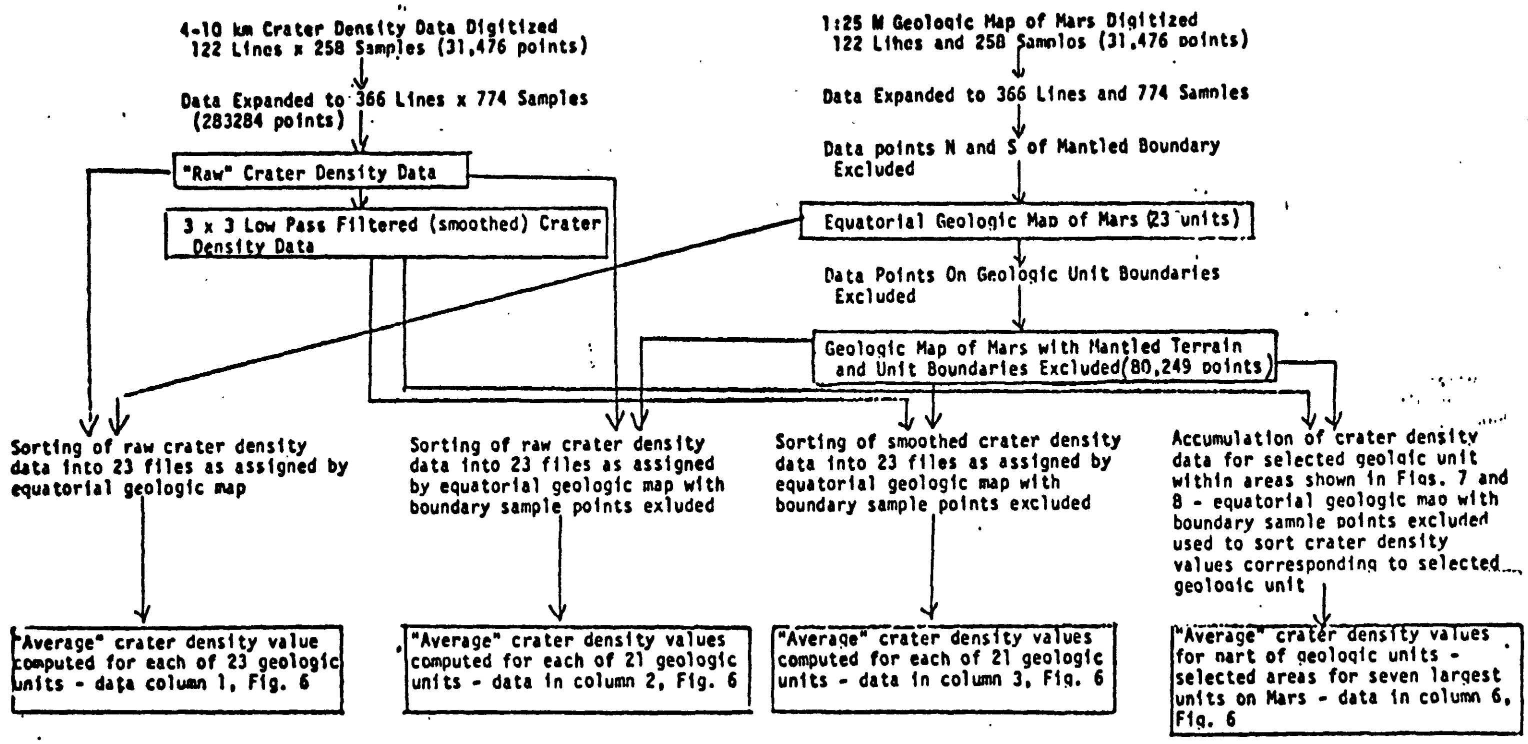

Figure 4. Flow chart showing steps involved in processing the data presented in table 2. The left hand column shows the initial processing steps of the crater density data; the right hand column shows the steps involved in processing the geologic data. The four lower columns depict how the crater density and geologic data were combined, and give the appropriate column in table 2 in which these data can be found.

Comparison of Mariner 9 and Viking crater counts

The recent acquisition of Viking orbital images offers a possibility to assess the accuracy of Mariner 9 crater counts in selected areas for which Viking frames have been mosaicked. Because of the large scale of the Viking images, it is doubtful that a planetwide mosaic of these images will be produced and therefore, it is important to evaluate the reliability of crater counts made from the global mosaic of Mariner 9 images. Ten Viking mosaics were examined, and intermediate crater counts obtained from them were compared to crater counts made from Mariner 9 images within the same area (table 1). The Viking images were taken from 9900 km to 1500 km altitude, the Mariner 9 images from 2800 km to 1700 km altitude. Column 3 of table 1 shows the number of craters counted using Mariner 9 and Viking images. Column 4 shows the relative percent, with Viking counts considered as the total. It is apparent from these figures, that small areas which have few craters give the highest percent error, which is not surprising considering the statistical errors of small sample numbers. However, when the overall number of craters counted are compared, 86 percent of all craters found in the Viking images were recognized in the Mariner 9 data. Because this study deals with geologic units much larger than the small areas represented in table 1, the author believes the results for <u>major</u> units would differ little if Viking data were used instead of Mariner 9 data. Column 5 of table 1 shows the total number of

Table 1. Comparison of Mariner-9 cratering data to cratering data collected from Viking images. Last column gives the number of degraded craters as compared to the total number of craters found on the Viking images.

