msrv

Take a look at p. 87, ¶3 (Nobody bothers to quote this prediction)

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INTERPLANETARY CORRELATION OF GEOLOGIC TIME

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Asteroid impact has produced a significant number of medium- and large-sized craters on the earth in comparatively recent geologic time, and the rate of impact can be interpreted to have remained fairly steady for at least the last half-billion years. By extrapolation of this rate, the lunar maria are found from the number and distribution of superimposed primary impact craters to have been formed at a very early period in the history of the moon. With appropriate modification, the same principle should be applicable to Mars when detailed photographs become available for photogeologic mapping.

A second potential method of interplanetary correlation depends upon the actual transport of impact debris from other planets to the earth, where the debris becomes incorporated in the terrestrial stratigraphic record. Some tektites may be formed by ejection of fused rock from the moon or by ablation of ejecta thrown into orbit around the earth. It may be possible to identify the craters from which the ejecta are derived at some advanced stage of lunar and planetary exploration and thus tie the age of these craters directly to the terrestrial time scale.

INTRODUCTION

Among the many new problems and fields of research opened up by the impending exploration of the solar system are the detailed histories of the terrestrial planets. The code in which these planetary histories are recorded consists of bodies of rock and rock debris. This code will be cracked by geologic mapping, for it is the spatial relationship of different bodies of rock that tells the sequence of events. The local sequence can generally be solved from the geometric relations of the rock units, but the absolute age of the rocks is another problem, which may be described as the correlation of geologic time on an interplanetary scale.

There are many reasons why we may expect difficulty in applying methods based on the decay of radioactive elements to determine the age of rocks or rock debris exposed on the surface of the moon or Mars. These methods are difficult enough when applied to the earth, for in spite of the great care and discretion that we can exercise here in selecting the samples to be analyzed the results are still commonly ambiguous.

Suppose the ejecta from an impact crater on the moon have been sampled and returned to earth by a remotely controlled probe. If the U and Pb isotopes or the K^{40} and A^{40} content of this sample or its mineral constituents are then measured, what will the results mean? It is unlikely that the ratios of these isotopes will reflect the age of the crater, because only a small fraction of the ejecta can be expected to contain new phases formed at the time of impact. The abundance and distribution of radiogenic elements in such a sample will probably be determined mainly by earlier events, perhaps highly complicated. As the chances are good that a major part of the surface of the moon has been built up of ejecta from impact craters, the standard methods of absolute age determination may be of secondary importance in establishing the dates of most events in the moon's history.

The interaction of the solid material of the solar system by collision, on the other hand, provides in principle two independent methods for the interplanetary

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correlation of geologic time. First, if the frequency of meteoroid impact and its variation with time on the different planets can be established, the age of rock bodies exposed on their surfaces can be estimated from the distribution of superimposed impact craters. With certain assumptions, this method can be applied at the present time to correlation between the earth and the moon, and should be applicable to Mars when high resolution photographs become available.

A second potential method depends upon the transport of impact debris from the moon and other planets to the earth, where the debris becomes incorporated in the terrestrial stratigraphic record. In order to complete the correlation it is essential to be able to identify the source of the debris. This will only be possible at an advanced stage of space exploration.

In this paper, these methods of correlation will be explored, and the method of impact frequency will be illustrated by evaluation of the age of the lunar maria. Similar attacks on the age of the maria have been made by Öpik [1] and Kreiter [2].

VARIATION IN THE SPACE DENSITY OF METEOROIDS WITH TIME AND POSITION IN SOLAR SYSTEM

It has been pointed out by Öpik [3,4,5] that the planets tend to sweep clean the space in their immediate neighborhoods. He estimates that objects which the earth actually meets at the present time, the meteoric particles and meteorites, came to the region of the earth's orbit perhaps not more than 100 million years ago. Average lifetimes of this order of magnitude can be computed for meteoroids that come within 1 AU on the assumption that the orbits of these objects undergo both secular and random perturbations. The present space density of meteoroids in the neighborhoods of the planets is determined by the balance between the rate of sweeping up and rate of injection of these objects into the space around the planets.

If the principal sources of objects large enough to form the recovered meteorites are the asteroids, as suggested by the trajectories of observed meteorite falls [6], then the rate of injection of these objects into the neighborhoods of the terrestrial planets is probably determined mainly by the breakup of asteroids by collision and by perturbation of the orbits of the asteroids and asteroid fragments. These are processes which can be imagined to go on at a rate that is fairly steady now and that will change only slowly with time at this stage in the history of the solar system.

Beginning at a very early point in the histories of Mercury, Venus, and the Earth, there must have been an initial period of sweeping up of whatever coarse solid material was left over in the planetary neighborhoods during planet formation. Within a few hundred million years the space density of meteoroids in these planetary neighborhoods probably approached some fairly steady value. Only in the vicinity of Mars would a significant fraction of the original planetoidal material have remained [5]. The rate of injection of asteroidal material into the neighborhoods of the terrestrial planets would be greatest for the Martian neighborhood and least for that of Mercury.

LOCAL VARIATIONS IN THE SPACE DENSITY OF METEOROIDS

In order to compare the frequency of impact on the terrestrial planets and the moon it is necessary to take into account the local condensation of the space density of meteoroids produced by the gravitational attraction of each planetary body. The gravitational effects are somewhat complex in the case of the earth–moon system.

The ratio F of the impact frequency for a sphere with mass to the impact frequency on a massless sphere is given by the ratio of the area of the capture cross section A_R to the cross-sectional area of the sphere A_r:

$$F = \frac{A_R}{A_r} \tag{1}$$

From conservation of angular momentum, it may be shown that the radius of the capture cross section R is given by

$$R = r\frac{V_r}{V_\infty} \tag{2}$$

where r is the radius of the sphere, V_r is the velocity of the meteoroid at the surface of the sphere, and V_∞ is the velocity of the meteoroid at an infinite distance from the sphere. From conservation of energy we have

$$V_r = \sqrt{2gr + V_\infty^2} \tag{3}$$

where g is the gravitational acceleration at r. Combining Eqs. (1), (2), and (3), we get

$$F = \frac{2gr}{V_\infty^2} + 1 \tag{4}$$

If it is assumed that the space density of meteoroids in the immediate vicinity of the moon is unaffected by the local gravitational attraction of the earth, then the ratio Q of the frequency of impact per unit area on the earth to the frequency of impact per unit area on the moon will be

$$Q = \frac{F_{\text{earth}}}{F_{\text{moon}}} = \frac{2g_e r_e + V_\infty^2}{2g_m r_m + V_\infty^2} \tag{5}$$

where

$$g_e = 9.8 \cdot 10^{-3}\ \text{km/sec}^2, \qquad r_e = 6.4 \cdot 10^3\ \text{km}$$

$$g_m = 1.67 \cdot 10^{-3}\ \text{km/sec}^2 \qquad r_m = 1.74 \cdot 10^3\ \text{km}$$

