LUNAR IMPACT CRATERS

Introduction

The term "impact crater" refers to a depression, generally floored, formed in a solid material by the conversion of the kinetic energy of a moving body striking it. This definition is necessarily broad, including features such as the micron-sized pits produced by micro-meteorites on spacecraft, craters thousands of feet in diameter produced by large meteorites on the earth, and perhaps the circular maria, hundreds of miles in diameter, of the moon.

A discussion of lunar impact craters is of course handicapped by our relative ignorance of the origin of the moon's surface features in general; many authorities have argued that there are no impact craters on the moon, or at least very few, preferring a volcanic origin. The roots of the well-known crater controversy go back almost to the initial discovery of the moon's craters by Galileo in 1610, and the controversy is still very much alive even after the recent achievement of Ranger VII in returning high-resolution pictures of the moon's surface. Excellent summaries of the various points of view are presented by Baldwin (1963), Shoemaker (1962), and Green (1962). Baldwin's book also contains a comprehensive list of dimensions of more than 200 lunar craters, which are quoted here.

This discussion cannot, then, be authoritative in the sense that the origins of any of the natural lunar craters are known with certainty. We shall instead describe selected craters which have been ascribed to impact, each of which is representative of a large class of similar craters. Two major classes are distinguished: primary craters, which

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have been formed directly by bodies falling from space, and secondary craters, which have been formed by ejecta from primary craters. The existence of tertiary craters is implied, but cannot be demonstrated.

In these descriptions, the astronautical direction convention is used; that is, to a person standing on the moon and looking north, east would be on his right.

Copernicus

The crater Copernicus, one of the most conspicuous on the visible hemisphere, is just south of Mare Imbrium at 10°N, 20°W. It is about 57 miles in diameter and 11,000 feet deep, with a rim height of 3300 feet.

The most outstanding feature of Copernicus is its spectacular bright ray system, which extends well over 200 miles from the crater in all directions. This ray system, and hence Copernicus itself, are demonstrably among the relatively youngest features on the moon because the rays overlie all other features with which they are in contact, with the exception of a few small dark-haloed craters. This relative newness is substantiated by the sharpness of the Copernican topography, the fact that very few primary craters cut the crater or its ejecta blanket, and presumably by its high albedo (since lunar rocks apparently darken with time).

Topographically and structurally, Copernicus is a depression. Its inner walls consist of a series of concentric terraces, which are normal fault blocks with the inner block on the downthrown side. A geologic map of Copernicus and its surroundings is presented by Shoemaker

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(1962). The inner floor is relatively flat, except for the conspicuous central peaks.

The outer rim of the crater merges with a blanket of hummocky material, apparently ejected from the crater, which in turn grades into the ray system. The ejecta blanket is cut by numerous chains of small craters visible only with high-powered telescopes. Farther out the crater is surrounded by a halo of small, elongated gouges considered to be secondary craters formed by ejecta from Copernicus.

The evidence that Copernicus is an impact crater can be conveniently summarized as follows.

1. Existence of large impact craters on the earth:

Recent geological, geophysical, and mineralogical investigations have strongly indicated an impact origin for such structures as the Ries Kessel, Germany (15 mile diameter), the Clearwater Lakes, Canada (16 and 20 miles diameter), and the Manicouagan Lake feature, Canada (40 miles diameter). If these are in fact impact craters, or their roots, we should expect to find comparable craters on the moon.

2. Independence of structural trends:

Unlike terrestrial volcanoes, Copernicus and similar craters seem to be randomly located on the moon, with no systematic relation either to each other or to observable pre-existing structures.

3. One-stage formation:

The formation of a feature as large as Copernicus must have been extremely complex in detail. We can, in fact, distinguish several discrete events which took place, such as the formation of the ejecta blanket, the faulting of the inner walls, and the later formation of small dark-haloed and chain craters. However, the main process of crater formation appears to have been a one-stage event. This is quite unlike the evolution of possible terrestrial analogues, such as Krakatoa-type calderas, which usually form over a long period of time by repeated eruption and subsidence.

4. Great size:

Copernicus is by no means the biggest crater on the moon, nor even the biggest ray crater (compare Langrenus, with a diameter of 82 miles); Baldwin lists 72 craters on the visible hemisphere with diameters over 50 miles. Circular terrestrial calderas, on the other hand, rarely have diameters over a few miles, the biggest, according to Williams (1941), being the Valles Caldera of New Mexico (16 by 18 miles). There are larger volcano-tectonic depressions, such as that of Lake Toba, Sumatra (60 by 19 miles), but these are quite different in form from craters of the Copernican type. It should be mentioned, however, that our knowledge of present and past terrestrial vulcanism is very incomplete, and it is possible that large volcanic structures more comparable to lunar craters may yet be discovered.