Area Number	Approximate center of mosaic	Approximate area of mosaic	Number of craters counted Mariner 9/Viking	Percent of Mariner 9 craters compared to Viking craters	Number of degraded craters as compared to total number of Viking craters
1	[illegible]	1.4 x [illegible]	[illegible]	89%	11/179
2	10°N,60°W	$1.4 \times 10^5 km^2$	25/25	100%	4/25
3	25°N,44°W	$1.4 \times 10^5 km^2$	9/12	75%	0/12
4	21°N,59°W	$9.5 \times 10^4 km^2$	18/22	82%	2/22
5	22°S,251°W	$1.1 \times 10^6 km^2$	154/197	78%	15/197
6	25°S,120°W	$1.4 \times 10^6 km^2$	98/98	100%	6/98
7	11°N,24°W	$7.5 \times 10^4 km^2$	22/36	61%	11/36
8	33°N,210°W	$4.8 \times 10^4 km^2$	9/9	100%	3/9
9	12°S,85°W	$1.7 \times 10^5 km^2$	29/29	100%	4/29
10	22°N,54°W	$1 \times 10^5 km^2$	13/19	68%	2/19
		Totals	536/626	86%	58/626 or 9.3%

craters counted in the Viking images as compared to the number of those craters which had been degraded into flat-floored craters. About 9 percent of the craters counted had been degraded, which suggests that within the unmantled zone (±35° lat.), 4-10 km diameter craters are large enough to have been preserved since the time of their formation and thus their net accumulation may be used as a reliable indicator of the relative age of the surface of Mars.

Limitations of the technique

The technique used to define relative surface ages of geologic units is, of course, only as good as the data base (given that the relative density of intermediate craters is an indicator of relative age). The map used as the base for digitizing the geologic units, and that digitization, are straightforward to discuss. The second data base, that of crater counts and the problems inherent in their statistical treatment, is more difficult.

The 1:25 M geologic map of Mars is a reinterpretation and condensation of the 1:5 m quadrangles mapped using Mariner 9 data as a base. The author feels that 1:25 M map, if regarded as a photo-geologic-geomorphic product and put into the context of a global synthesis, is useful as a first approximation of the areal extent of geologic units. The comparison of Viking mosaics with existing 1:5 M geologic maps has lead the author to conclude that most boundaries on the 1:5 M maps will probably change very little in the equatorial maps (where the Mariner 9 images were good), although there may be reinterpretation of lithologies and better definition of gradational geologic contacts. The new Viking images will undoubtedly enable planetary mappers to further subdivide units, but this does not affect a smaller scale map. The 1:25 M map is at an ideal scale for comparison with the global intermediate crater densities. However, there is one difficulty with the digitization of the map, this dictated by the size of the sample cells of the digitized crater data. Because the digitization is fairly coarse, small units and abrupt changes in unit boundaries are often lost. Also, data points which straddle unit boundaries will not accurately assign crater densities to the proper unit. Little can be done about the former and therefore, units with small numbers of points must be regarded as relatively inaccurate. In order to eliminate possible data points which in digitization straddles unit boundaries, all points which were in contact with dissimilar geologic units were eliminated from the sorting process. Thus, crater density values which coincide in location with geologic unit boundaries are lost, a trade off in that while density values will not be assigned to the wrong geologic unit, the statistical strength (that is, the number of data points) in each unit will suffer.

Two problems must be addressed when assessing the accuracy of the intermediate crater counts. The first is that of collection. As has been pointed out, the Mariner 9 images, on an average showed 86 percent of the craters found in the Viking images. This quality varied, due to operator bias collecting the data but more importantly to Mariner 9 image quality. MTVS images, from early in the Mariner 9 mission are poor in quality because of atmospheric haze. Also, images taken from high orbital altitudes lack the resolution of lower-orbit images. The Viking mosaic at 11°N lat., 24°W long. (area 7, table 1) is an example of the complex problem of collecting data from a small area ($7.5 \times 10^4 km^2$) in which a large percentage of the craters are degraded and thus could not be recognized from the 2200 km altitude of the Mariner 9 A-frames.