The modal observed entry velocity of recovered meteorites into the earth's atmosphere [6] is about 15 km/sec. This may be a representative figure for asteroids that come within 1 AU. From Eq. (3), the equivalent modal velocity of approach at infinity is 9.95 km/sec, and the equivalent impact velocity on the moon is 10.2 km/sec. For these velocities,

$$Q = \frac{126 + 99}{5.8 + 99} = 2.15 \tag{6}$$

5.81

The local condensation of the space density of meteoroids in the earth's gravitational field does, however, affect the impact frequency on the moon. This effect may be examined in two parts. First, consider the direction of approach of meteoroids toward the earth–moon system as random. Essentially, we wish to find the flux of meteoroids through the surface of a sphere with a radius equal to the mean distance between the moon and the earth. The problem is, therefore, analogous to the case of impact on a sphere except that nearly all meteoroids will intersect the surface of the sphere twice instead of once. The present ratio of the flux of meteoroids through this reference sphere when the earth is at its center and the flux through the reference sphere when it is massless is given by F in Eq. (4) when r is taken as the mean distance to the moon, $3.84 \cdot 10^5$ km, and g as the gravitational acceleration of the earth at the distance r, $2.8 \cdot 10^{-6}$ km/sec^2. For the modal equivalent velocity of approach at infinity of 9.95 km/sec, the condensation of the space density of meteoroids at the present distance of the moon from the earth is given by

$$F = \frac{2.1}{99} + 1 = 1.02 \tag{7}$$

or 2%. At this velocity, the earth would absorb by impact only about 0.02% of the flux through the present reference sphere. As there is a secular increase in the distance between the moon and the earth, a precise treatment requires an integration of this effect for varying distance with geologic time.

Secondly, as a refinement, we may imagine that the moon traces out the loci of all points in a belt about 10° wide on the reference sphere and that any position for the moon within this belt is equally probable. The belt is bisected by the ecliptic. If the orbits of the meteoroids were truly random, the earth would have no further effect on the impact frequency on the moon. The data assembled by Whipple and Hughes [6], however, suggest that the orbits of many objects large enough to form impact craters of interest in the present problem have only low inclinations to the ecliptic. In this case, the earth will have a focusing effect on the flux of meteoroids inside the reference sphere. The frequency of meteoroids leaving the sphere will be decreased near the diameter normal to the ecliptic and increased in the belt traced out by the moon. The frequency of impact on the side of the moon facing the earth will, therefore, be increased. The magnitude of the effect depends upon the distribution of the inclinations of the meteoroid orbits and the geocentric velocities of the meteoroids.

Qualitative considerations show that the maximum possible increase in impact frequency on the side of the moon facing the earth due to the focusing effect may be greater than a factor of 2 but must be less than a factor of 3. A factor of 2 is given as the maximum increase by Beard [7]. More detailed calculations on the focusing effect will be employed in a subsequent paper on the spatial distribution of lunar craters.

IMPACT FREQUENCY ON THE EARTH

Brown [8] has estimated the present impact frequency of meteoritic bodies upon the earth over a broad range of impacting mass from an evaluation of the frequency of observed meteorite falls in the most densely populated countries and the mass distribution curve of these meteorites. Estimated impact frequencies for masses far greater than the observed falls may be obtained by extrapolation of the observed mass distribution curve on the basis that the slope of this curve is remarkably similar to that of the mass distribution curve of the asteroids (Fig. 1). If Brown's maximum estimates for the frequency of fall of stone and iron meteorites are combined, the frequency may be expressed as

$$f = \left[\frac{6.9 \cdot 10^{11}}{(10^6\ \text{km}^2)(10^9\ \text{yr})(g^{-0.80})}\right] M^{-0.80} \tag{8}$$

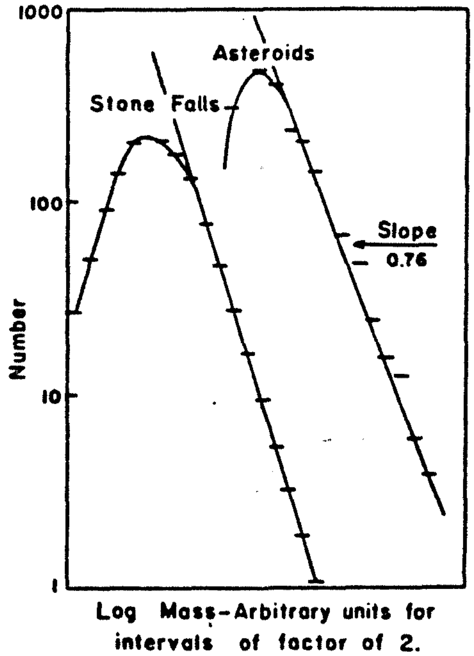

Fig. 1. Comparison of mass distribution of meteorites and asteroids (after Brown [6]).

where f is the total impact frequency of bodies of mass greater than M and M is the mass of impacting body in grams.

In order to compare this frequency with the geologic record of impact, a relation must be found between the mass of the impacting body and the size of crater formed. The most pertinent empirical data on crater dimensions to be expected from the impact of large meteorites in rock are provided by underground nuclear explosions, which generate shock pressures comparable to those produced by high-speed impact [9].

The diameter of nuclear-explosion craters varies systematically with the scaled depth of burst [10,11,12] (Fig. 2); in impact craters the effective depth of burst depends mainly upon the velocity of the meteorite and the density and equations of state of the meteorite and target rocks [9]. For ordinary rocks and meteorites, the effective scaled depth of burst ranges from 0 to about 10 m per (kiloton TNT equivalent)$^{1/3.4}$. A representative scaled depth of burst for stony meteorites striking a target of the same density [13] would be about 2.7 m per (kiloton TNT equivalent)$^{1/3.4}$.

