No. 65 MARTIAN CRATERING*

by William K. Hartmann
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ABSTRACT

Independent counts of Martian and lunar craters are used in a new analysis of the Mariner IV records. The difference in impact velocities on the two planets introduces an appreciable effect. The Martian surface layer that has retained craters larger than 50 km in diameter is found to be 4×10^9 years old, within a factor of about 2. The diameter distribution of Martian craters agrees with that expected from impacts of asteroidal fragments, to the accuracy of the observations. At diameters less than 50 km, "crater retention ages" are less than 4×10^9 years, apparently because of an erosive process. The retention time for a crater 1 km in diameter is found to be on the order of 10^8 years; an erosive process flattens large-scale relief at an average rate of about 10^{-4} cm/yr. Fundamental conclusions about Mars' erosion history therefore cannot be drawn from the ages of the large craters only.

Although refinements in the data from the Mariner television system are still in progress (B. Murray, private communication, Jan. 1966), it is not untimely to consider at least qualitatively the Martian cratering history. It is probable that the quantitative data used in this paper will not be changed greatly by reanalyses of the television system, and thus tentative conclusions about the Martian surface can be made.

1. *Crater Counts*

Figure 1 compares the crater densities on Mars and the moon. The lunar crater counts were made from Ranger and earth-based photographs and the catalogs of Arthur *et al.* (1963, 1964, 1965); the method of reducing the data has been described elsewhere (Hartmann 1964, 1966). The author used an incremental plot because it depicts the actual measurements more clearly than does a cumulative plot. The frequency F, a function of diameter D, is defined by

$$F(D) = \frac{\text{number of craters of } D \text{ in } \Delta \log D}{\text{km}^2}. \quad (1)$$

Log intervals are to the base $\sqrt{2}$.

The Martian craters included in the graph were counted from press-release prints of Mariner IV photographs. In order to get counts as complete as possible, the frames were chosen according to the crater size; for the smallest craters only the best resolution frames were used. Table 1 summarizes this selection of frames. The early and late frames were discarded because of poor resolution and contrast, and *completeness* in a small area was considered more important than maximizing the number of craters by counting in a large but poorly resolved area.

2. *Earlier Analyses*

In four previous analyses of these data (Leighton *et al.* 1965; Witting, Narin, and Stone 1965; Anders and Arnold 1965; Baldwin 1965), the "age of the Martian surface" was derived from a comparison of

*An article by the author under the same title is being published concurrently in *Icarus*. The present paper, though somewhat different in content, draws the same conclusions. This version is published with the kind permission of the editors of *Icarus*.

TABLE 1

Frames Selected for Martian Crater Counts

DIAMETER INTERVAL (km)	FRAMES USED	NO. CRATERS
$D < 11.3$	9–11	24
$11.3 < D < 22.6$	7–11	28
$22.6 < D < 32.0$	7–12	10
$32.0 < D$	7–15	23

the lunar and Martian crater densities, corrected for the estimated difference in cratering rates. These analyses, which are summarized below, were oversimplified.

Leighton *et al.* (1965) compared the Martian data with lunar counts; however, they made no distinction between lunar upland and maria, and as the crater density on the moon is up to 45 times higher in the uplands than in the maria, the comparison was in effect with the uplands. They concluded correctly that the Martian crater density resembles "remarkably closely the lunar uplands," and found the Martian surface age to be 2 to 5 $\times$ 10^9 years old. Their Martian crater counts included some earlier low-resolution frames, which in part account for the lower crater densities than found here.

Witting, Narin, and Stone (1965), accepting the statement of Leighton *et al.* that the Martian crater density was comparable to that of the moon, made corrections for the higher Martian cratering rate. Concluding that the latter is at least 15 times the lunar rate, they estimated the age of the Martian surface to be less than 0.3 $\times$ 10^9 years.

Anders and Arnold (1965) found that the Martian cratering rate was 25 times that of the moon (compatible with the calculations of Witting *et al.*), but pointed out that the Martian crater counts made by Leighton *et al.* fell between the counts for the lunar upland and maria. They estimated that the Martian surface was about 1/6 the age of the lunar maria, and dated it at 0.3 to 0.8 $\times$ 10^9 years.

Baldwin's (1965) analysis was similar to the preceding. He computed a Martian cratering rate of 5 to 10 times the lunar rate on the basis of Öpik's calculations and from observations of the micrometeorite flux. Estimating the lunar maria to be 2 $\times$ 10^9 years old, he set the age of the Martian surface at 0.3 to 0.7 $\times$ 10^9 years.