When dealing with the number of craters which are correlated to a given square unit area on the surface of a planet, several limiting factors must be considered. While it is important to keep as high a resolution as possible, it is also necessary that this area be large enough so that the number of craters per unit area will be large enough to be statistically accurate. This obviously becomes a trade off -- in order to increase the area to give a large enough sampling of craters to be statistically reliable, resolution must be sacrificed. The data in this paper as displayed in table 2 were treated in three ways (fig. 4). Column 1 shows the average "raw" or unfiltered crater density data as accumulated using the geologic data set without the edges of the units removed. Column 2 shows the same data, but uses a sorting routine in which crater density data from the edges of the geologic units have been excluded. Column 3 uses a sorting routine in which crater density data from the geologic edges has been excluded, and in which the average crater density value is obtained from data

Table 2. Four to Ten Km diameter crater density statistics for geologic units and parts of geologic units on Mars. The numbers given in columns 1, 2, 3, and 6 give the average number of craters/10^6km^2 for the unit or part of unit listed on the left of the figure. The variations between these average numbers result from different processing techniques as summarized in figure 4 and the text. The parts of geologic units examined as listed in columns 6-8 are outlined in figures 5 and 6.

	Raw Crater Data 1	Raw Edge Removed 2	3x3 LPF Edge Removed 3	4	5	3x3 LPF Edge Removed Area	6	7	8
	Mean	Mean	Mean	Population Number	%	Area and Approximate Center of Area	Mean	Population Number	% of Total Population (80249)
Aurole Material	14.3	4.6	5.0	676	0.84				
Tharsis Volc Plains	27.6	21.9	20.9	4,637	5.78				
1 - N						pT-1 15°N 96°W	16.7	1,987	2.47
2 - S						pT-2 14°S 115°W	24.4	2,423	3.01
Young Volcanics	35.4	36.1	32.9	401	0.51				
Canyon Floor	43.0	36.5	36.7	203	0.25				
Mottled Plains	33.2	41.0	40.4	118	0.15				
Volc. Interm.	48.2	44.2	41.6	1,383	1.72				
Volc. undivided	54.0	NONE	NONE	NONE	NONE				
Smooth Plains	58.8	58.0	56.6	6,548	8.14				
1						ps-1 15°N 138°W	43.0	2,304	2.87
2						ps-2 15°N 246°W	57.1	1,711	2.13
3						ps-3 38°S 123°W	16.4	343	0.43
Channel Material	91.1	62.8	62.4	324	0.40				
Rolling Plains	73.4	67.8	66.2	4,140	5.16				
1						pr-1 9°S 157°W	76.5	1,045	1.30
2						pr-2 19°N 201°W	59.0	351	0.43
Plains Material	88.9	82.8	80.4	15,251	19.00				
1						p-1 20°N 105°W	63.8	3,004	3.74
2						p-2 20°S 70°W	99.1	2,512	3.13
3						p-3 26°N 22°W	36.7	3,020	3.76
4						p-4 20°N 240°W	95.0	3,690	4.60
Fractured Plains	90.2	96.2	93.8	1,257	1.57				
Crater Material	107.4	100.3	114.0	38	0.05				
Old Vol. Material	140.9	116.9	118.1	94	0.12				
Fissured Material	140.0	139.2	126.0	25	0.03				
Ridged Plains	124.2	131.5	128.4	8,841	11.02				
1						prg-1 21°N 68°W	113.3	2,792	3.48
2						prg-2 22°S 90°W	140.1	3,358	4.18
3						prg-3 3°S 278°W	141.1	1,373	1.71
4						prg-4 28°S 232°W	154.3	748	0.93
Knobby Material	99.6	133.0	131.3	506	0.63				
Hilly & Cratered	141.4	142.3	137.1	14,302	17.82				
1						hc-1 30°S 158°W	175.0	1,050	1.31
2						hc-2 12°N 337°W	82.4	2,986	3.72
3						hc-3 22°S 337°W	115.5	2,585	3.22
4						hc-4 23°S 246°W	159.4	2,131	2.66
5						hc-5 30°S 233°W	126.9	1,572	1.96
Cratered Plateau	134.8	140.6	137.8	19,587	24.41				
1						plc-1 30°S 142°W	128.2	3,493	4.35
2						plc-2 18°S 7°W	159.7	4,060	5.06
3						plc-3 27°S 195°W	159.0	667	0.83
Streaked Plains	133.2	152.2	148.7	705	0.88				
Chaotic Material	110.5	167.9	162.9	115	0.14				
Basin Rim	173.6	172.0	167.5	1,090	1.36				
Mountain	218.9	NONE	NONE						
				80,249					61.28
				Total Population					Percent of total population checked