The most critical and difficult step in applying the nuclear explosion data to the prediction of dimensions for craters 1 km in diameter and larger lies in selecting the appropriate scaling relation between crater dimensions and energy. In the past, scaling laws have commonly been used that give crater diameters as proportional to the cube root of the energy released [14]. A quadratic equation fitted by Baldwin [15] to data for small craters produced by chemical explosion is approximately equivalent to cube root scaling in the energy range of 1 kiloton to 1 megaton TNT equivalent. Baldwin's curve leads to overestimation of the diameters of craters produced by nuclear explosions at the lower end of this range by more than a factor of 3. Recent experimental studies of the dimensions of craters produced by explosion have suggested that, for a given medium and scaled depth, the diameters of craters are more nearly proportional

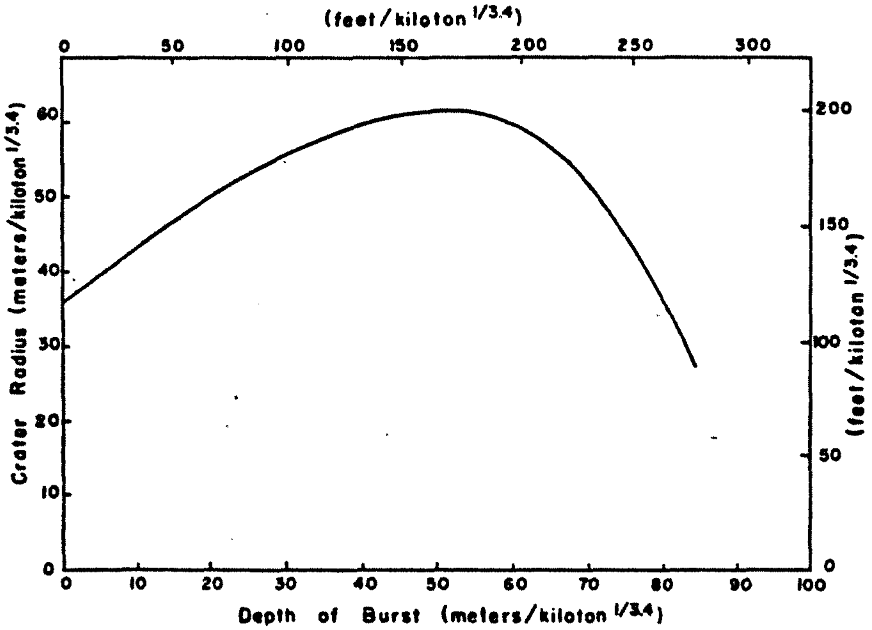

Fig. 2. Crater radii as a function of depth of burst for explosion craters in alluvium (after Johnson [10]).

to the $^1/_{3.4}$ power of the energy released [16,17]. On purely theoretical considerations of shock propagation it may be anticipated that crater diameters will be proportional to some power of the energy lower than $^1/_3$.

Curves are shown in Fig. 3 for effective depths of burst of 2.7 m and 10 m at one kiloton TNT equivalent, assuming two different scaling laws. The equations represented by these curves are:

$$D = (74 \text{ m/kt TNT equivalent}^{1/3})\, W^{1/3} \quad (9)$$

$$D = (85 \text{ m/kt TNT equivalent}^{1/3})\, W^{1/3} \quad (10)$$

$$D = (74 \text{ m/kt TNT equivalent}^{1/3.4})\, W^{1/3.4} \quad (11)$$

$$D = (85 \text{ m/kt TNT equivalent}^{1/3.4})\, W^{1/3.4} \quad (12)$$

where D is the diameter in meters and W is the energy released in kilotons TNT equivalent. (One kiloton TNT equivalent is 4.185 10^{19} ergs.) The constants have been derived from the lip to lip diameters of the Jangle U and Teapot Ess nuclear-explosion craters in alluvium measured by Shoemaker [9]. Both craters were formed by a device with a yield [18] of 1.2 ± 0.05 kilotons.

The energy released by impact of a meteorite is simply the geocentric kinetic energy

$$\frac{4.185 \cdot 10^{19} \text{ ergs}}{\text{kt TNT equivalent}}\, W = \tfrac{1}{2} M V_e^2 \quad (13)$$

Combining Eqs. (8), (9), (11), and (13), families of curves may be drawn for the size frequency distribution of terrestrial impact craters using different assumed modal impact velocities (Fig. 4). The equations represented by these curves are

$$f = \left[\frac{2.72 \cdot 10^8}{(10^6 \text{ km}^2)(10^9 \text{ yr})(\text{km/sec})^{1.6}(\text{m})^{-2.4}}\right] V_e^{1.6} D^{-2.4} \quad (14)$$

and

$$f = \left[\frac{1.08 \cdot 10^9}{(10^6\ \text{km}^2)\ (10^9\ \text{yr})\ (\text{km/sec})^{1.6}\ (\text{m})^{-2.4}}\right] V_r^{1.6} D^{-2.72} \tag{15}$$

where f is the total frequency per million square kilometers per billion years of impact craters larger than diameter D and V_r is given in km/sec.

The largest well-studied observed meteorite fall occurred in 1947 in Sikhoté-Aline, on the eastern coast of Siberia [19]. Entering the atmosphere at a calculated velocity of 14 to 15 km/sec, the meteorite broke up and formed a strewn field of fragments and a group of small impact craters, the largest of which was 28 m in diameter. More than 30 tons of meteoritic matter was recovered and the total mass that fell to the ground immediately was estimated to be about 100 tons. Nearly 200 tons were calculated to have been left in a dark turbulent wake that remained in the atmosphere for several hours. The initial mass was thus on the order of 300 tons or more. From Eq. (8), such a body would be expected to enter the earth's atmosphere about once every 20 years. The most nearly comparable observed fall* occurred in central Siberia nearly 40 years earlier [21]. Considering that the chances of observation of such an event are reduced over the ocean areas and drop off sharply if we go back into the 19th century, the agreement with the predicted frequency is perhaps as good as we may expect.

