Reports

Martian Craters: Number Density

Abstract. *The incremental frequency distribution of Martian crater diameters larger than 20 to 30 kilometers follows an inverse-square law, with density equal to that of craters on the lunar continents. This finding accords with the prediction that lunar continents and the Martian surface carry an equilibrium density (saturation) of craters originating in meteoroidal impact. Therefore crater statistics alone cannot be used for estimation of the age of the Martian surface.*

Mariner IV discovered that Mars has a heavily cratered and surprisingly Moon-like surface. The major difference between craters on Moon and on Mars is that the former seem to be very much shallower, with lower rims and flatter floors than "sharp" lunar craters of the same diameter. This flattening is usually attributed to processes operating on the Martian surface, such as erosion by and deposition of wind-blown sand. Nevertheless, craters on Moon and Mars have large-scale similarities.

The expected number density of craters, as a function of diameter, can be related to the crucial parameters of the processes by which craters are formed and then destroyed by obliteration, flooding, erosion, and sedimentation. The consequences of the meteoroidal-impact hypothesis (*1*) are applied to the Mars data; the hypothesis, which adequately predicts the size distribution of large lunar craters in continental and mare regions, also adequately predicts the distribution of craters on Mars.

Early counts of Martian craters (*2*), based essentially on the first press-kit photographs, yielded a number density roughly intermediate between those of the lunar continents and maria. Later counts (*3, 4*) essentially verified these densities; they were based on 70 to 110 craters for all the usable Mariner IV photographs [for this purpose, frames 3 to 16 (*2*)]. Although these densities were generally accepted, they were known to be low by a large factor (*5*) since only relatively sharp and pristine craters were counted; the many "ghost" craters, often conspicuous in spite of their low relief, were ignored (*6*).

Because their corners overlap, each consecutive pair (for example: frames 3 and 4, 5 and 6) of Mariner IV photographic frames is published (*7*) on a single-sheet mosaic, except for frames 1 and 2. No frame taken after frame 16 showed enough detail to merit cartographic reduction. The poor photography in frames 1, 2, 15, and 16 discouraged their use in this analysis.

The basic crater counts (Table 1 and Fig. 1) are displayed in "incremental" rather than the more familiar "cumulative" form. Incremental counts preserve the essential shape of the number density while giving a much better picture of the fluctuations than do the cumulative counts (*9, 10*). Each bar on the graphs represents the number of craters, between x and $x(2^{1/2})$ km in diameter ($x = 2^{k/2}$ for $k = 3$, 4, 5, and so on), per square kilometer. The parameters of the two forms are easily related in the case or which we have an inverse-power-law type of distribution: [cumulative number of craters per unit area whose diameters are between x and $x(2^{1/2})$ km] $= C(x^{-s})\,(1 - 2^{-s/2})$ where s and C are positive constants known as the population index and the density coefficient, respectively. On a log-log graph, both cumulative and incremental counts of inverse-power-law type appear as straight lines with slope $-s$.

Lunar continents are known to be characterized by $s = 2.0$ and $C = 0.10/\text{km}^2$ for craters larger than 1 km in diameter (*8*). This lunar area includes both the Southern Highlands on the near side and the most densely cratered regions on the far side. Craters on the lunar maria are much lower in density and characterized by a smaller population index ($s = 1.55$ to 1.80 and $C = 1 \times 10^{-3}$ to $2.5 \times 10^{-3}/\text{km}^2$ according to the mare being considered). The straight line in Fig. 1 gives the lunar-continental incremental density, $0.05x^{-2}/\text{km}^2$, for craters of diameters between x and $x(2^{1/2})$ km, which should be compared with the left ends of the bars on the graphs, since the left end of each bar corresponds to the diameter x in the smoothed incremental density.