which has been smoothed using a 3-line by 3-sample low-pass filter. This filter smooths data so that such crater density data point is averaged with its eight surrounding values and the original value replaced with this average value. If the geologic boundaries of the units are valid, the mean of the 3 x 3 low-pass filter with the edge removed should give the "average" relative age of the geologic unit. This average relative age is as valid statistically as the area of the geologic unit defining the number of crater density values included in the average. This number is given in the fourth column of table 2 as the population number. It should be pointed out that this population number must be divided by 9 in order to obtain the actual number of digitized points originally counted. The total population of all crater density values used, after units north and south of the mantled boundaries and also all unit edges have been excluded, is 80,249. The fifth column gives the percentage of crater density data points in each geologic unit with respect to the total population of 80,249. Thus units with a smaller percent must be regarded as relatively less accurate than those with a larger number of points.

Evaluation and speculations

Because of both statistical limitations, and those imposed by the data base, the average crater densities given in table 2 should be regarded as approximate values for global wide geologic units. When the seven largest units considered are subdivided into smaller areas (as outlined in figures 5 and 6 with values given in columns 6-9 in table 2), several areas of disagreement are apparent. These areas of disagreement may arise from several sources in both the crater density data set and the geologic data set. Problems in the crater density data set include: 1) crater counting techniques, 2) limitations of the photographic quality, 3) coarse digitization, 4) statistics of small numbers, and 5) lack of error bars in the "average" crater density values. Problems in the geologic data set include: 1) gradational contacts, 2) possible similar geomorphic signature of units which formed at different times, 3) the necessity of defining stratigraphy from a photographic data base, and 4) variations in the crater-retention ages of various materials. In spite of those problems, a general agreement can be seen between the average crater density value of the units, as defined in this study, and that shown by Scott and Carr (1976) in figure 7. In this figure, average crater density values are shown with the stratigraphic sequence of the units. Average crater density values with the best statistical foundation are underlined, those with less foundation are in parentheses, and those with the least are enclosed in brackets.