3. *Discussion of the Data*

Although for the most part methodologically correct, the earlier analyses of the Martian craters may be subject to improvement because of uncertainties in the lunar data used as a reference. There appear to be discrepancies between the lunar data used in the work summarized above and the more recent data presented here. The earlier data are summarized by Baldwin (1963), whose post-mare crater density curve is based on counts by Shoemaker and Hackman for individual maria. Baldwin's curve is found to be as much as 30 percent higher than the accepted average post-mare crater frequency curve. The Arthur catalogs provide improved and more uniform coverage. (An independent analysis of the Arthur catalogs by R. Le Poole is in close agreement with the results presented here, both as to crater counts and total area measurements [R. Le Poole, private communication].) Baldwin determined his curves for the lunar uplands by counting the largest craters, in diameter intervals of a factor of 2, in an area of 1.9 $\times$ 10^7 km^2 (with the assumption that pre-mare craters would project through the mare material), and by using the 1963 counts of Palm and Strom for three small upland regions near Ptolemaeus, which have a total area of about 4.3 $\times$ 10^4 km^2. These counts are roughly 30 percent lower than the counts of this paper. The present counts, however, are intended to represent the most heavily cratered or "pure continental" areas, as these are assumed to be the best preserved of the ancient upland surfaces; it is not surprising, therefore, that they give a slightly higher crater density. The pure continental area of these counts is the third quadrant upland region, which includes the vicinity of Tycho and has an area of 1.5 $\times$ 10^6 km^2.

Figure 2 presents the raw data for both the mare and the pure continental surfaces; it also includes examples of the most and least heavily cratered maria on the moon — Mare Tranquillitatis and Mare Serenitatis, respectively (these two were chosen and recounted by the author after an unpublished review of various published crater counts). The true variation in mare crater densities is seen to be a factor of about 2.5, although most of the mare area falls into a much smaller range of crater density. This in turn implies a variation in age, though this is probably less than the factor of 2.5, as the older maria were probably subjected to the last stages of the intense cratering that produced the higher crater density of the pure continental areas. It is probable that the ages of the lunar maria range from about 2 to 4.5 $\times$ 10^9 years. That is, the "average mare" crater counts presented in Figures 1 and 2 are assumed to give the crater density accumulated over roughly 4 $\times$ 10^9 years within a factor of 1.3 (cf. Hartmann 1965).

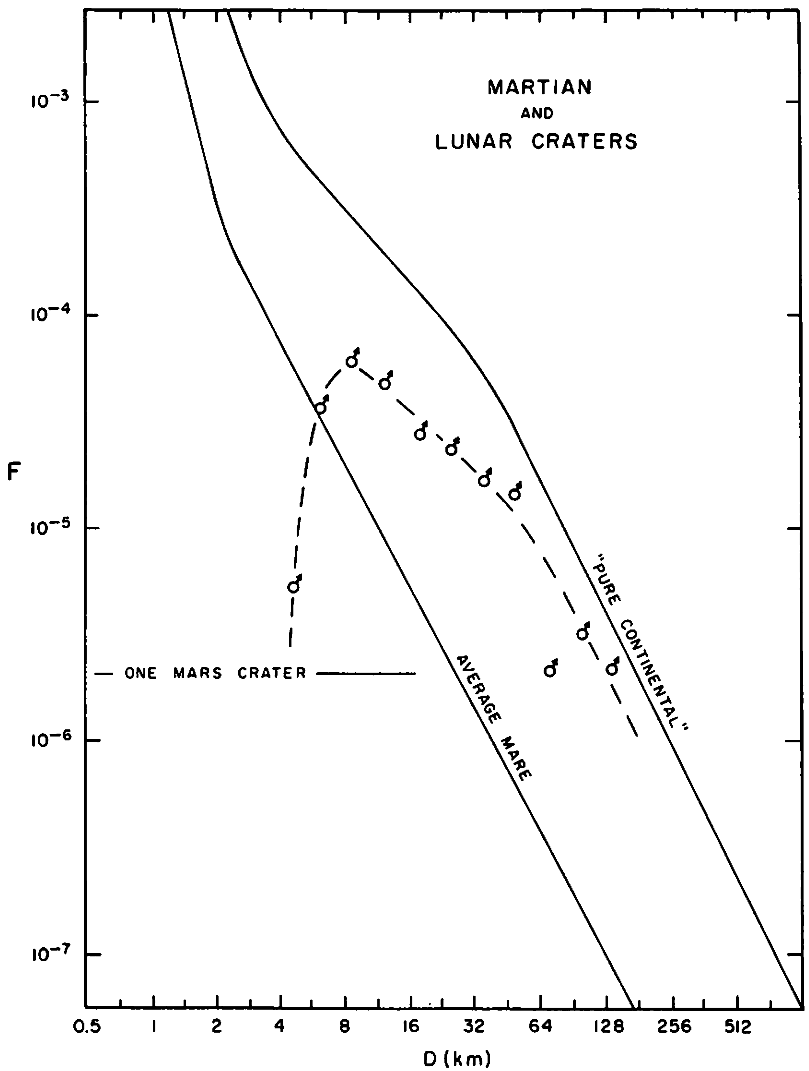

Fig. 1 Martian and lunar crater densities compared. Two types of lunar terrain are included in this incremental plot. F gives the number of craters per square kilometer in the $\log \sqrt{2} D$ intervals marked at the bottom. The F value corresponding to one Martian crater of size D is shown.

