crater formation can be taken to be directly proportional to the collision rates.

The observed craters of comparable size are equally dense on Mars and the Moon (*1*). The observed craters on Mars are, therefore, only the last few percent to be formed during the lifetime of a lunar crater. If the rate of formation has been constant over this time interval (assumption 2), then the ratio of the age of an observed Martian crater to that of an observed lunar crater is inversely proportional to the ratio of collision rates per unit area. With the most conservative number for this ratio from Eq. 7, 15, the average age of the Martian craters is only about 1/15 that of lunar craters. Since the lunar craters are certainly no more than 5 billion years old, this places an upper limit to the age of Martian craters of about 300,000,000 years, which is considerably less than the 2 to 5 × $10^9$ years suggested by Leighton *et al.* (*1*).

Aside from difficulties in extrapolating asteroidal data to lunar distances, which can lead to substantial errors, the whole case for concluding that the Martian craters are relatively young hinges on the three assumptions we have stated. Since the validity of these assumptions (especially the second) seems unlikely to be checked in the near future, this study must be looked on as merely an alternative to the earlier suggestions, and not regarded as a definite prediction of the age of Martian craters.

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## Mars: An Estimate of the Age of Its Surface

Abstract. *Intercomparisons of crater counts on Mars and the Moon suggest that the age of the visible Martian surface is approximately 340 to 680 million years.*

The recent Mariner IV pictures show that Mars has a remarkably moonlike surface, as was predicted in 1949 (*1*). It is pitted with numerous craters which appear to duplicate the familiar lunar structures and which probably were produced by meteorite impact.

The craters vary from 3 to 120 kilometers in diameter in the small area of Mars photographed. (The area of Mars covered by the photographs is 0.67 × $10^6$ km$^2$.) Crater counts (*2*) show that, over most of the range of diameters, the plot of cumulative numbers of craters $N_c$ larger than a given diameter versus diameter $D$ may be represented by a straight line on a log-log scale (Fig. 1). The equation of this line is

$$\log N_c = 4.000 - 2 \log D_{km} \quad (1)$$

If Mars is like the Moon, the tailing off of the plot in the small-crater end is not real but measures the difficulty of identifying small craters.

The slope of the line, −2, is almost exactly the same as that found from counts of lunar craters.

The counts of lunar craters have been interpreted to suggest that the lunar maria are about 2 × $10^9$ years old (*3*). An intercomparison of crater frequencies may yield some information about the age of the Martian surface. The equation for the cumulative frequency of craters on the terrae portion of the Moon is

$$\log N_c = 3.604 - 2.120 \log D_{mi} \quad (2)$$

and that for the lunar maria is

$$\log N_c = 1.903 - 1.707 \log D_{mi} \quad (3)$$

The crater diameter is given in miles in Eqs. 2 and 3, and the area considered is $10^5$ km$^2$.

The lower slope in Eq. 3 may be simply statistical. Two or three fewer large craters on the maria would permit the line to have about the same slope.

From the present rate at which objects of different masses are striking Earth, the correction factor to the Moon, the size of crater which a given meteorite can produce if it strikes at a typical velocity, and the observed numbers of craters on terrae and maria, we may derive an approximate probable age for the maria (*3*). The essence of the argument is as follows.

Hawkins has given the highest estimate of the frequencies with which large iron and stone meteorites are now striking Earth (*4*). These data were converted into the numbers of meteorites which would strike the Moon in $10^9$ years and within an area of $10^5$ km$^2$. If these results are divided into the counted lunar crater abundances from Eqs. 2 and 3, we find a ratio of about 180 for the terrae areas and 10 for the maria.

If the rate of infall of such objects has fluctuated wildly in the past, we can draw no conclusions about the age of the lunar maria, but if the rate has continually declined, as seems probable, from the Moon's beginning to the present, like a sort of compound interest problem in reverse, we may use the equation

$$A = P(1 + r)^n \quad (4)$$

where $A$ is the relative number of objects originally (181 approximately), $P$ is the remaining number of particles (=1), $n$ is the number of billion years before the present, and $r$ is −0.685.

If $A$ is 10, as determined from the maria, then the age of the maria is 2 × $10^9$ years.

Unless the average rate of infall on the Moon over the last $10^9$ years has been at least 10 times higher than the highest estimate we can now give, the maria cannot be as young as $10^9$ years. According to many lines of argument (*3, 5*), they cannot approach the age of the Moon.

With this background, we may now return to Mars. Equation 1 may be converted from kilometers to miles and to an area of $10^5$ km$^2$:

$$\log N_c = 2.761 - 2 \log D_{mi} \quad (5)$$

Intercomparison of Eqs. 2 and 5 shows that the Martian craters are less abundant than the craters on the lunar terrae, per unit area, by a factor of 7. If we divide 180 by 7, we get approximately 26. With $A$ = 26, we may solve Eq. 4 for $n$, which becomes −2.8. This process implies that if the fluxes of large masses which have struck Mars and the Moon in the past are the same and the age of the lunar maria is