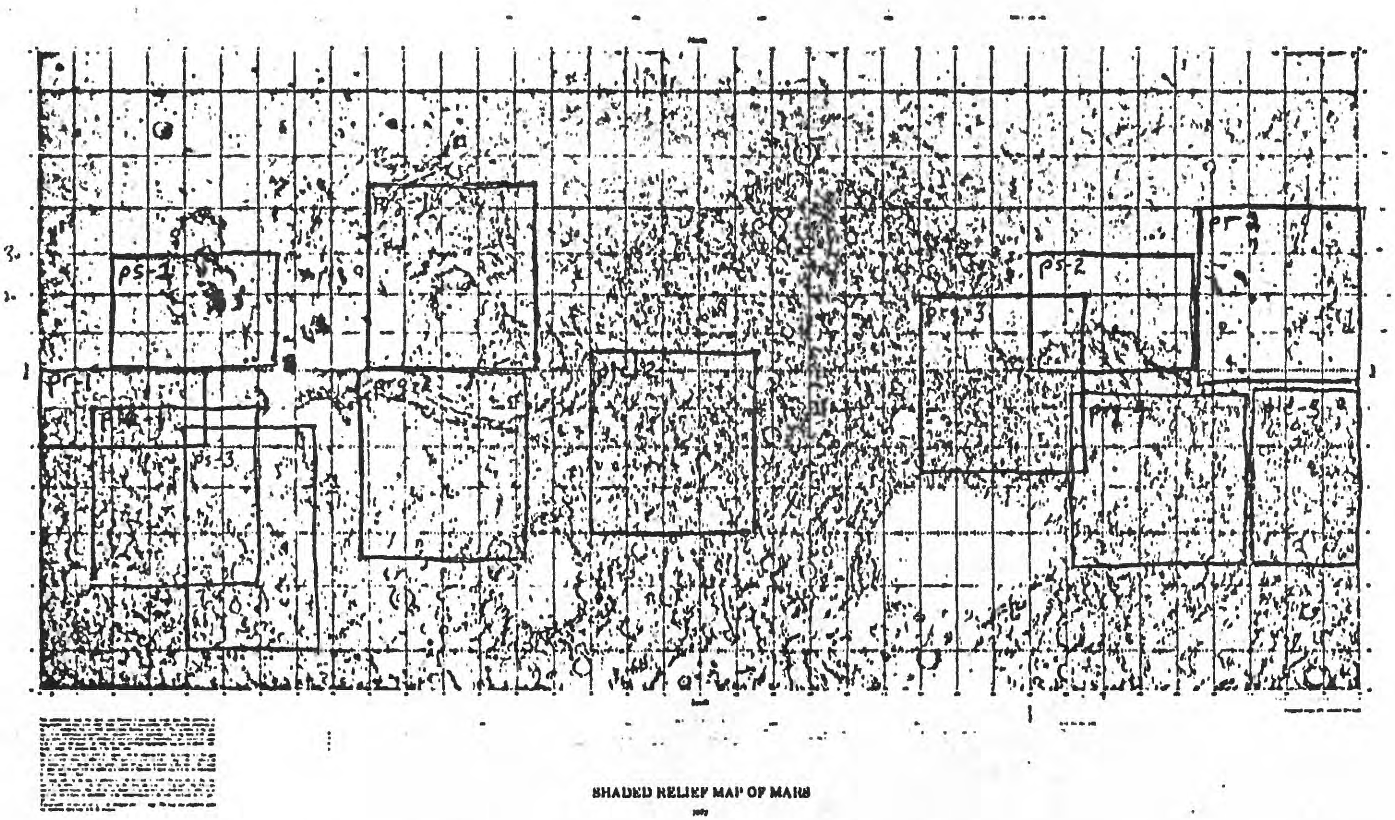

Figure 5. Shaded relief map showing parts of geologic units for which average crater density data has been obtained. The average crater density for these areas can be found in column 6 of table 2. Parts of geologic units examined which are on this map include: (smooth plains) ps-1 to ps-3; (rolling plains) pr-1 and pr-2; (ridged plains) prg-1 to prg-4; (cratered plateaus) plc-1 to plc-3.

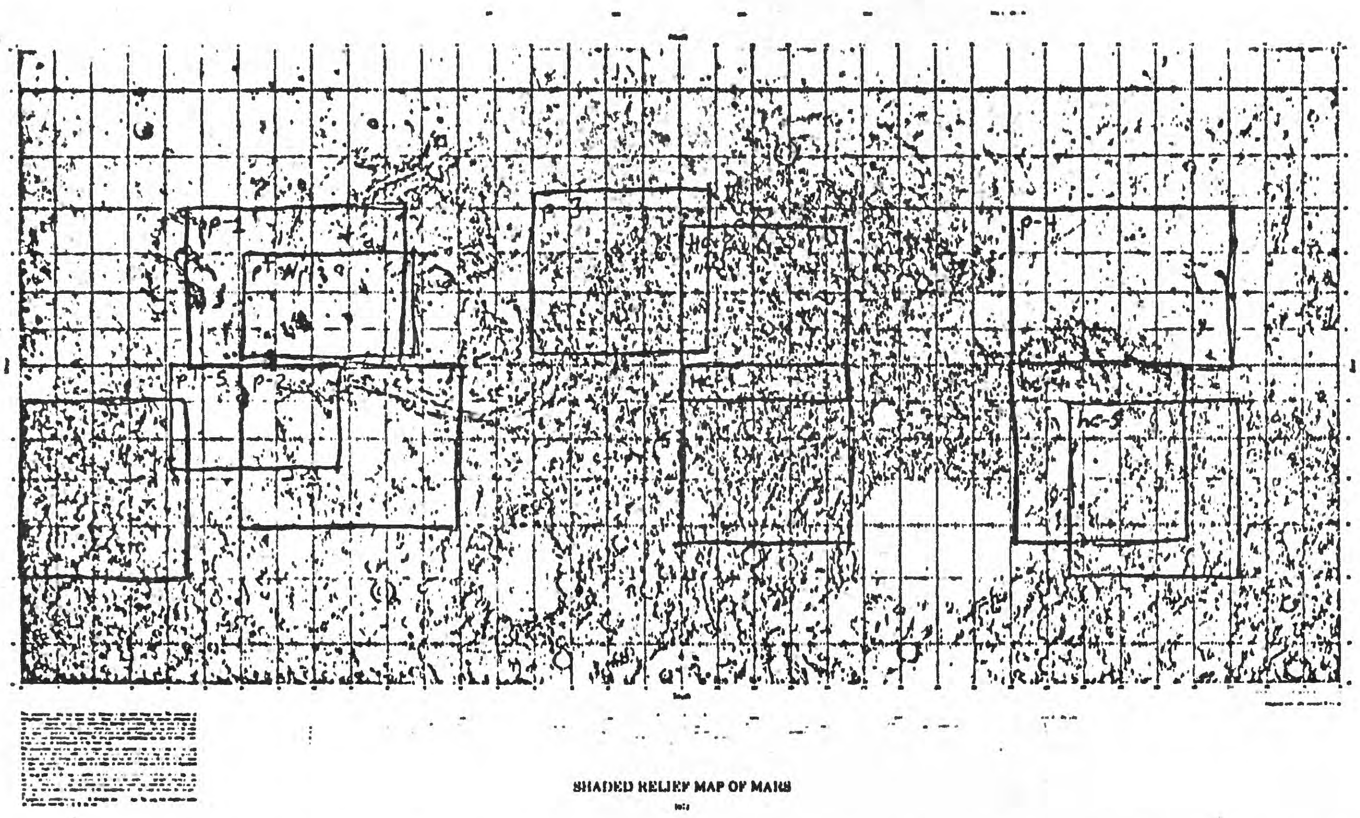

Figure 6. Shaded relief map showing parts of geologic units for which average crater density data has been obtained. The average crater density for these areas can be found in column 6 of table 2. Parts of geologic units examined which are shown on this map include: (Tharsis volcanics) pT-1 and pT-2; (plains p-1 to p-4; (hilly and cratered) hc-1 to hc-5.