At large diameters the Martian crater counts are in excellent agreement with

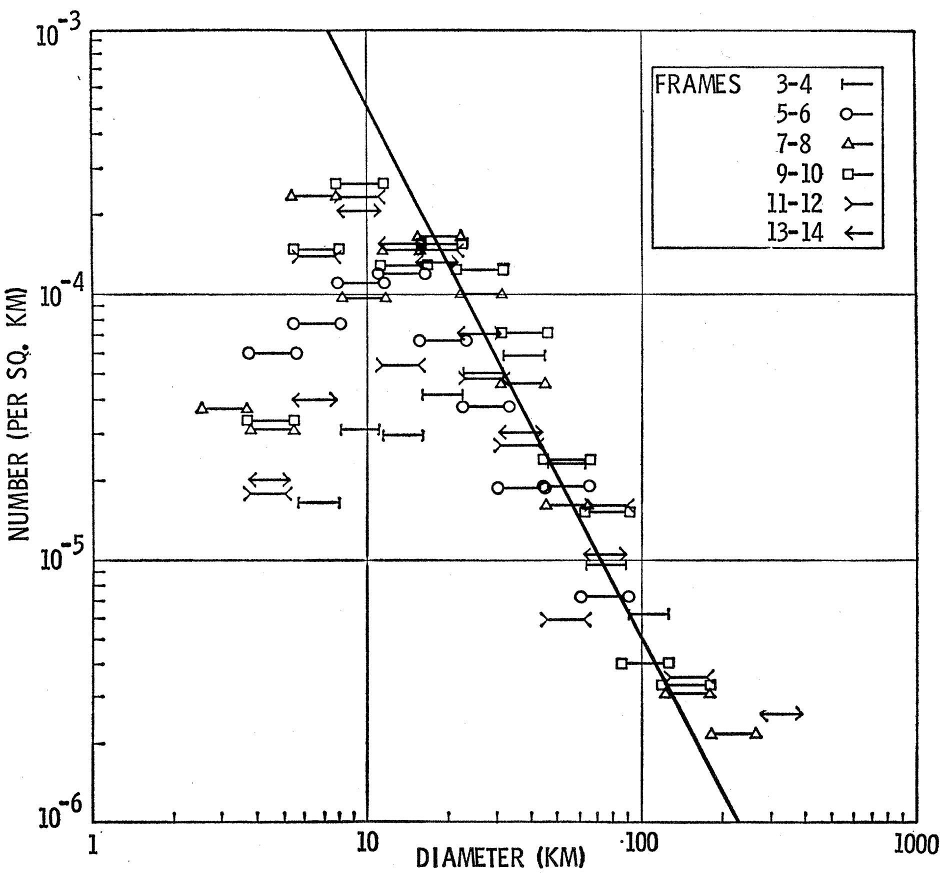

Fig. 1. Incremental number densities of craters appearing in Mariner IV photographs of Mars.

Table 1. Numbers of craters having diameters between x and $x(2^{1/2})$.

Frames	x (km)													Field ($\times 10^5$ km²)
	2.8	4	5.6	8	11.3	16	22.6	32	45	64	90	128	180	
3 and 4	0	4	0	8	8	12	15	18	8	4	3	0	0	2.45
5 and 6	0	10	13	19	22	13	8	4	5	2	0	0	0	1.64
7 and 8	5	4	31	13	20	23	16	8	3	0	0	0	1	1.34
9 and 10	0	4	17	33	17	20	18	11	4	3	1	1	0	1.18
11 and 12	0	2	17	28	7	20	7	4	1	3	0	1	0	1.16
11	0	2	8	22	6	12	3	3	1	1	0	1	0	0.548
13 and 14	0	2	4	21	16	13	7	3	0	1	0	0	1 (?)	1.00

the lunar-continental counts when one takes into account the small number of observations (Table 1). We note first of all that the index $s = 2.0$ is justified in every instance. The density coefficients may vary slightly from region to region. Table 2 shows the density ratio of large craters on Mars and on the lunar continents, as well as the minimum diameter $x_{\min}$ at which an inverse-square law is applicable to the Martian counts.

Note that the number densities in Fig. 1 are not simply number:area ratios from Table 1. There is an important practical reason for this. I counted all craters of which any parts of the perimeters extend into the Mariner frame; consequently the true area within which we are looking for craters of diameter x comprises the field of the photograph plus a strip roughly $x/2$ in width surrounding the region photographed. For lunar counts, this factor is seldom important, but on the Mariner-IV frames the craters are large relative to the size of the photograph, so that the effective search area for large craters is significantly greater than the area photographed. This very significant factor greatly modifies the estimated densities.

Important problems remain in the (necessarily) subjective identification as craters of objects in the Mariner IV photographs.

I have developed a detailed statistical theory of the formation and survival of craters; it takes into account the randomness, in space and time, of the birth of primary and secondary craters, the destruction or obliteration of older craters by newer ones that formed nearby, and the obliteration of craters by flooding or filling (*1*). I assume that the most important factor in the survival of large craters on the lunar continents and on Mars is obliteration of old craters by new. It can be shown quite generally that, if the size distribution of newborn craters does not change with time, the observed distribution approaches a statistical state of equilibrium (saturation) in which smaller craters are formed and destroyed by larger ones at the same rate. Thus one cannot estimate, from the number of craters observed on a heavily cratered surface, the total number of craters that have been formed on that surface—a fatal defect in attempts to estimate the ages of heavily cratered surfaces from crater statistics. (It is assumed that the equilibrium density has been reached for all large craters present in statistically significant numbers.)

