Gilbert and the Moon

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If the record of her scarred face has now been read aright, all that remains
of the old narrative is its denouement: the moon is dead.

G. K. Gilbert

ABSTRACT

Sketches made by G. K. Gilbert and based on telescopic observations of the Moon look amazingly similar to photographs obtained 75 yr later by spacecraft. He was very successful in correlating lunar surface features with counterparts on Earth. His observations and experiments led him to the conclusion that most lunar craters are the product of impact. After establishing this, he studied the Coon (Meteor) Crater of Arizona. He did not have as much success applying what he had learned from the Moon to the terrestrial case. He conducted a topographic study of the crater to check whether there was an added volume due to the incoming projectile. An overestimation of the size of the meteorite and neglect of the possibility of its fusion, evaporation, and ejection forced him to rule out an impact origin for this crater.

In his observations on lunar features, Gilbert had expressed the basic elements of a lunar stratigraphic system. His discussion of crater rays, and particularly of the “sculpture” that surrounds the Imbrium basin, greatly influenced the thinking of lunar geologists of our day. Coupled with his recognition of the importance of crater density and overlap relationships, he can be easily considered the father of lunar stratigraphy. Today there is a crater on the Moon bearing the name of Gilbert in commemoration of his many contributions to geology.

INTRODUCTION

In attempting to understand the surface features of the Moon, geologists transported their controversial concepts 400,000 km away. Before the space age, evidence for the origin of lunar surface features was limited to telescopic observations and comparisons with terrestrial features. Pivotal to the evaluation of such evidence was consideration of the concepts of catastrophism and uniformitarianism. According to the former concept, the surface of the Earth is thought to have been formed by several catastrophic events. According to the latter, geologic features are viewed as the result of a gradually evolving Earth.

At the end of the nineteenth century, uniformitarianism had gained many supporters. Thus, the Earth was viewed as a product of slow and continuous change that could be easily explained in terms of the same processes that are observable today. The Moon was considered along similar lines of thought, with the consequence that most of its surface features were interpreted to be the result of endogenetic processes. Gradual and prolonged volcanism was credited with the formation of the lunar surface features, particularly its craters, which constitute the most predominant of lunar landforms.

LUNAR CRATERS

Gilbert was fully aware that most writers of his time, and before him, assumed that lunar craters were of volcanic origin. Because these craters differed in size, abundance, and shape from terrestrial volcanoes, they were thought to represent a special type of volcanism that resulted from the Moon’s peculiar physical conditions.

He realized that the problem was largely one of interpretation of observed forms. His observations were limited to 18 nights during two lunations in August through October of 1892. He used mostly the 400-power, 67.31-cm (26.5-in.) refracting telescope of the U.S. Naval Observatory.

Gilbert recognized that although there existed a great range of lunar crater sizes, within this range were varieties whose occurrence more or less correlated with size. He further observed that their intergradation was so perfect that they could easily be regarded as phases of a single type.

With this in mind, Gilbert started to examine the detailed characteristics of the form type of lunar craters:

Picture to yourself a circular plain, ten, twenty, fifty, or one hundred miles in diameter, surrounded by an acclivity which everywhere rises steeply but irregularly to a rude terrace, above which is a circular cliff likewise facing inward toward the plain. This cliff is the inner face of a rugged, compound, angular ridge, composed of shorter ridges which overlap one another, but all trend concentrically. Seen from above, this ridge calls to mind a wreath,
and it has been so named. From the outer edge of the wreath a gentle slope descends in all directions to the general surface of the moon, which it is convenient to call here the outer plain. The outer slope of the crater may be identical in surface character with the outer plain, or it may be radially and somewhat delicately ridged, as though by streams of lava. The inner slope, from the base of the cliff to the margin of the inner plain, is broken by uneven and discontinuous terraces, which have the peculiar habit of landslip terraces as one sees them about the flanks of a plateau capped by a heavy sheet of basalt. From the center of the inner plain rises a hill or mountain, sometimes symmetric but usually irregular and crowned by several peaks. [Gilbert, 1893, p. 243-244]

This description of lunar crater forms is among the best ever published up to Gilbert’s time. His drawing of an example so typifies lunar craters that it looks hauntingly similar to spacecraft views of the craters (Fig. 1). Furthermore, his cross section that is based on this drawing does not vary much from profiles drawn on the basis of photogrammetric measurements of stereophotographs taken by the Apollo missions from lunar orbit (Fig. 2).

To Gilbert, the central hill was an important part of the lunar crater form, but it perplexed him that these hills were not universally present. This was the case even in craters of similar sizes. Also, in very large craters (150 km and larger), the occurrence of a central hill was rare; it disappeared altogether in the largest of craters.