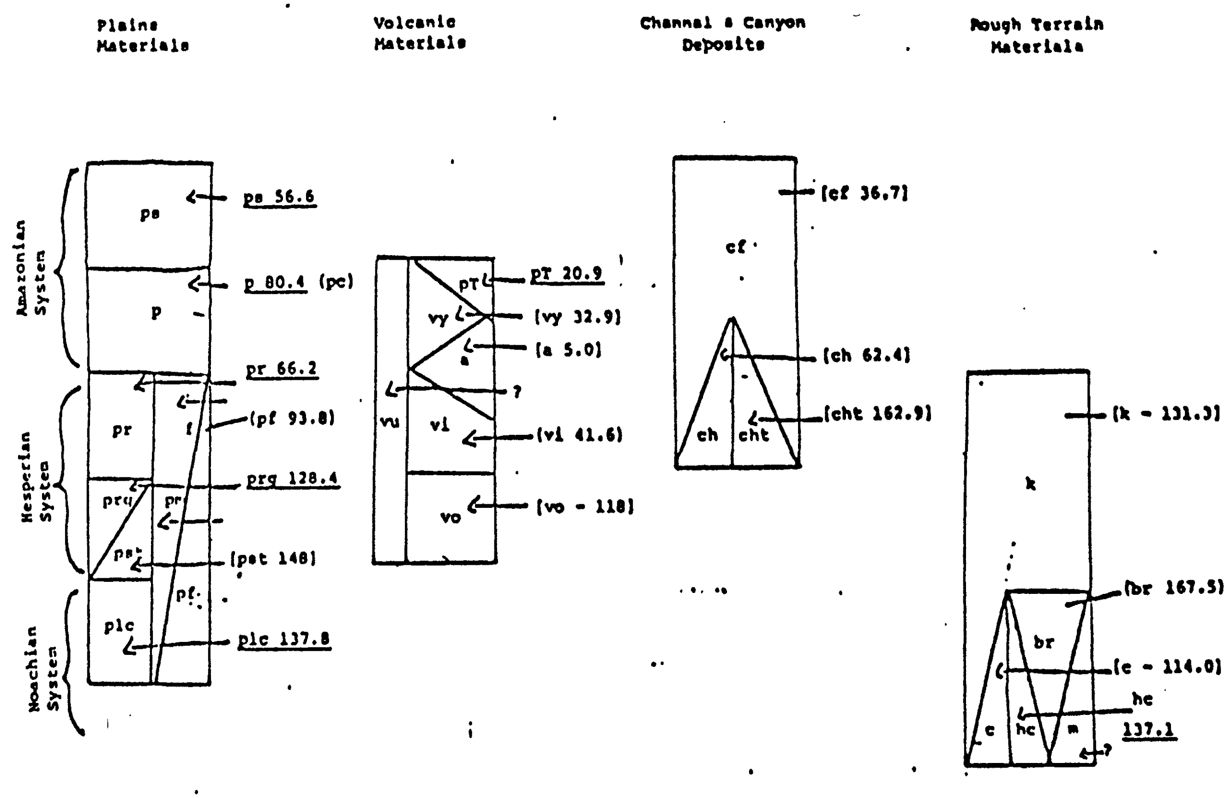

Figure 7. Comparison of original stratigraphic sequence proposed by Scott and Carr (1976) with average crater density values compiled in this study. Values with greatest statistical strength are underlined; those with less strength are (in descending order) contained in parenthesis and finally in brackets. A general agreement in relative age is apparent from this figure. Rock unit symbols can be found in figure 8 caption.

A subsequent comparison of crater density data and the stratigraphic sequence resulted in figure 8 (Scott and Condit, 1977) which compares the stratigraphic sequence of martian rocks as plotted against the number (N) of intermediate (4-10 km) craters/10^6km^2. A good correlation can be found between the boundaries of the younger geologic units, and boundaries defined by the changes in crater density map-specifically the Tharsis volcanics (unit pT), the smooth plains (unit ps) and the plains (unit p) materials (figs. 1 and 3).