5. Similarity to terrestrial impact craters:

All the probable impact structures on the earth which approach Copernicus in size are "fossil" craters, in that they are old enough to have been severely modified by erosion and deposition. Consequently, we know little of their original topography and structure. However, several smaller modern craters, such as Meteor Crater, Arizona, the New

Quebec Crater, Canada, and the Henbury craters, Australia, have been shown to be similar in many respects to lunar craters. For example, at Meteor Crater we find a hummocky ejecta blanket and concentric faulting similar to those of Copernicus; in the Steinheim Basin, Germany, we find an apparent central peak. Further support, though indirect, for the impact origin of Copernicus is found in the similarity of its ejecta-ray pattern to the ejecta patterns around nuclear explosion craters, which have been demonstrated (Shoemaker, 1962) to be closely analogous to impact craters.

Eratosthenes

This crater lies about 150 miles northeast of Copernicus, cutting the Apennine Mountains bordering Mare Imbrium. Its diameter is about 36 miles, its depth 10,300 feet, and its rim height 3300 feet.

Eratosthenes is a smaller version of Copernicus in most respects, including the possession of a halo of apparent secondary craters. Unlike Copernicus, however, it does not have a visible ray system, and in general has a lower albedo than Copernicus. The secondary craters around Eratosthenes have been found by Michael Carr (Shoemaker, 1964) to be noticably more subdued than those around Copernicus.

Perhaps the most important characteristic of Eratosthenes is the fact that it is older than Copernicus, as demonstrated unequivocally by the overlying Copernican ray material. Although we do not know how much time elapsed between the formation of the two craters, this proven relationship shows first, that the rays fade with time, and second, that some sort of erosive process is active on the lunar surface.

The similarity between Eratosthenes and Copernicus implies, of course, that most of the evidence favoring an impact origin for the latter applies to it as well.

Archimedes

Archimedes is about 400 miles northeast of Copernicus, in the southeast part of Mare Imbrium, and has a diameter of just 50 miles, a depth of 6100 feet, and a rim 4800 feet high. It is one of the most spectacular of a class of large craters which are floored with the dark, smooth, mare material. Other members of this class are Plato, Billy, and Pitatus.

We are dealing here with a crater which is clearly much older, at least relatively, than Copernicus and Eratosthenes. This is demonstrated qualitatively by the fact that Archimedes was formed before emplacement of the mare material, which fills it, whereas Copernicus and Eratosthenes are post-mare, as shown by the fact that their ejecta overlies mare material. Further indication of this greater age is found in the smaller craters which cut the Archimedian ejecta blanket.

Craters such as Archimedes are of incidental interest because they prove that an appreciable interval of time elapsed between the formation of the mare basins and the emplacement of the mare material (generally considered to be volcanic rock). Archimedes and Plato, though in or very near Mare Imbrium, are essentially unaffected by the structures associated with it, such as the radiating fracture pattern, and are therefore younger than the mare basins; but they are older than the mare material, since they are partly overlain and filled by it. The sequence of events, then, was: formation of the Imbrian basin; formation of

Archimedes and Plato; and finally emplacement of the mare material.

The normal erosive processes affecting the lunar surface together with deposition of mare material have destroyed much of any similarity which may have existed between Archimedes and Copernicus. Nevertheless, detailed telescopic mapping by R. J. Hackman has shown that Archimedes does have an ejecta blanket, secondary craters, and internal faulting analogous to those of Copernicus. There is no reason to doubt that similar features can be found around other mare-filled craters to the extent that they are not covered by the mare material. The arguments for an impact origin for Copernicus apply, then, to Archimedes; but the evolution of the latter is obviously complicated by the origin and emplacement of the maria.

<u>Grimaldi</u>

Located on the far western limb, just south of the lunar equator, Grimaldi is one of the largest features generally considered a crater. Its diameter is 127 miles and its depth about 8700 feet; its rim height is unmeasured because of its location.

In topography and general structure, Grimaldi resembles Archimedes, possessing the remnants of internal terraces and an ejecta blanket. However, it is clearly older, as shown by the many newer craters superimposed on it, and by the much greater degree of erosion (presumably due in part to the impact of small meteorites). It is hardly necessary to mention that it has no visible rays.

Grimaldi is of great interest as a possible link between smaller craters such as Archimedes (and, by implication, Eratosthenes and Copernicus) and the circular maria such as Mare Crisium. It appears, in fact, to possess all the major characteristics of the circular maria, including mare ridges, bordering mountains, and a "shelf" area, and could reasonably be considered a small mare.

The direct evidence of an impact origin for Grimaldi has largely been removed by erosion, later cratering, and mare deposition; only the remnants of a possible ejecta blanket are visible. Nevertheless, its secure place in an apparently continuous series of craters including Archimedes, Eratosthenes, and Copernicus supports such an origin, although there have obviously been many major geologic events since the original impact.

Clavius

Clavius is in the extreme southern part of the moon's visible hemisphere on a densely cratered highland area. Its dimensions, exceeded in Baldwin's tabulation only by those of Bailly, are: diameter, 144 miles; depth, 16,100 feet; and rim height, 5400 feet.