If we adopt 15 km/sec as the most probable mode for the velocity of impact of asteroidal objects, it may be seen from Fig. 4 that we would expect about one impact crater larger than 1 km in diameter to be formed in an area the size

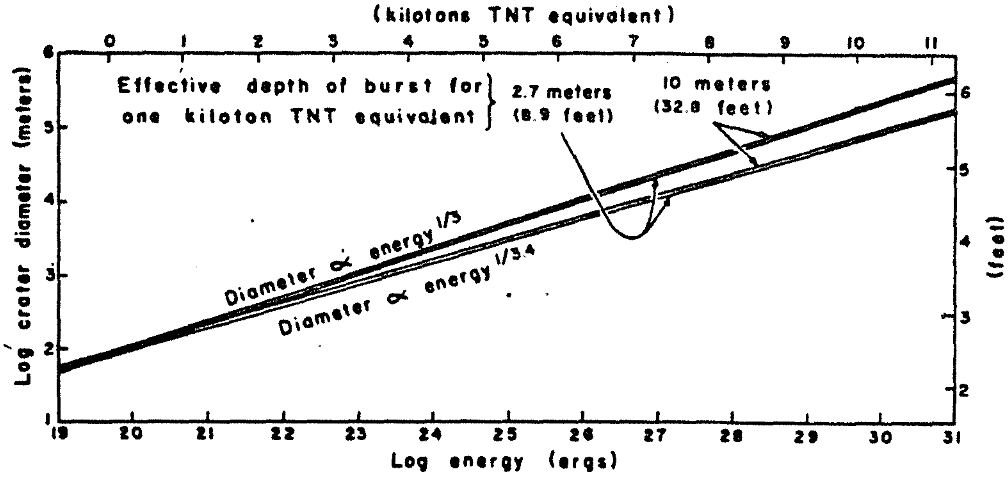

Fig. 3. Crater diameters as a function of energy released.

of the North American Continent about every 50,000 years. For the last 50,000-year period this expectation is fulfilled in North America by Meteor Crater, Arizona, which is slightly more than 1 km across and is probably between 20,000 and 50,000 years old. An impact crater the size of the New Quebec (Chubb) crater of Canada, which is about 3 km in diameter [22], would be expected to be formed in North America about once every $\frac{1}{2}$ to $1\frac{1}{2}$ million years.

*As no fragments have been recovered and the object appears to have had a retrograde orbit, Fessenkov has suggested that the object was of cometary origin. Its mass has been estimated to be on the order of a million tons [20].

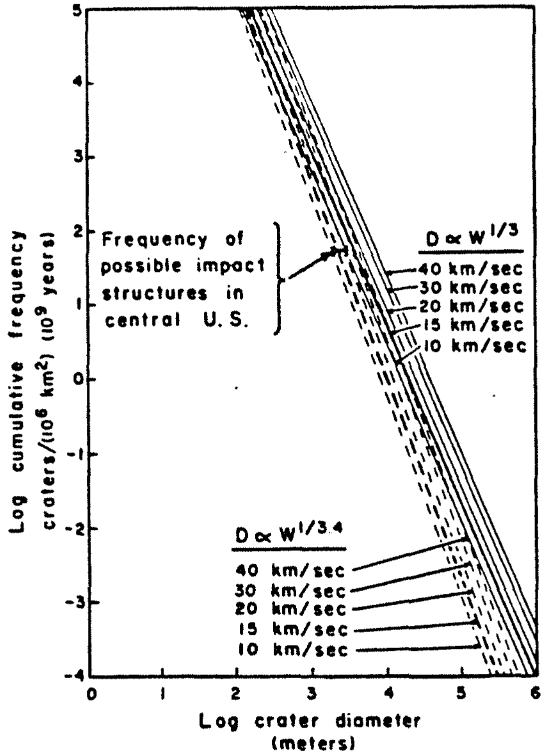

Fig. 4. Cumulative frequency of craters as a function of crater diameter.

The age of the New Quebec crater is known only within broad limits, but its rim has been deeply scoured by glaciers [23], and it may date from the middle or early Pleistocene, roughly 100,000 to 500,000 years before the present. In the past 15 million years, we would expect from one to four asteroids large enough to make a crater 27 km in diameter or larger to have struck the earth. This is the diameter of the Ries basin of Bavaria, the largest known crater of probable impact origin [24, 25], which is late Miocene in age or about 15 million years old. On the basis of the frequency curves of Fig. 4, the chances would appear to be perhaps 50% that one such crater would be formed on the continents in that period of time. The predicted frequencies are all increased if we adopt higher estimates of the modal impact velocity.

If the record of the more distant geologic past is examined, we should not expect to find craters, which are filled in or eroded away in time, but the subsurface structures associated with large impact craters may be preserved. A structure that appears to correspond to the subsurface features of an impact crater is well exposed at Sierra Madera, Texas (Fig. 5). It consists of a lens of breccia nested in a collar of turned-up and overturned beds that may once have underlain a crater about 3 km across.

Many similar structures have been found in the central United States; they have remained something of an enigma to the geologist. Bucher [27], who mapped several of them, thought they were produced by cryptic or hidden volcanic forces. Some geologists [28-31] that have studied the so-called "cryptovolcanic" structures in the field have supported the suggestion of Boon and Albritton [32] that they were produced by meteorite impact. Recently several additional structures, some of which are ancient filled-in craters, have come to light in Canada [33].