Other possibilities exist for the use of this type of technique using a better crater data base, perhaps one incorporating the best Mariner 9 images replaced where possible by Viking images. Where boundaries in geologic units are indistinct or gradational, crater density maps may aid in defining the boundary. Also, several areas, such as the one located at 30°N lat., 20°W long. may be re-examined and assigned to another unit. Here the plains materials with an average value of 80.4 craters/10^6km^2 has an anomalously low value (area 3 of plains material) of 36.7 craters/10^6km^2 and might better be classified as smooth plains which has an average value of 56.6 craters/10^6km^2. The crater density data in areas 1 (north) and 2 (south) of the Tharsis volcanics, although possibly reflecting the statistics of small numbers, might lead to the observation that the northern surface of the Tharsis volcanic material is younger than the southern surface. These are speculations, however, but do indicate a useful application for a strengthened data base using a similar technique.

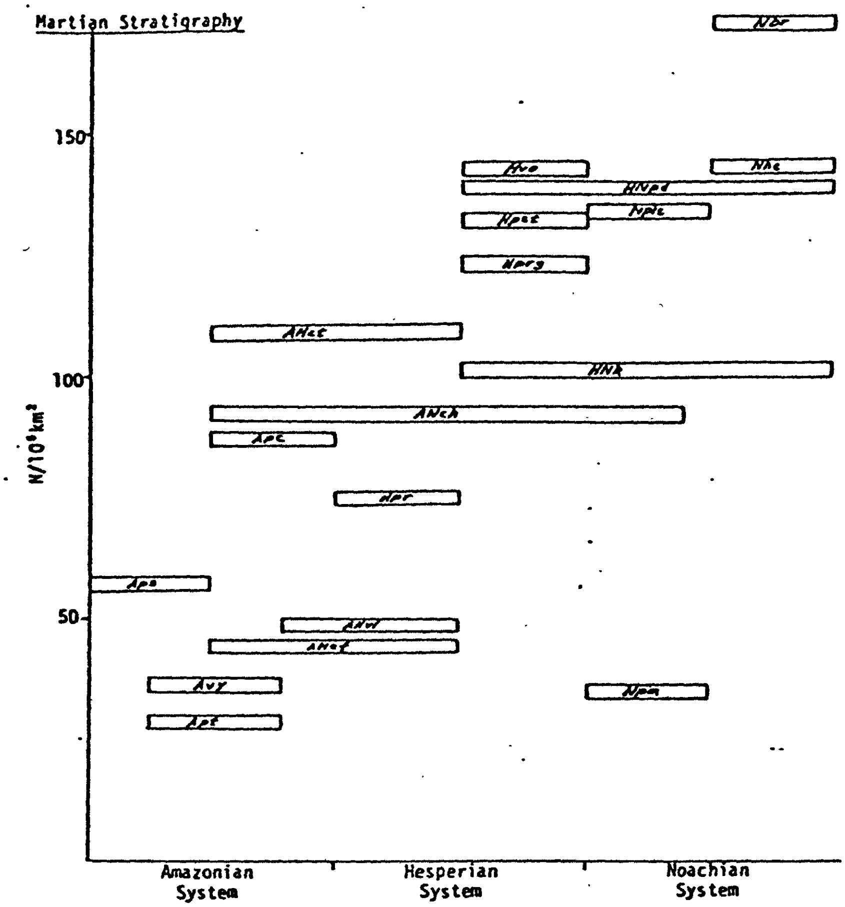

Figure 8. Stratigraphic sequence of martian rock units plotted against number (N) of intermediate-size (4-10 km) craters/$10^6 km^2$ (after Scott and Condit, 1977).

Rock Units

Nbr-basin rim	Hvo-old volcanics	AHvi-intermed. volcanics
Nhc-hilly & cratered	Hpst-streaked plains	AHcf-canyon floor
Nplc-cratered plateau	Hprg-ridged plains	Apc-cratered plains
Npm-mottled plains	Hpr-rolling plains	Avy-young volcanics
HNpd-deflation plains	ANch-channel deposits	Apt-Tharsis plains
HNk-knobby terrain	AHct-chaotic terrain	Aps-smooth plains