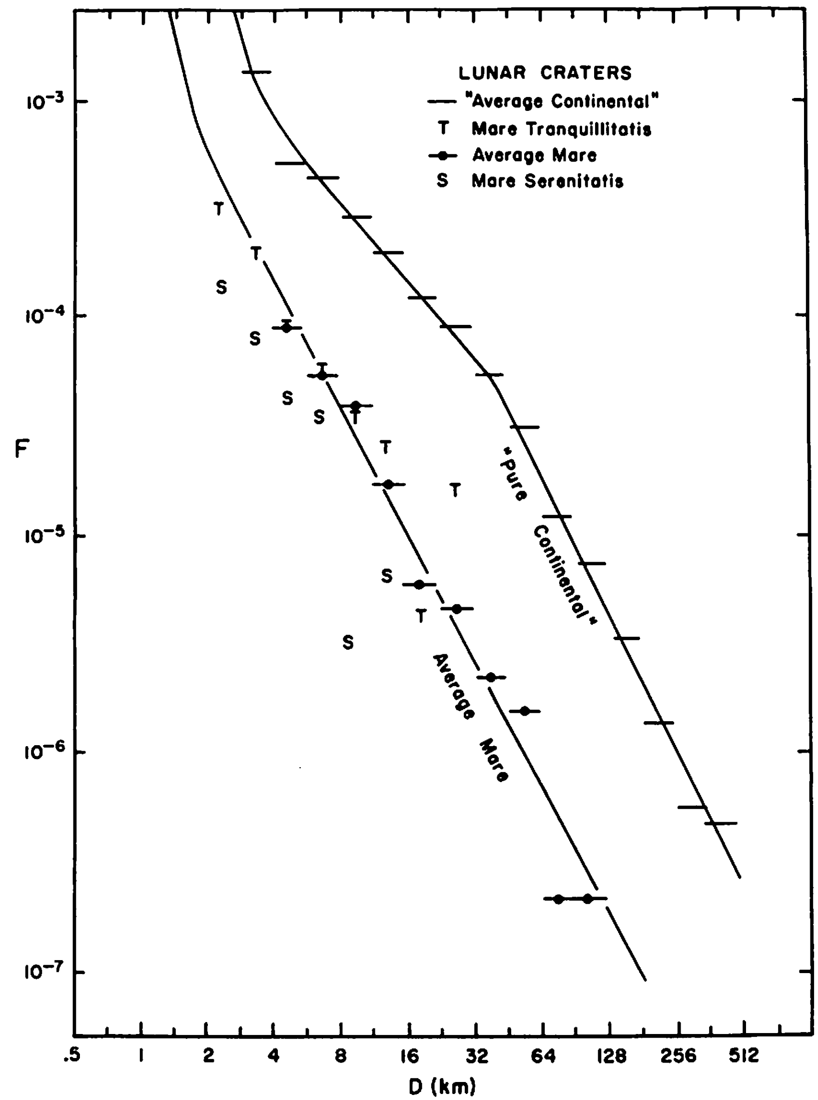

Fig. 2 Lunar crater densities. This diagram illustrates the actual lunar counts with the same scales as Figure 1. The maria Tranquillitatis *(T)* and Serenitatis *(S)* are included as extreme examples of highly and sparsely cratered maria, respectively.

In addition to F in Equation (1), we may now define

$$\mathcal{G} = \text{asteroidal flux} = \frac{\text{no. projectiles of mass in } \Delta \log m}{\text{km}^2 \text{ yr}}. \quad (2)$$

In principle, the earlier analyses multiplied the assumed age of the lunar surface by the ratios $\mathcal{G}_l/\mathcal{G}_m$ and F_m/F_l to get the Martian age (the subscripts m and l representing Mars and the moon, respectively). Leighton *et al.*, Witting *et al.*, Anders and Arnold, and Baldwin respectively took the former ratio to be about 1, 1/30, 1/25, and 1/10, and the latter about 1, 1, 3.4, and 2.6.

For the ratio $\mathcal{G}_l/\mathcal{G}_m$, I accept Anders and Arnold's value, 1/25, as it is based on a computer calculation of asteroid histories. It should be noted that the last three papers criticized the first for its implicitly assumed value of unity; the last three values, all estimated theoretically, vary by only a factor of 3.

For the ratio F_m/F_l, I use my own determination of 14. This should be correct within a factor of 1.5, as the two extreme maria cited above give a range of about 10 to 30. The value 14 is in marked contrast to the earlier ones, the first two of which stem from the misleading statement in the first paper that the Martian crater density approximates that of the moon. The second two values are based on Baldwin's crater counts (1963), which are reviewed above.

The present counts of Martian craters made by the author have been substantiated by A. B. Binder (private communication, 1965), who made independent counts; these new figures run as much as a factor of 2 higher than the counts used in the four earlier papers. (As mentioned, the latter included lower resolution frames.) Thus the earlier estimates are considered low because of errors in both lunar and Martian crater counts. It is important to note that the Martian and lunar crater densities can be compared only at crater diameters greater than 50 km; at smaller diameters the two curves are no longer parallel. The significance of this is discussed below.