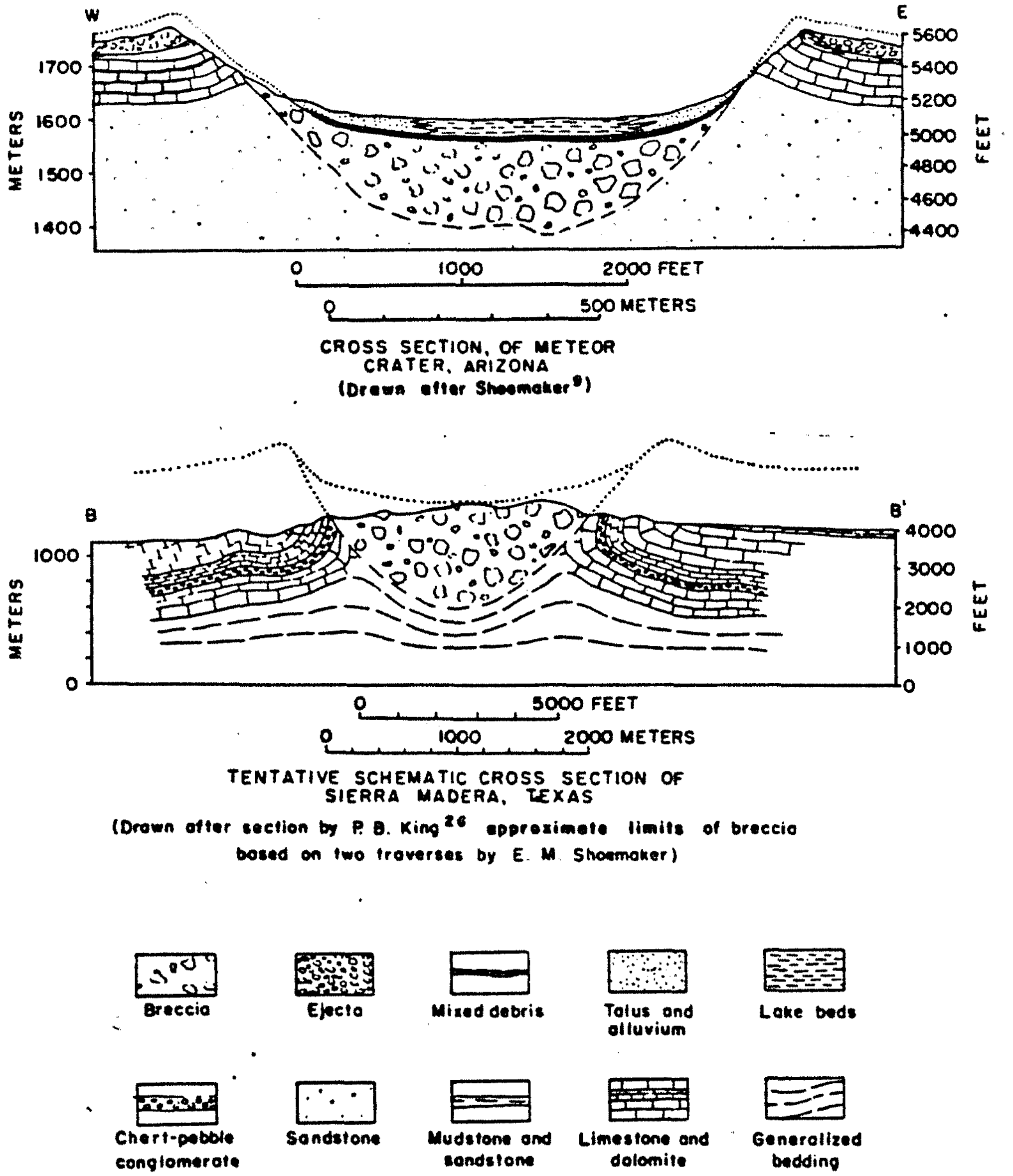

Fig. 5. Cross sections of Meteor Crater, Arizona, and Sierra Madera, Texas.

Ancient impact structures are likely to be found in considerable number only in the stable interiors of continents where there has been relatively little erosion or deposition of sediments for a long stretch of geologic time. Recognition of these structures would be greatly favored in regions underlain by nearly flat-lying sedimentary beds of contrasting lithology. The Mississippi lowland of the central United States, where numerous structures of the Sierra Madera type are found, is an area that fulfills these conditions.

A sample rectangular area of 770,000 km^2 that contains ten recognized structures of possible impact origin was chosen to calculate the impact fre-

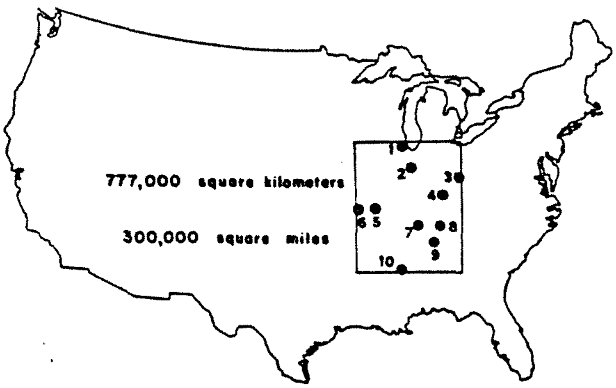

Fig. 6. Structures of possible impact origin in the central United States. (See Table I for list of structures.)

quency (Fig. 6). About 1% of the area is covered by the Great Lakes and 8% is underlain by structurally complex rocks of the southern Appalachian Mountains and Precambrian rocks where impact structures are not likely to be recognized. The average age of the beds underlying the remaining 91% of the area, weighted according to area of exposure, is about 235 million years (calculated on the basis of Holmes' B time scale [39]). The actual age of the individual structures ranges from late Cambrian or early Ordovician (about 400 million years) to Eocene or younger (less than 50 million years). If these structures are all of impact origin, the indicated impact frequency is about $60/(10^6\ km^2)(10^9\ yr)$ (see Table I). The authors believe that most of these structures correspond to craters about 3 km in diameter or larger, but the smallest structures, at Jeptha Knob, Kentucky, and Howell, Tennessee, probably do not correspond to craters this large. On the basis of a modal impact velocity of 15 km/sec, the predicted frequency from the curves of Fig. 4 for craters 3 km in diameter and larger is about 30 to $100/(10^6\ km^2)(10^9\ yr)$. This comparison, it should be noted, is sensitive to the estimate of the lower limiting diameter. If a diameter of 2 km is chosen, the predicted frequency is about 80 to $300/(10^6\ km^2)(10^9\ yr)$.

TABLE I. List of Structures of Possible Impact Origin in Sample Area in Central United States

1. Des Plaines disturbance, Illinois [34]
2. Kentland disturbance, Indiana [35]
3. Serpent Mound disturbance, Ohio [27]
4. Jeptha Knob disturbance, Kentucky [27]
5. Crooked Creek disturbance, Missouri [28]
6. Decaturville disturbance, Missouri [27]
7. Wells Creek disturbance, Tennessee [27]
8. Flynn Creek disturbance, Tennessee [36]
9. Howell disturbance, Tennessee [37]
10. Kilmichael disturbance, Mississippi [38]

The largest known structure of the Sierra Madera type is the so-called Vredefort Dome in South Africa [26,32,40]. If this structure is of impact origin it should correspond to a crater about 70 km in diameter. From the curves of Fig. 4 we find, for a 15-km/sec impact velocity, an expected frequency of $^1/_2$ to 6 such structures formed on the land areas of the earth per billion years. The age of the Vredefort structure is not closely known. It is developed in Precambrian beds and is overlain unconformably by late Paleozoic rocks; its probable age is of the order of a half-billion years.