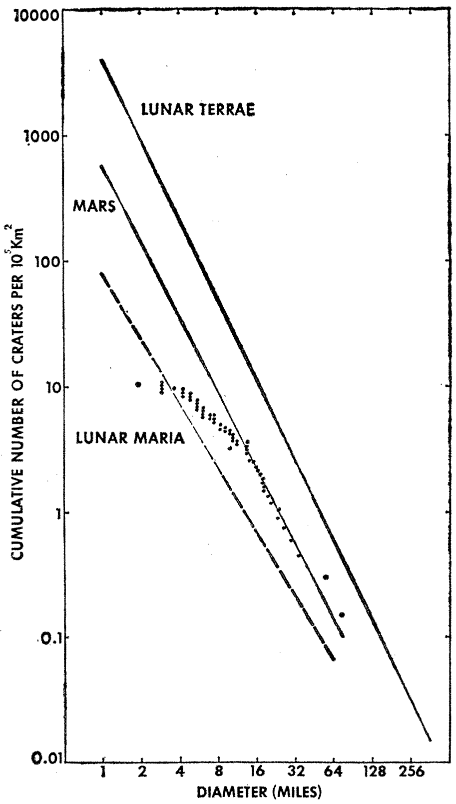


Fig. 1. Relation between the number of craters and their diameter on Moon and Mars.

about $2 \times 10^9$ years, as seems probable, then the age of the visible Martian surface is about $2.8 \times 10^9$ years. If we limit our comparison to the straight-line portion of the Martian crater-count chart, diameters greater than 20 km, then the Martian craters are less abundant than the craters of the lunar terrae by a factor of 3.7 instead of 7; then $A = 50$ and the calculated age is $3.4 \times 10^9$ years.

It might be expected that the proximity of Mars to the asteroid belt would lead to a greater number of impacts there than on the Moon. In this event, the surface of Mars will be younger than calculated above, and it is almost certainly younger than the lunar maria.

Only if the rate of infall on Mars is considerably less than it has been on the Moon and if the age of the lunar maria is very considerably greater than has been calculated could the age of the Martian surface approach the age of the solar system, $4.5 \times 10^9$ years. Neither alternative appears likely.

Öpik's very important papers (*6*) suggest that the rate at which asteroids and comets will strike a given area on Mars is considerably higher than their collision rate with Earth or Moon; the difference may approach a factor of 25.

Mariner IV showed (*7*, *8*) that the flux of micrometeorites increased by a factor of about 5 as the spacecraft moved from Earth to Mars. This value is somewhat smaller than the earlier data for larger masses.

Let us assume that the factor actually is 10 for those objects capable of producing larger craters and the age of the lunar maria is $2 \times 10^9$ years and the frequency of impacts has declined at the same rate for Mars as for the Moon, then the present Martian surface is $(3.4 \times 10^9)/10$ years old, or about $3.4 \times 10^8$ years.

Conversely, if the rates of infall of asteroids on Mars and the Moon differ by the factor of 10 but have been constant in the past at the present rates, then the age of the lunar maria would be calculated as an impossible $10^{10}$ years, and the Martian surface would be $10^{10} \times 50/(10 \times 10)$, or $5 \times 10^9$ years. Both figures are greater than the accepted ages of the planets.

Inasmuch as the rate of infall on the lunar maria, since their formation, has decreased by a factor of about 9 if their age is $2 \times 10^9$ years, and by a larger factor if they are somewhat younger, it seems reasonable to suggest that the rate of infall on Mars has similarly declined and that the age of the Martian surface is not very far from $3.4 \times 10^8$ years.

If the present frequency of large infalls on Mars is as low as the observed micrometeorite flux near the planet, the age of the Martian surface would only be doubled, to about $6.8 \times 10^8$ years. It appears highly probable that the surface of Mars which was photographed by Mariner IV is quite young, geologically speaking.

A substantial amount of erosion on Mars is indicated.


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## Terrestrial Heat Flow: Measurement in Lake Bottoms


Abstract. *The feasibility of measuring terrestrial heat flow in lakes has been investigated in Lake Superior. The temperature gradient and thermal conductivity of the sediment were measured at each of four stations in water depths exceeding 250 meters. Consideration of the effects of climatic variations suggests that they may not seriously affect the values for heat flow obtained by this method. The values measured are in reasonable agreement with other continental values in the shield areas.*


Theories of the dynamics of tectonic forces reshaping the face of the earth invariably call upon thermal sources and imbalances as the driving energy; measurement of heat flow thus becomes an important test of the validity of the theories. The radioactive decay of elements within the earth produces a flow of heat through the surface of about $1 \times 10^{-6}$ cal cm$^{-2}$ sec$^{-1}$. Measurement of this heat flow and its geographic variations may provide information on the distribution of radioactive elements in the earth and on the nature of the processes by which the heat reaches the surface.

Meaningful values for heat flow can be obtained only in areas where steady-state conditions prevail. On land this requires measurements in mines or boreholes at depths of some hundreds of meters where effects of variations in atmospheric temperature are negligible. In the oceans, because of the apparent long-term temperature stability of oceanic bottom waters, measurements may be made in the upper few meters of sediment (*1*). Continental measurements have lagged behind oceanic measurements because of the difficulty and expense entailed in bore-hole measurements. Because variations in atmospheric temperature are greatly reduced at the bottom of deep lakes, we thought it possible, by applying oceanic techniques to lakes, to greatly accelerate and broaden knowledge of continental areas regarding heat flow. Work was initiated in Lake Superior during July 1963 from the U.S. Coast Guard cutter *Woodrush*.

Temperature gradients in the bottom sediments of Lake Superior were determined at four stations (Table 1) by means of thermistor probes attached to outrigger fins on a 4-m piston corer; equipment and techniques resembled