Another factor, neglected in the earlier papers, should be considered: The ratio of Martian to lunar crater densities at a given size is not the relevant ratio. It is assumed that the craters are the result of impacts from asteroidal fragments of varying mass; thus we can compute the ratio of Martian to lunar crater densities only after considering the size of crater each Martian projectile would have made had it struck the *moon*. That is, the age of the Martian craters depends on the ratio of mass flux rates on Mars and the moon, and this is not equal to the ratio of crater densities because the impact velocities are not the same. Of the four earlier analyses, only Witting *et al.* touched on this problem, but concluded that because the dependence of crater diameter on velocity is small, the effect could be neglected. This problem, however, merits closer study.

One can compare the Martian and lunar crater densities directly by converting the Martian crater diameters, here called "Mars diameters" (D_m), to "lunar diameters" (D_l). The energy relation is roughly

$$D \propto E^{1/3.3} = \left(\frac{MV^2}{2}\right)^{1/3.3}. \quad (3)$$

Thus, with a projectile of mass M and impact velocity V, one has the ratio

$$\frac{D_m}{D_l} = \left(\frac{V_m}{V_l}\right)^{2/3.3}. \quad (4)$$

Therefore, in Figure 1, the Martian crater curve must be moved to the right or left in order to compare it directly to the lunar curves. Obviously, a corresponding shift occurs in the frequency F. Since the slope of the log-log distribution is about -1.9, the correction factor is

$$\left(\frac{D_m}{D_l}\right)^{-1.9} = \left(\frac{V_l}{V_m}\right)^{1.15}. \quad (5)$$

Thus, the correct expression for the age of the Martian surface is

$$T_m = T_l \cdot \frac{\mathcal{G}_l}{\mathcal{G}_m} \cdot \frac{F_m}{F_l} \cdot \left(\frac{V_l}{V_m}\right)^{1.15}. \quad (6)$$

The ratio of lunar to Martian impact velocities, V_l/V_m, must still be determined. From the principles of conservation of energy, we have

$$V_I^2 = V_\infty^2 + V_E^2$$

where

V_I = final impact velocity
V_∞ = approach velocity at ∞ with respect to planet
V_E = escape velocity at planetary surface.

Asteroidal fragments come to the earth-moon system from the vicinity of the asteroid belt after perturbation by Mars (Anders 1964, p. 689) and are swept up relatively quickly, with a high probability of collision within about 10^8 years (Öpik 1951), which is in accord with the orbits calculated for well observed meteorite falls. This gives a well determined value for V_∞, which must be corrected to a mean value depending on the orientation of the velocity vectors. The accepted value for lunar impact velocity is about 15 km/sec (Shoemaker, Hackman, and Eggleton 1962; G. P. Kuiper, private communication, 1965). Determination of the impact velocity on Mars is somewhat more complicated. It is assumed that the atmosphere has a negligible effect. Applying the method of calculation used for the moon, one would take the Martian escape velocity of about 5.1 km/sec and a mean vector approach velocity of about 7 km/sec for asteroids with perihelions slightly inside Mars' orbit to find an impact velocity of about 8.7 km/sec. However, asteroidal fragments that cross only Mars' orbit have a much longer lifetime against capture — several times 10^9 years (Öpik 1951), which agrees with Anders' (1965) finding that the dispersal time of Hirayama asteroid families is more than 2×10^9 years. One would thus expect repeated encounters with Mars to increase the spread in orbital parameters of the impacting objects. With this spread, an increase occurs in the absolute value of typical approach velocity and, hence, in the impact velocity. Taking this into account, we assume an impact velocity of 10 km/sec for Mars.

All factors in Equation (6) are now defined, and the age of the surface layer retaining the large Martian craters ($D > 50$ km) is

$$T_m = 4 \times 10^9 \left(\frac{1}{25}\right)(14)\left(\frac{15}{10}\right)^{1.15}$$
$$= 3.6 \times 10^9 \text{ years,}$$

within an estimated factor of 2. This age has a specific meaning: Rather than being a generalized "age of the surface of Mars," it is the duration of stable conditions in a crustal layer that has retained all craters above a certain diameter — in this case, above 50 km. Obviously, if any sort of erosion is present, the smallest craters will have the shortest lifetimes. Thus, one can see that "crater retention age" is a function of crater diameter. However, the age determined above is the time interval during which all craters above a limiting diameter are retained, and we may term it a "*total* crater retention age" — the amount of time since the formation or last major disturbance of the layer at a depth equal to the depth of the crater of limiting diameter. The age found above, however, may apply to only a very small fraction of the Martian surface, for the degree of uniformity of the whole Martian surface is still unknown.

Baldwin (1963) estimated the depth of a fresh impact crater of 50-km diameter to be about 3 km. The total crater retention age of approximately 4×10^9 years thus signifies that the crustal layer of Mars, to a depth of roughly 3 km, has been relatively stable for the past 4×10^9 years, and that surface erosion and transport has been insufficient to fill in or erode craters 50 km in diameter and 3 km in depth. This situation is in striking contrast to the earth, where in many areas orogeny, volcanism, and erosion result in a stability duration of only 10^8 years or less at a depth of 3 km.