Insofar as it is known, the geologic record may be interpreted as consistent with the frequency of impact of large meteoroids predicted by the extrapolation of the observed mass distribution curves of recovered meteorites. Within the large uncertainties necessarily involved in making the comparison, the geologic record may be considered consistent both with the predicted mass distribution of the bolides and with the hypothesis that the present frequency of impact has remained about the same over the last one-half billion years. It is important to note that both the estimated present frequency of meteorite falls and the frequency estimated for the past are likely to be low because of incompleteness of observational data.* Even in the most favorable area, the geologic record is likely to be incomplete because of losses due to erosion, inadequate mapping, and obscuring surficial deposits such as glacial drift. As several asteroids that may be large enough to produce a structure the size of the Vredefort Dome are known to come within 1 AU, it appears likely that the frequency of formation of the larger craters, in particular, may be underestimated.

NATURE AND DISTRIBUTION OF CRATERS ON THE LUNAR MARIA

We may now ask whether the number and distribution of craters on the moon is compatible with the frequency of impact suggested by the terrestrial data. It should be noted at the outset that there is no justification for extrapolating the present frequency of impact indefinitely into the past, particularly to the earliest period in lunar history.

The most conspicuous fact about the moon is that its surface may be roughly divided into two classes of terrain, one class with much lower aereal density of craters than the other. The terrain with low crater density, the lunar maria, is underlain by material that overlaps the terrain with higher crater density and buries or partially fills older craters. Younger craters are superimposed on the material of the maria.

As a first step in correlating events on the moon with the terrestrial time scale, it is appropriate to attempt an estimate of the age of the material that fills the maria, which may serve as a widespread stratigraphic datum. To do this we will assume that certain types of craters are of impact origin and that the material of the maria is all of about the same age. The consistency of both assumptions will be partially tested by comparison of the crater distribution with prediction.

It is essential to recognize that not all craters superimposed on the maria are likely to be formed by impact of objects derived from sources external to the moon. Certain small craters aligned in rows or along rills have almost surely been produced by forces originating within the moon. These craters, together with others that occupy the summits of conical and dome-shaped hills

*Since the completion of this paper the writers have received a copy of a manuscript by Professor Harrison Brown which indicates that the frequencies given in his earlier paper [8] should be multiplied by 3.

Fig. 7. Index map of the moon showing distribution of mare terrain and some associated major craters.

and perhaps others surrounded by dark halos are likely to be of volcanic origin [41,42,13].

Another type of small crater is a relatively shallow, commonly elongated, gouge-like depression that occurs in great numbers associated with the ray systems of some of the larger craters. These gouges are probably secondary impact craters formed by fragments ejected from the large craters [13]. More than a thousand such secondary impact craters, many of which are superimposed on mare surfaces, surround the large ray crater Copernicus [13,43]. Similar systems of secondary craters surround other large craters such as Tycho, Theophilus, Langrenus, Aristoteles, and Eratosthenes (Fig. 7).

The remaining craters that are not readily assignable to a volcanic or secondary impact origin by the criteria of alignment or shape will be considered as formed by the primary impact of large meteoroids. The frequency and size distribution of presumed primary impact craters larger than 1 mi (1.6 km) in diameter that are superimposed on eight different mare areas (Fig. 7) are given in Table II. One-mile diameter has been taken as the lower practical limit in size at which craters of different types may be objectively discriminated on the best lunar photographs. The frequencies given for craters in the 1- to 2-mi-size class are subject to considerable error owing to uncertainties in the appraisal of crater type, poor resolution on photographs available for certain areas, and imprecision in the determination of the lower limiting diameter.

The frequencies given in Table II for 1- to 2-mi-diameter craters and 2- to 4-mi-diameter craters in Mare Imbrium are significantly lower than the frequencies found by Öpik [1] and Kreiter [2]. This difference is due mainly to the elimination from our tabulation of secondary impact craters surrounding Copernicus and Eratosthenes.

Comparison of the frequency of primary impact craters in the different areas scattered over the lunar disc shows that, with one exception, the percentage variation in aereal density of craters from one area to another is only slightly

TABLE II. Size Frequency Distribution of Primary Impact Craters on the Lunar Maria

Area	Approximate square kilometers	Number of craters, according to size: Crater diameter in miles 1–2	2–4	4–8	8–16	16–32	32–64	64–128	Craters per $10^5 km^2$
Mare Imbrium	864,000	199	117	37	10	5	1	0	42.8
Lacus Somniorum	64,500	103	68	41	15	5	2	0	46.5
Mare Frigoris	439,000								
Mare Serenitatis	318,000	88	41	7	1	1	0	0	43.7
Mare Fecunditatis	311,000	56	34	28	6	3	1	1	41.5
Mare Tranquillitatis	402,000	89	57	39	11	6	0	1	50.5
Palus Epidemiarum	28,800	111	64	27	11	0	1	0	54.0
Mare Humorum	107,000								
Mare Nubium	261,000								
Mare Nectaris	96,400	26	16	2	1	0	0	0	46.7
Mare Crisium	165,000	20	10	6	4	0	0	0	24.2
Total	3,056,700	692	407	187	59	20	5	2	44.9

greater than the percentage variation in the ratios of the frequencies in the first and second size classes. Thus, with the exception of Mare Crisium, the assumption that the material of the maria floors is everywhere about the same age would appear to be consistent with the observed distribution of craters. Most of the areas studied are located toward the center of the lunar disc. However, in Mare Crisium which is located near the limb, the crater frequency appears to be significantly lower than average.

The low crater frequency in Crisium may indicate that this mare was formed at a later date than the others, or it may be due to the focusing effect of the earth on objects with orbits of low inclination to the ecliptic. The focusing effect would produce the greatest increase in impact frequency near the center of the lunar disc.

A more detailed breakdown of crater frequencies by area shows that the aereal crater density in Mare Humorum, which is located away from the moon's center but is not as close to the limb as Crisium, is also somewhat lower than average. A lower than average crater density is also observed in Mare Frigoris and Mare Fecunditatis, which lie toward the limb, but the effect is not as great as would be expected from the crater density in Crisium. A detailed study of the crater distribution in the Oceanus Procellarum is expected to throw more light on this question, and the whole pattern of crater distribution on the maria must be subjected to a rigorous analysis before any definite conclusions can be drawn about the focusing effect.