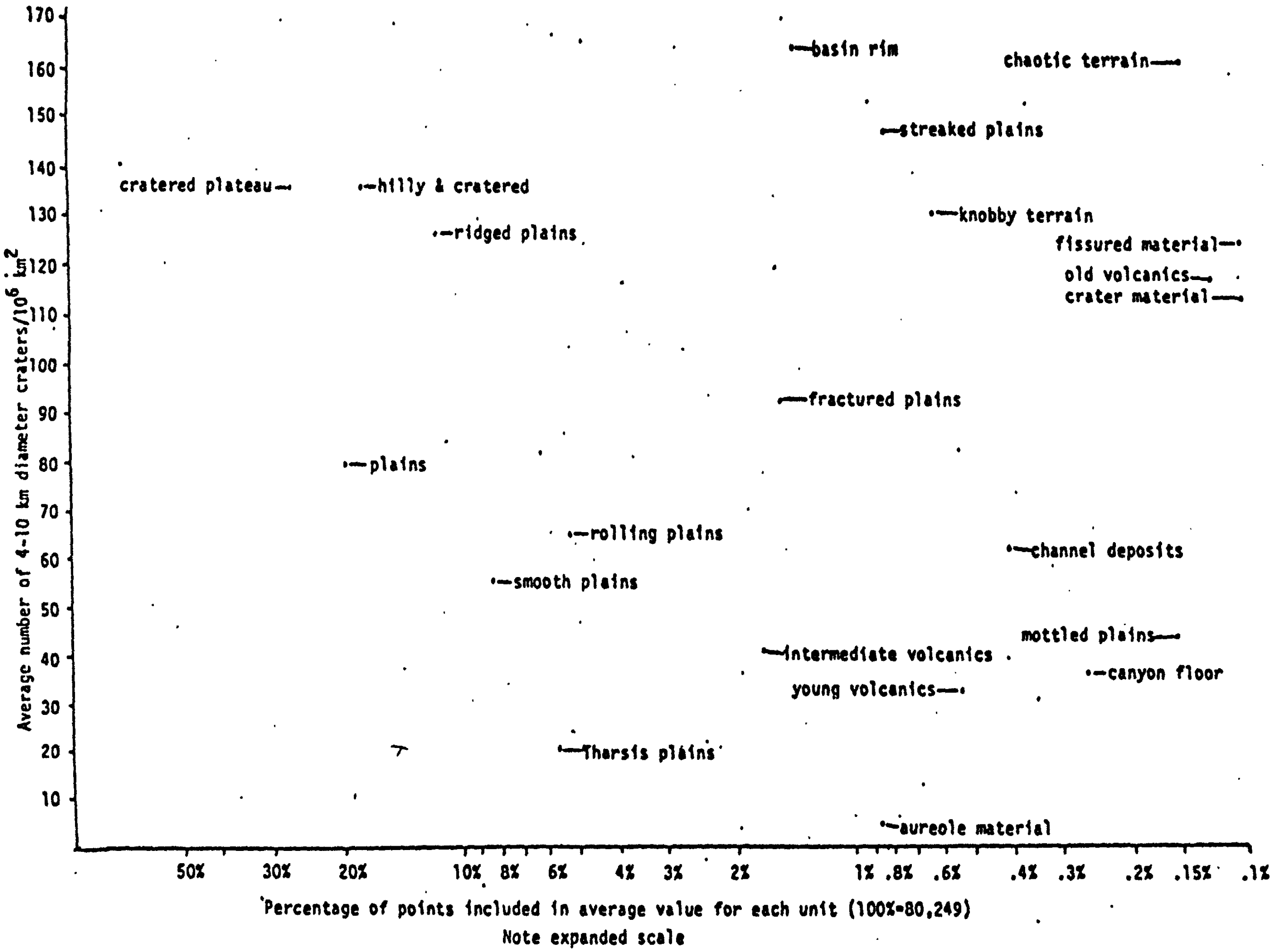

Figure 9. Average number of 4-10 km diameter craters/10^6km^2 per geologic unit plotted against the relative percent of all points (80,249) considered in equatorial geologic map with points falling on contacts of geologic units excluded. The vertical axis (average number of 10^6km^2) is a linear scale; the horizontal axis is logarithmic. The statistical strength of the crater density values becomes increasingly lower for geologic units further to the right to this figure due to the smaller areal extent of the units (and thus fewer data points). Rock unit designations can be found in figure 8 caption.

Summary

The technique and data derived from it, as shown in table 2 must be regarded in its global context. The crater density values for the units of largest areal extent are the most reliable indicators of the relative emplacement age of the geologic units on Mars. These include (from youngest to oldest): Tharsis volcanic material, 20.9 craters/10^6km^2; smooth plains material, 56.6 craters/10^6km^2; rolling plains material, 66.2 craters/10^6km^2; plains materials, 80.4 craters/10^6km^2; ridged plains material, 128.4 craters/10^6km^2; hilly and cratered material, 137.1 craters/10^6km^2; and cratered plateau material, 137.8 craters/10^6km^2. Figure 9 summarizes the average crater density for 21 of the 23 equatorial geologic units (excluding mountain and undivided volcanic materials) as plotted against the percent frequency of the unit. As can be seen, slightly more than half of the units had less than 1 percent or 80 actual points accumulated in the crater density data and are thus, at best, only approximate indicators of relative age. The positive correlation of the average crater density values of geologic units with the stratigraphic sequence as proposed by Scott and Carr (1976) indicate this technique may be a valuable aid in correlating the relative age of Martian geologic units.

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