The fact that the calculated total retention age of Mars is very close to the accepted period of planetary formation is good evidence that the large craters date as far back as the original formation or exposure of the Martian crust — which took place after any major heating by radioactive isotopes — and that Mars has not subsequently had such active orogeny and crustal unrest as the earth. Figure 1 confirms the absence of significant erosion for the larger craters by the parallelism of the curves for the larger Martian and lunar craters: *A straight segment in the curve for any planetary surface parallel to that in the curve for the lunar surface indicates that an undisturbed layer has existed for a very long time.*

The calculation of a layer 4×10^9 years old departs markedly from the conclusions of Witting *et al.* (1965), Anders and Arnold (1965), and Baldwin (1965), all of whom computed ages on the order of 3×10^8 years. It agrees only fortuitously with the result of Leighton *et al.* (1965), who used very different data. Advocates of a small age, on the order of 10^8 years, have still to explain why the Martian surface suddenly began to retain all large craters so recently, and why very large craters ($D > 100$ km) do not show through from earlier epochs.

4. *Asteroidal Impact Origin of Martian Craters*

Further support for the assumption that the craters result from impacts of asteroidal fragments — aside from the assertion that the number of craters is equal to that expected from asteroidal impacts in 4×10^9 years — is that the slope of the diameter-distribution curve in Figure 1 at the larger diameters, where all craters are assumed to be preserved, is estimated to be close to that expected from asteroidal fragments.

Kuiper *et al.* (1958) found that the mass distribution of asteroids can be represented in cumulative or incremental form by the equation

$$N = kM^{-b}. \quad (7)$$

According to Kiang's (1962) counts of the faintest asteroids, the smaller fragments have a constant b value of 0.63. It can be seen from Equation (3) that we can predict the diameter-distribution curve in Figure 1 to be linear with a slope of 0.63×3.3, or -2.1. Allowing for observational and statistical errors, this is in close agreement with the lunar and Martian crater data. At large diameters, the Martian curve in both Figure 1 and Leighton's plot is linear with a slope of -1.9.

5. Crater Retention Ages and Martian Erosion

A break occurs in the diameter-distribution curve (Fig. 1) at $D = 50$ km, and at smaller diameters the number of craters increases only slowly. This situation cannot be explained by lack of resolution and contrast, as many photographs show craters with diameters as small as 4 km, and only these high-resolution photographs were used in plotting the $F(D)$ values for small craters. This feature of the $F(D)$ curve can therefore be considered a real characteristic of the Martian craters and is tentatively attributed to Martian erosion (which may have lunar or terrestrial analogs).

One type of erosion (in the broadest sense) is volcanic. Examples abound on the moon. Figure 3 compares some Martian and lunar terrain at the same scale and angle of illumination. Some Martian craters are shallower than fresh lunar craters, and the Martian landscape resembles in both crater density and albedo variations the partially flooded lunar regions, intermediate between pure continental uplands and the flatter maria. If the larger craters on Mars date back to the formation of the surface as suggested above, they may have been altered by early volcanic and tectonic activity, as has apparently happened on the moon.

Examples of a terrestrial process that may be relevant to this discussion are shown in Figures 4 and 5. Here, large volcanic craters (D up to 1.1 km) in the Pinacate volcanic region of northern Sonora, Mexico, are being inundated by light ash and the sands of the coastal Grand Desierto. (The transport is both eolian and fluvial in these terrestrial examples.) MacDougal, the crater shown in Figure 4, is quite shallow compared to some unfilled craters in the Pinacate uplands, and Figure 5 shows still shallower examples.

Assuming that some erosion or obliteration process has gradually erased the smaller craters on Mars, one can find the rate of erosion by using crater retention age expressed as a function of crater diameter. Figure 6 shows how the percentage of surviving craters can be found from Figure 1. The difference between the observed curve and a linear extrapolation of the large-diameter curve gives the depletion factor. The extrapolation is valid because it is parallel to both the predicted asteroidal curve and the post-mare lunar curve, the latter being characteristic of total preservation of craters. The crater retention age is assumed to be proportional to the percentage of surviving craters at each diameter, where 100 percent corresponds to the 4×10^9 years calculated above. The results of these measures are plotted in Figure 7. This graph shows that craters with diameters larger than 50 km have been retained throughout the history of the Martian surface, and that smaller craters have shorter lifetimes. A 1-km crater is estimated to have a lifetime (defined by recognition in aerial photographs) on the order of 10^8 years.

Figure 7 may be compared with Figure 8, which illustrates crater erosion on the earth (Hartmann 1964). In order to construct Figure 8, the author prepared a catalog of estimated meteorite crater ages. These ages are poorly known, but as the ordinate covers ten orders of magnitude, large errors in estimated age have little effect. The graph illustrates that on the earth a 1-km crater, even under favorable conditions, would rarely be recognizable after 10^7 or even 10^6 years. As new data become available, substantial improvement in such crater retention diagrams will be possible.