The mean cumulative size frequency distribution of the primary impact craters for the eight areas studied is given in Fig. 8. The curve is linear over

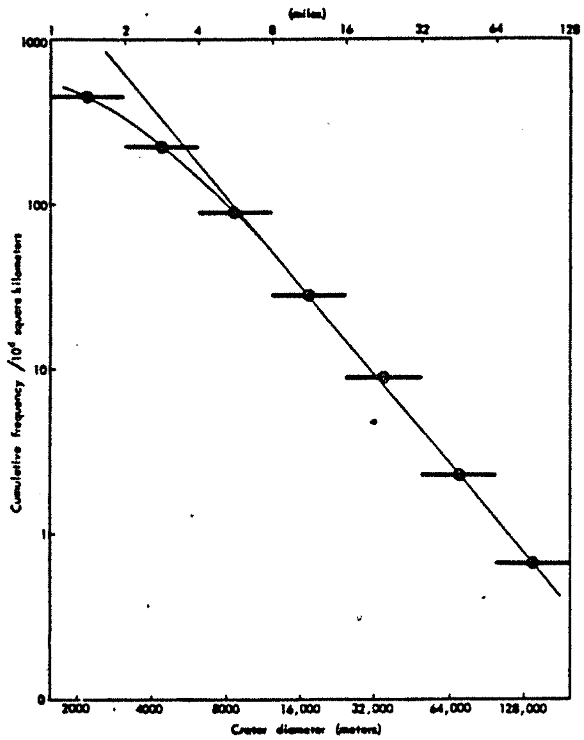

Fig. 8. Size frequency distribution of craters of probable primary impact origin superimposed on the lunar maria.

the range of the larger sized classes, as would be expected from the meteorite and asteroid mass distribution curves, but the frequencies in the two lowest sized classes drop away from the slope determined for the larger size classes. Some drop would be expected from the fact that ejecta from the larger craters and the large craters themselves tend to cover up or obliterate smaller craters. Craters superimposed on the maria are sufficiently widely spaced, however, that the covering or obliteration of small craters by the large is quantitatively insufficient to account for the observed departure from the linear part of the curve. Other possible causes will be considered in connection with the over-all slope.

AGE OF THE LUNAR MARIA

In order to compare the observed frequency distribution of craters on the maria with the estimated frequencies for the earth, we must find the corresponding predicted frequencies for the moon. With high probability, the modal entry velocity of meteorites and asteroids into the earth's atmosphere lies in the range from 15 to 30 km/sec. We will use this velocity range to find the range of predicted frequency distribution of craters on the moon. From Eq. (3), the corresponding impact velocities on the moon are found to be 10.2 and 27.9 km/sec. Applying the ratios given by Eqs. (4) and (5), it is found that the frequency of impact on the moon at a 10.2-km/sec modal velocity should be 0.474 times the frequency of impact on the earth at 15 km/sec, and the frequency at 27.9 km/sec impact velocity on the moon should be 0.87 times the frequency for 30 km/sec impact on the earth. The moon is taken at its present distance from the earth in calculating these ratios, and therefore the small effect of the secular recession of the moon from the earth was not included. No account is taken of the focusing effect of the earth, which will be considered separately. The equations for the limits of the predicted cumulative frequency distributions on the moon are

$$f_{moon} = 1.29 \cdot 10^{8} V^{1.6} D^{-2.4} \quad (16)$$

$$f_{moon} = 2.36 \cdot 10^{8} V^{1.6} D^{-2.4} \quad (17)$$

for $D = W^{1/3}$; and

$$f_{moon} = 5.18 \cdot 10^{8} V^{1.6} D^{-2.72} \quad (18)$$

$$f_{moon} = 9.40 \cdot 10^{8} V^{1.6} D^{-2.72} \quad (19)$$

for $D = W^{1/3.4}$. No account is taken of the fact that, for the same energy released, a crater is likely to be somewhat larger on the moon than on the earth, owing to the lower gravitational acceleration. A theory of cratering which takes the gravitational attraction into account leads to prediction of crater diameters up to 90 km on the moon that scale according to the $\frac{1}{3}$ power of the energy with the data from the nuclear craters [13].

The hypothesis has been put forward that the maria were formed at a very early stage in lunar history [15, 44, 45], specifically about 4.5 billion years ago, which is the age estimated by Patterson, Tilton, and Inghram [46] for the earth and for the crystallization of the meteorites. If the observed frequencies of craters on the maria are divided by 4.5 billion years, this hypothesis may be tested by comparison with the predicted frequencies given by Eqs. (16) to (19) (Fig. 9). Alternatively, we may view the same comparison as extrapolating the present estimated impact frequencies back 4.5 billion years to see if they will account for the number and distribution of craters on the maria.

From Fig. 9 it may be seen that only the frequency of craters up to 8 km in diameter falls within the predicted range of frequencies. If the predicted frequencies were multiplied by a factor of 2, to take into account a possible strong focusing effect of the earth, then the frequencies of craters up to about

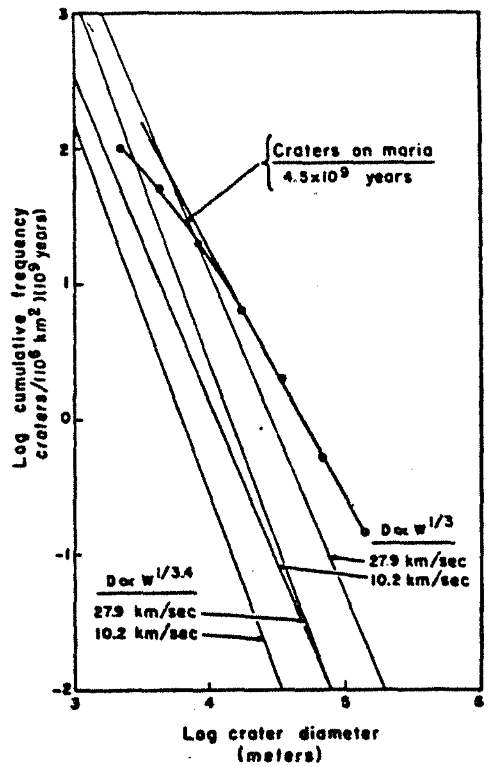

Fig. 9. Predicted frequency of impact craters on the moon compared with observed crater frequency distribution on the maria.