The expected equilibrium number density $\xi(x)$ (expected number of craters of diameter x per unit area, per unit diameter interval) is simply related to the probability density $p(x)$ of crater diameter at the time of birth (*1*):

$$\xi(x) = p(x) / \left[\int_x^\infty \pi(y-x)^2 \cdot p(y) \cdot dy/4 \right]$$

It is assumed that a crater is a perfectly circular object that destroys everything within its perimeter but leaves everything outside intact. I have also invoked the approximation that a crater is obliterated if and only if it is completely overlapped by a larger crater.

The hypothesis of meteoroidal impact predicts that the functional form of $p(x)$ is an inverse-power law:

$$p(x) = \gamma x^{-\gamma-1} \quad \text{for } x > 1$$
$$p(x) = 0 \quad \text{for } x < 1$$

where the diameter of the smallest "observable" crater is taken as the unit of distance (1 km is convenient for my purpose). The constant γ is the product of two rather poorly known constants: the cumulative population index γ_1 of the masses of planetesimals that presumably bombarded the surface, and the exponent γ_2 in the scaling law that relates crater diameter x to the energy W of the explosion that caused the crater:

$$x = (\text{constant})\ W^{1/\gamma_2}$$

The most plausible ranges of parameter values are $0.6 \leq \gamma_1 \leq 0.8$ and $3 \leq \gamma_2 \leq 4$. The extreme range of possible values of γ is 1.8 to 3.2, but the most likely range is $2.1 \leq \gamma \leq 2.7$.

Assuming that the inverse-power-law form for $p(x)$ is correct, I derive an expected equilibrium density (for $\gamma > 2$):

$$\xi(x) = 2\gamma(\gamma-1)(\gamma-2)/\pi x^3$$

an expected cumulative equilibrium density:

$$\int_x^\infty \xi(y)dy = \gamma(\gamma-1)(\gamma-2)/2\pi x^2$$

and an expected incremental equilibrium density:

$$\int_x^{x(2^{1/2})} \xi(y)dy = \gamma(\gamma-1)(\gamma-2)/\pi x^2$$

For any $\gamma > 2$, the cumulative or incremental equilibrium density is an inverse-square law. Equating the observed lunar-continental density coefficient to this value, I derive $\gamma = 2.13$, which is rather uncertain. Although the Martian crater statistics are too poor to permit definite determination of whether the index of the observed distribution is 2.00, the lunar-continental observations are accurately characterized by this value. The lunar-continental and Martian crater counts are therefore consistent with the hypothesis that these surfaces have an equilibrium density of primary impact craters. As usual one cannot preclude the hypothesis that most large craters are of internal origin, because there is no quantitative theory

Table 2. Density ratio of large craters on Mars and on the lunar continents ($C:C$); $x_{\min}$ is the smallest diameter for which an inverse-square-law incremental frequency distribution is valid.

Frames	$C:C$	$x_{\min}$ (km)
3 and 4	1.0	32
5 and 6	0.6	45
7 and 8	1.0	16
9 and 10	1.1	22
11 and 12	0.8	16
11	1.0	16
13 and 14	0.7	16

of the origin of endogenous craters.

It is not certain that either lunar-continental or Martian surfaces are saturated with large craters. If both are saturated, then, even if the flux history of the meteoroids and planetesimals that presumably bombarded these surfaces were accurately known (including now-extinct populations of primeval planetesimals), one could obtain at best only the minimum age of each surface. But the flux history is not well known. Improvements in experiments with satellites and in terrestrial photography of meteors have frequently revised substantially estimates of the present near-Earth flux of small meteoroids; neither these uncertain data nor our data on present asteroidal and cometary objects can be safely extrapolated for prediction of the flux of large primeval planetesimals in the neighborhood of Mars. Finally, internal flooding complicates the use of the lunar maria as historical impact counters (*1*).

For these reasons one must regard with considerable caution some earlier attempts (*2, 4, 9, 11*) to estimate the age of the Martian surface from crater statistics. These statistics alone justify neither a long age scale ($\sim 3 \times 10^9$ years) nor a short one ($\sim 500 \times 10^6$ years). More accurate estimates of age will require better knowledge of the early Martian meteoroid flux and of the processes that modify Martian surface topography.

A. H. MARCUS
Bellcomm, Incorporated, 1100 17th Street, NW, Washington, D.C. 20036

References and Notes

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12. Supported by NASA contract NASW-417.