The crater-depth scale in Figure 7 enables one to study the crustal stability of Mars. Crater retention age refers to the duration of time during which relief comparable to the depth of the crater has been retained. We find that on Mars structures 100 m in relief have lifetimes (against photographic detection) on the order of 10^8 years; in average circumstances on the earth, the lifetime is less. The Martian crustal situation is more analogous to the stable shield areas on the earth. For example, in the Canadian shield where there has been no orogeny for as much as 2×10^9 years, large impact craters seen on aerial photographs are extremely old; small craters are, of course, much younger. But in unstable areas on the earth where orogeny and erosion are continuing, large craters are not found at all because the length of time the surface has been exposed has been too short to record such infrequent major impacts.

Although further interpretation of the physical meaning of crater retention ages must await further information concerning Martian erosion, one can

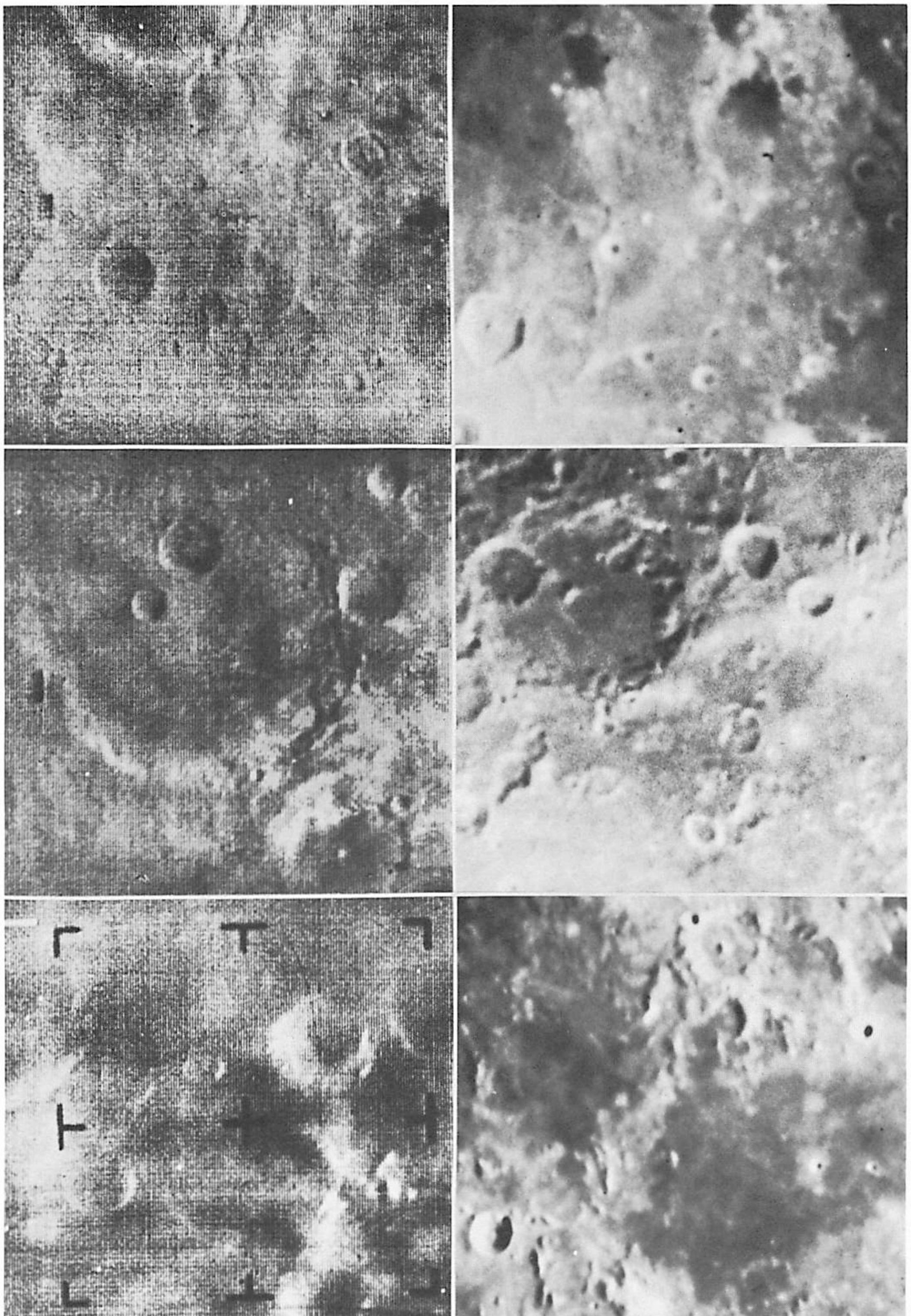

Fig. 3 Mariner IV frames of Mars compared with photographs of the moon, with similar scales and illumination angles (A = altitude of sun). Mars is shown on the left and the moon on the right: (a) Frame 10 compared with partially flooded lunar terrain; A = 49°. (b) Frame 11 compared with upland lunar terrain; A = 43°. (c) Frame 14 compared with partially flooded lunar terrain; A = 30°.