25 km in diameter would fall within the predicted range. The frequencies of the largest craters on the lunar maria, however, are too high to be accounted for by extrapolating the frequencies estimated for the present back over geologic time.

The basic discrepancy can be seen to lie in the fact that the absolute value of the observed slope of the cumulative frequency distribution of the craters superimposed on the maria, contrary to the opinion of Jaschek [47], is less than the slope predicted from the mass distribution curves for the meteorites and the asteroids. Jaschek's good fit was obtained by assuming the highly improbable scaling relation between crater diameter and energy of $D \propto W^{2/5}$. The more likely explanation of the discrepancy is that the mass distribution of large objects in the neighborhood of the earth and moon over the last several billion years has been significantly different than the calculated distribution for recent meteorites or the asteroids. It is possible that the albedo varies systematically with the size of the asteroids, or that the asteroids lying between Mars and Jupiter are not representative of the objects injected into the neighborhood of the earth, or that with the passage of time their mass distribution has been changed rather drastically by collision. It should be noted, however, that several of the largest craters superimposed on the maria are ray craters that can be shown to be younger than most of the other craters. Another possibility is that many or most of the larger craters were formed by the collision of the nucleii comets, rather than asteroids.

If we reverse our viewpoint by adopting the age of the maria as 4.5 billion years and take the observed frequency distribution of the craters as the best data on the mass distribution of objects in the earth's neighborhood, the predicted frequency of impact of the larger objects on the earth may be increased. An increase of an order of magnitude in the probabilities of finding an impact structure the size of the Vredefort Dome would relieve the necessity of attributing the exposure and recognition of this structure to good luck. Such an increase probably would also be in better accord with the fact that 13 asteroids have now been discovered in the neighborhood of the earth, particularly when it is considered that their discovery has largely been accidental and many more are likely to be found. If the probable incompleteness of our information on terrestrial impact structures is taken fully into account, it would appear that the geologic record of impact is consistent with the hypothesis that the lunar maria are about 4.5 billion years old, that the craters assumed to be of primary impact origin are indeed formed by impact, and that the space density and mass distribution of large solid objects in the neighborhood of the earth have remained nearly constant over most of geologic time. A corollary of this hypothesis is that the rate of formation of craters on the moon in the period prior to the development of the maria was much greater than during subsequent geologic history.

INTERPLANETARY TRANSPORT OF IMPACT EJECTA

Experimental investigation of hypervelocity impact on metal targets has shown that a small amount of material is ejected from near the projectile-target interface at speeds exceeding that of the impacting projectile [48]. The bulk of the material ejected leaves the crater at some small fraction of the initial impact speed, but even this small fraction is a relatively high velocity. From an impact crater in rock, a similar proportion of material is ejected at high velocity; and, in addition, a comparatively large volume of rock is thrown out at lower velocities. A theory of cratering for very large impact craters in rock, based on an idealized treatment of shock propagation [13], suggests that, starting with fragments ejected at low angles and low velocity from the edge of a crater, the ejection velocity increases with increasing angle of ejection up to angles exceeding 45° that are observed in laboratory experiments.

The occurrence of secondary impact craters in the rays extending as much as 500 km from some of the large craters on the moon shows that fragments of considerable size are ejected at speeds nearly half the escape velocity from the moon (2.4 km/sec). At least a small amount of material from the lunar surface and perhaps as much or more than the impacting mass is probably ejected at speeds exceeding the escape velocity by impacting objects moving in asteroidal orbits. Some small part of this material may follow direct trajectories to the earth, some will go into orbit around the earth, and the remainder will go into independent orbit around the sun. Much of it is probably ultimately swept up by the earth.

It is, therefore, pertinent to inquire whether and how such free samples from the moon might be recognized. Urey [49] has suggested that the stony meteorites may be precisely these samples, although the available data on the trajectories of observed chondrite falls suggest that they come from a more distant region of the solar system. Perhaps Urey's idea deserves closer consideration in connection with the achondrites. The petrographic study of the Moore County achondrite by Hess and Henderson [50] suggests it was derived from a body of lunar or planetary dimensions.

There is another class of objects of possible lunar origin that has been the subject of much controversy. These are the tektites. Verbeek [51] originally suggested in 1897 that tektites were ejected from lunar volcanoes, and this idea was considered by Suess [52] and many subsequent European students of these strange drops of glass. Later it was proposed that the tektites were ejected from the moon by impact [53], and this concept has been elaborated in various forms. Varsavsky [54] and Chapman [55] have examined the possibility that the australites were ejected from the moon as a spray or jet of rock melted by the impact-produced shock, and were subsequently reheated aerodynamically in the earth's atmosphere. O'Keefe [56] proposed that the australites and other tektites were formed entirely by aerodynamic heating as ablation drops from lunar fragments moving in a decaying orbit.

The tektites are of special interest in the problem of interplanetary correlation of geologic time because the position of the major tektite showers in the geologic record is partly known and can probably be closely determined. If these objects are of lunar origin, their time of transport from the moon to the earth must be very short in terms of geologic time on either the Varsavsky and Chapman or O'Keefe type of hypothesis. By comparison of the chemical composition of the tektites with the composition of ejecta from various lunar craters, it may be possible at some advanced stage of lunar exploration to identify specific craters from which each group of tektites was derived and thus tie the age of these craters directly to the terrestrial time scale. If all the australites and associated Pleistocene Indomalayan tektites are derived from a single fragment, as suggested by the hypothesis of O'Keefe, then the search for their source can probably be narrowed to a group of the larger, very bright ray craters such as Tycho.

Finally we may consider briefly some possible consequences of asteroid impact on Mars. Öpik [3, 5] has already summarized cogent reasons for expecting the frequency of impact per unit area to be higher on Mars than on the earth and moon. The chances that the distribution of recognizable impact craters on Mars may be used to correlate geologic time, perhaps when close-up photographs are available in the fairly near future, are excellent. Some features on Mars already visible through the telescope may be of impact origin [3, 57]. There is also a possibility that fragments can be ejected at escape velocity from Mars by asteroid impact, though not as large a fraction as is ejected from the moon. If some small amount of material escapes from Mars from time to time, it seems likely that at least some very small fraction of this material would ultimately collide with the earth. Whether it could ever be recognized is difficult to say, but the possibility that such material could carry organic hitchhikers, however remote, may present a vexing question to those who are concerned with the origin of life.

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