In addition to its great size, Clavius has several interesting characteristics. The most striking of these is the immense amount of erosion it has undergone since its origin; the outlines of the crater have been greatly modified by the formation of a dozen large craters and many smaller ones. In addition, the albedo of Clavius is very close to that of the surrounding terrain (except for bright areas surrounding a few small craters), so that it can hardly be identified at high sun angles. Taken together, these characteristics indicate strongly the great relative age of Clavius and similar craters of the southern highlands, such as Longomontanus, Maginus, and Scheiner.

It seems clear, nevertheless, that Clavius belongs to the same natural class of objects as the other craters discussed here. It is roughly circular, cut by concentric internal faults, and surrounded by an ejecta blanket. If one allows for differences in initial pre-crater topography, size, and apparent age, it is easy to see the essential similarity of Clavius and Copernicus. Clavius must therefore be considered another possible impact crater, of greater age and size than most.

The Circular Maria

It is clear that no sharp distinction can be made between large craters such as Grimaldi and the circular maria; this fact suggests that such maria are actually very large impact craters, a theory advocated by Gilbert (1893), Baldwin (1949), and Shoemaker (1962). They should accordingly be considered in any discussion of lunar impact craters.

Much of the support for an impact origin for the circular maria comes from Mare Imbrium, which is generally considered the youngest of the large maria. Its roughly circular appearance is obvious; in addition, it is surrounded by what appears to be an immense ejecta blanket comprising the Carpathian, Apennine, and Jura Mountains, and the Alps. On the southeast side, at least, Mare Imbrium is bordered by a series of concentric normal faults, and is the approximate center for a set of radial fractures (called the "Imbrium sculpture" by Gilbert) trending to the northeast and southeast.

In general, then, Mare Imbrium appears analogous to Copernicus. However, this analogy should not be extended to the maria in general without some qualifications. First, the fact that the radial fractures extend inward from the Apennines to Archimedes suggests that the present mountain front does not represent the actual rim of the supposed impact crater; it seems likely that the crater itself was much smaller than the present mare basin. Second, the emplacement of the mare material was a subsequent event entirely separated, at least in time, from the formation of the mare basin, as explained in reference to Archimedes. Third, Mare Imbrium is unique, or nearly so, in possessing a well-defined ejecta blanket, possibly because of its relatively lower age. Finally, much of the mare material lies outside the mare basins (see, for example, Oceanus Procellarum), emphasizing the need for clear distinction, in discussions of origin, between the two features.

Subject to these qualifications, however, it seems reasonable to consider the circular maria genetically related. If such a relationship actually exists, then, we see that these, the most prominent of the moon's surface features, are members of a family which includes craters ranging in size down to the one-foot pits photographed by Ranger VII.

Secondary Craters

Frequent reference has been made to the small, gouge-like depressions surrounding Copernicus and similar craters. These are considered secondary impact craters formed by ejecta from the parent crater. Evidence for this origin includes the existence of similar features around terrestrial explosion craters, their gradational relationship with the ejecta blanket, and their association with rays (whose impact origin, it must be admitted, is not agreed upon). The recent Ranger VII mission produced many photographs showing that these secondary craters are more numerous than expected, and in fact dominate the topography visible with high resolution.

The general agreement on the impact origin of secondary craters does not imply agreement on the impact origin of their related primary craters. Jack Green has shown that similar features exist around the volcano Kileauea, in Hawaii, and have been formed by blocks of rock thrown out in eruptions; he therefore suggests a similar origin for the secondary craters of Mare Cognitum discovered by Ranger VII.

Summary

Despite the great increase in our knowledge of the moon in the past few years, debate about the origin of its craters remains nearly as active as ever. A discussion of lunar impact craters would not be complete without mention of some of the evidence indicating volcanic origins.

First, it seems obvious that if the mare material is volcanic rock, then craters such as Grimaldi and Archimedes have been the site of extensive volcanic activity during at least one stage of their history. To this extent, then, they must be considered volcanoes, even if they were initiated by impact. However, there is other evidence suggesting that even craters which are not floored by mare material may undergo later volcanic activity. The dark-halo craters and some of the chain craters near Copernicus are generally considered to be volcanoes, probably of the maar type, and similar craters can be seen in and near Aristarchus. Aristarchus has also been the site of the recently observed emissions of gas, widely reported as the first confirmed changes on the moon, by observers in the United States and Russia. These emissions of course suggest continuing internal activity in Aristarchus, although its exact nature is not clear.

Further evidence for volcanic origin of the large lunar craters is found in similar structural features observed in calderas. Green (1962) presents many examples of terrestrial calderas with concentric faulting, central peaks, and rows of associated craters. Such examples can of course be criticized; for example, the supposed terrestrial analogues are generally much smaller than the comparable lunar features. However, the fact that our present interpretations of lunar geology depend heavily on topographic and structural criteria suggests that volcanic features resembling lunar craters should be studied carefully.

The general concensus on the origin of lunar craters seems to be that although much of the material exposed on the moon's surface is volcanic rock, most of the landforms are chiefly the direct or indirect result of meteoritic impact.