Fig. 4 Volcanic crater MacDougal, partially filled by sand and volcanic ash. Diameter is 1.1 km. Pinacate lava fields, Sonora, Mexico. (Photo by author.)

Fig. 5 Craters in the Pinacate lava fields being partly filled by sand from the bordering Grand Desierto, Sonora, Mexico: (a) photo by Richard Laidley; (b) same area photographed from Gemini spacecraft (courtesy of NASA).

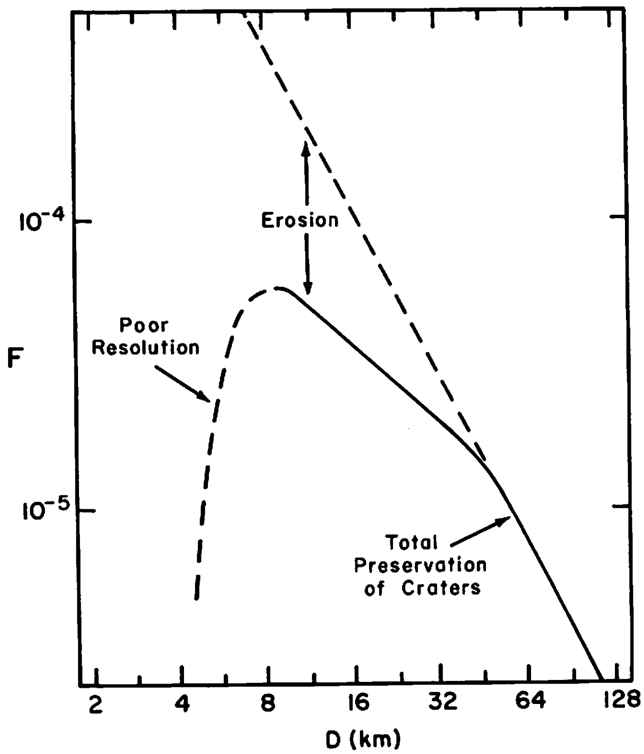

Fig. 6 Schematic interpretation of erosion of Martian craters.

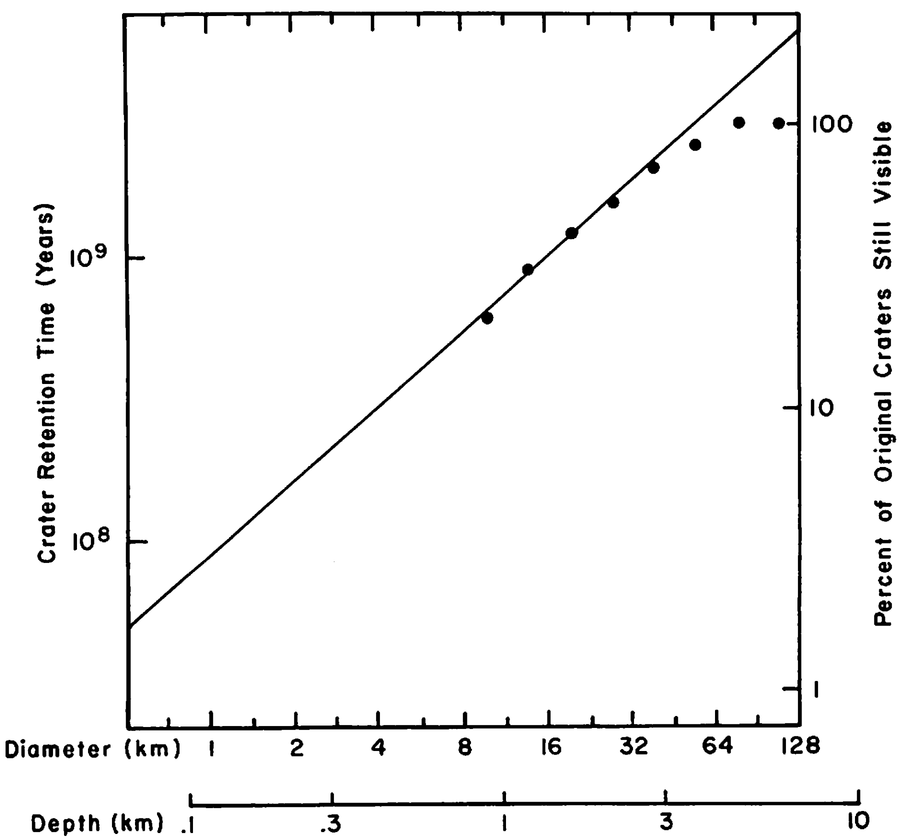

Fig. 7 Crater retention time as a function of crater dimension. This relation is interpreted as evidence for Martian erosion.