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Oxygen-Isotope Analysis of Recent Tropical Pacific Benthonic Foraminifera

Abstract. *Analysis by the oxygen-isotope method of samples of benthonic Foraminifera, collected at different depths on the continental shelf and slope off western Central America, yielded isotopic temperatures agreeing closely with the temperatures measured in the field. The validity of the oxygen-isotope method as a means of analysis of paleotemperatures is further supported.*

The $O^{18}:O^{16}$ ratios in the calcium carbonate of shells of pelagic and (to a much smaller extent) benthonic Foraminifera have been extensively used for study of the temperature variations of surface and bottom ocean water during the Pleistocene (*1*, and references). The values obtained from foraminiferal samples, separated from the top few centimeters of deep-sea cores from different oceanic areas, indicate that Foraminifera deposit their calcium carbonate in isotopic equilibrium with the ambient sea water. In order to test further this conclusion, $O^{18}:O^{16}$ analyses have been made on several specimens of Recent benthonic Foraminifera collected from water for which actual temperatures were known.

The species were taken from core samples collected (*2*) off Central America in December 1955; paired core samples were taken across the continental shelf and down the slope at depths from 20 to 3200 m, over a distance of about 80 nautical miles. Samples were taken primarily to provide information on the geographic and depth distribution of benthonic foraminiferal species in the area, and information about the physical and chemical factors affecting that distribution (*3, 4*). The samples analyzed isotopically range in depth from 47 to 885 m and include six monospecific samples and one multispecific. Five species of Foraminifera from four genera are represented; one species was

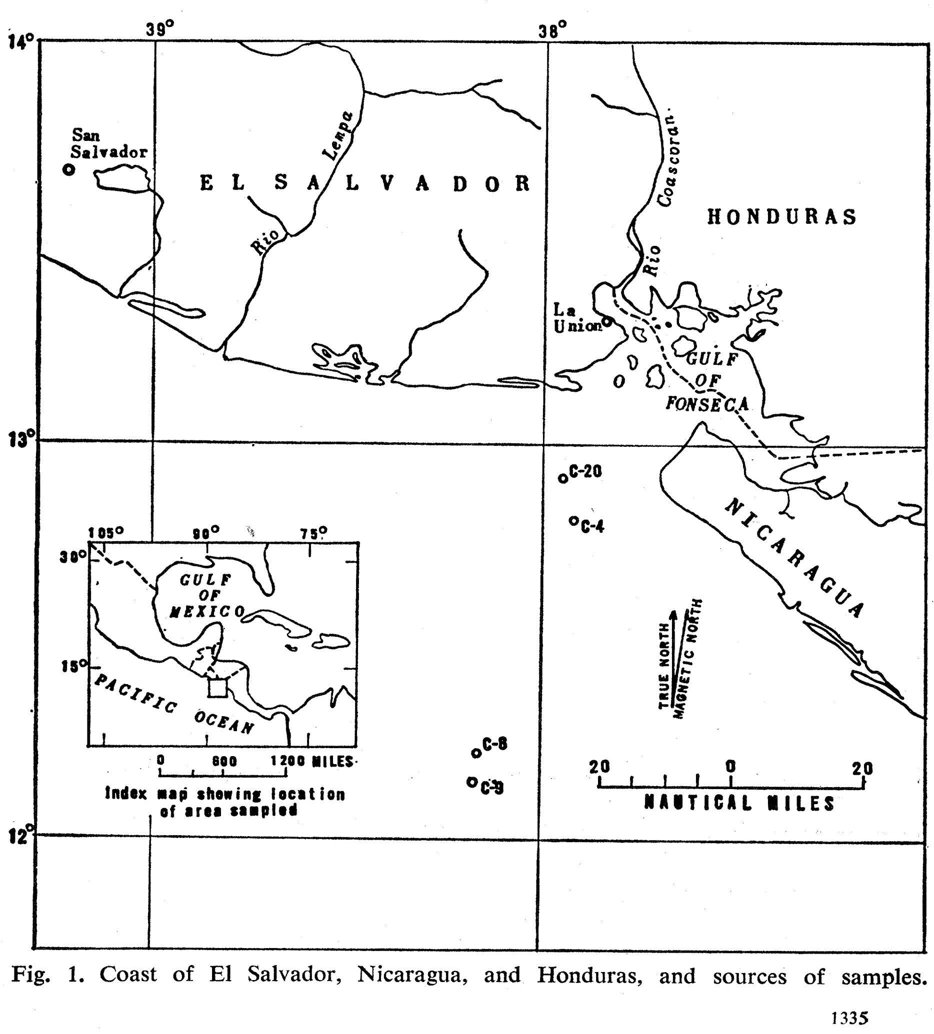

Fig. 1. Coast of El Salvador, Nicaragua, and Honduras, and sources of samples.