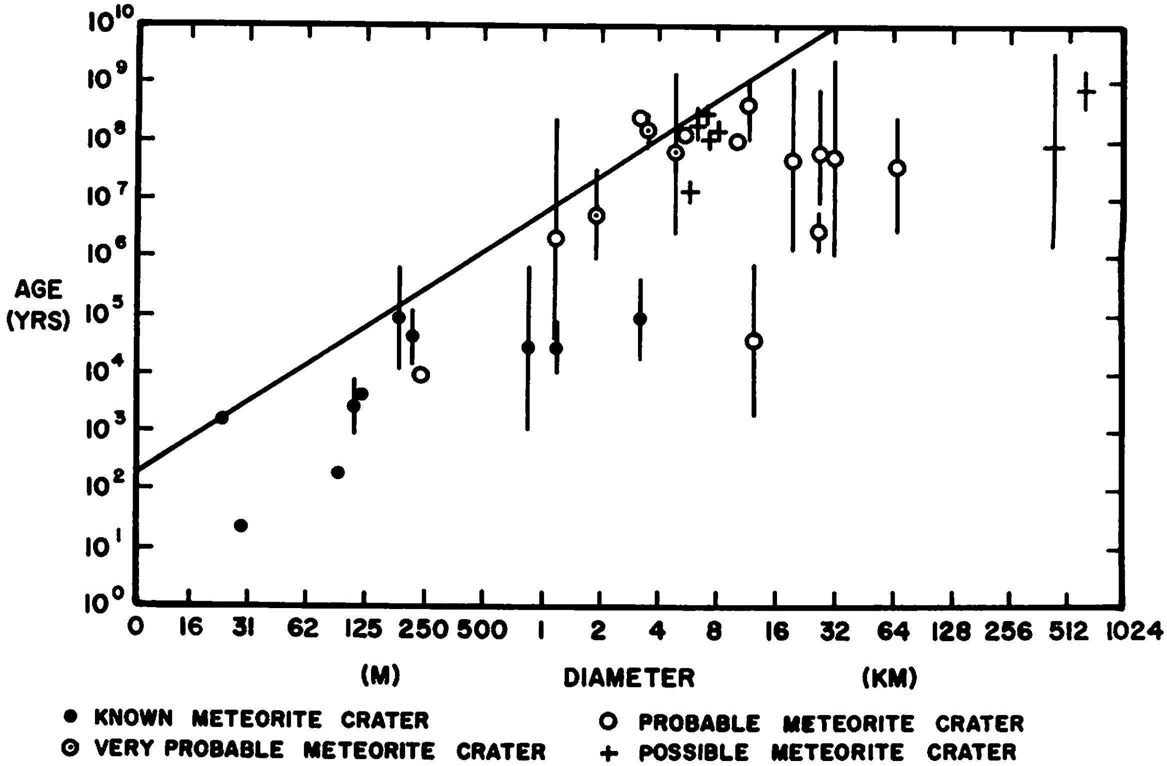

Fig. 8 Estimated crater retention time on earth for comparison with Martian craters of Figure 7. Each point represents a terrestrial crater, and the line shows maximum crater retention under optimum conditions.

estimate a "leveling" or "filling" rate on the basis of a schematic model in which the craters are being gradually filled. As the log-depth scale of Figure 7 is nearly linear and the slope of the line is near unity, one can easily find the average rate for large craters ($1 \text{ km} < D < 100 \text{ km}$), which is 10^{-4} cm/yr. This estimate is uncertain, for if the crater counts are deficient the rate might be lower, and if the asteroidal flux has increased significantly in time through production of fragments, the rate might be higher.

6. *Implications for Martian History and Life*

It has been widely reported (e.g., *New York Times,* July 30, 1965) that the existence of very ancient craters on Mars virtually rules out the possibility of life there. Leighton *et al.* (1965), who calculated an age for the surface of 2 to 5×10^9 years, stated that "the remarkable state of preservation of such an ancient surface" excludes the likelihood of a dense atmosphere or appreciable free water at any time during the history of the surface; however, they also clearly pointed out that the Mariner IV photographs do not preclude the existence of life there.

The photographic identification of *large* craters about 4×10^9 years old does not *in itself* rule out the presence in the past of either a dense atmosphere or water, as is clear from the example of the Canadian shield. Only proof of total retention of very small craters would do so. That old Martian craters are better preserved than terrestrial examples indicates that the erosive agents on Mars are less effective, but this has long been obvious. Furthermore, it is most likely that on any terrestrial planet there is some critical diameter above which all craters have been preserved since the formation of the surface.

More important to the question of planetary history and life are the dimensions of the crater of critical diameter and the behavior of the crater retention curve of Figure 7, for these are determined by erosion and crustal unrest, and erosion and unrest imply conditions more suited to life. The observations of this paper suggest that there has in fact been substantial erosion on Mars, and that at linear scales of 1 km or less — the regime in which life would have more noticeable effects — we see back in time not more than 10^8 years. Thus, the morphological argument against life is quite flimsy, and the popular assertion that the age of the Martian craters rules out life may be as specious as suggesting that the large Canadian shield craters rule out life around Hudson Bay. Furthermore, some of the original observations that led to the suggestion of life on Mars (e.g., seasonal variation) still stand. The physical observations by Mariner IV of the Martian atmosphere are more damaging to the concept of life on Mars than are the photographs.

In any case, the presence of numerous ancient craters and the lack of mountain ranges imply that Mars has indeed had a tectonic history markedly different from that of the earth.

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