Considering that he lacked the close-up photography we have today, his observations of crater morphology and its relation to size are amazingly accurate. He correctly recognized that the depth of a crater varies with the width, but less rapidly. Detailed measurements from Apollo photographs (Pike, 1974) have demonstrated that the following relationships apply, where \( R \) = crater depth and \( D \) = crater diameter: \( R = 0.196D^{0.66} \) for small fresh

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Figure 1. Top, sketch of the type form of lunar crater (Gilbert, 1893, p. 243). Bottom, oblique view of the lunar crater Theophilus, 100 km in diameter, obtained by Lunar Orbiter III (frame 78M).
craters (less than about 15 km) and $R = 1.044D^{0.401}$ for larger fresh craters.

What he called the inner plain is now referred to as the crater floor. Gilbert noted that this inner plain was a constant feature in large- and medium-sized craters, but it was rare in craters with small diameters: "to my eye the interiors of most craters under four miles and of all under two miles appear as simple cups" (Gilbert, 1893, p. 245). Present data place the diameter of transition between simple and complex craters at about 10 to 20 km (Pike, 1975). Gilbert had anticipated this by noting the absence of central peaks as crater diameter decreased.

Considering the limitation of his instrument:

I am conscious that as the limit of telescopic vision is approached, the details of craters must disappear before the craters themselves are lost, and I am therefore anxious to have this observation verified by those who are able to use higher powers than I could. [Gilbert, 1893, p. 245]

As it turned out, the observations of Gilbert were found to hold, even after the limit of resolution was increased several fold by the use of the Apollo panoramic camera, which has a lens with a 610-mm focal length and was flown only 100 km above the lunar terrain (Masursky and others, 1978).

As he completed the description of the form of lunar craters, Gilbert had in effect provided us with a classification of their morphologies. His illustration of their variety includes most of the basic forms of lunar craters as photographed by spacecraft (Fig. 3). This thorough morphological analysis allowed him to contrast lunar craters with terrestrial counterparts in order to deduce their genesis. Naturally, most terrestrial craters known at his time were volcanic in origin.

THE IMPACT THEORY

Perhaps Gilbert’s most significant contribution to lunar studies was his 1893 discussion of the origin of lunar craters. He presented a convincing case that these features are the product of impact. The theory was developed by pointing out the differences in form between the majority of terrestrial volcanoes and lunar craters:

Ninety-nine times in one hundred the bottom of the lunar crater lies lower than the outer plain; ninety-nine times in a hundred the bottom of the Vesuvian crater lies higher than the outer plain. Ordinarily the inner height of the lunar crater rim is more than double its outer height; ordinarily the outer height of the Vesuvian crater rim is more than double its inner height. The lunar crater is sunk in the lunar plain; the Vesuvian is perched on a mountain top. The rim of the Vesuvian crater is not developed, like the lunar, into a complex striae, but slopes outward and inward from a simple crest-line. If the Vesuvian crater has a central hill, that hill bears a crater at summit and is a miniature reproduction of the outer cone; the central hill of the lunar crater is entire, and is distinct in topographic character from the circling rim. The inner cone of a Vesuvian volcano may rise far higher than the outer; the central hill of the lunar crater never rises to the height of the rim and rarely to the level of the outer plain. The smooth inner plain characteristic of so many lunar craters is either rare or unknown in craters of Vesuvian type. Thus, through the expression of every feature the lunar crater emphatically denies kinship with the ordinary volcanoes on the earth. [Gilbert, 1893, p. 250]

Gilbert noted that terrestrial maars do resemble small lunar craters but provide no explanation for intermediate and larger ones. He also examined and rejected other proposed hypotheses such as the “snow theory,” which stated that water vapor derived from localized pools fell as snow upon the pools and surrounding areas, eventually forming circular ridges.

He concluded that “all other theories which I have been able to discover appeal in one way or another to the collision of other bodies with the moon’s surface” (Gilbert, 1893, p. 256). For the impact theory of lunar crater formation he coined the term “meteoric.” He then proceeded to make experiments to study the shape of craters resulting from impact (Fig. 4). He used simple analogies:

If a pebble be dropped into a pool of pasty mud, if a rain drop falls upon the slimy surface of a sea marsh when the tide is low, or if any projectile be made to strike any plastic body with suitable velocity, the scar produced by the impact has the form of a crater. This crater has raised rim suggestive of the wreath of lunar craters. With proper adjustment of material, size of projectile, and velocity of the impact, such a crater scar may be made to have a central hill. [Gilbert, 1893, p. 256]

His conclusion that a “meteoric” theory best explained the observed lunar features was coupled with an understanding that it was not without problems. The most significant of these problems to him was the general circularity of the craters, which he felt indicated predominantly vertical impacts. To explain this observation he proposed that the Moon formed from the coalescing of
debris located in a ring around the Earth and that craters were the scars of the final stages of collision. Recent experimental laboratory data, however, show that oblique impacts may produce circular craters (Gault, 1975).

**METEOR CRATER**

Now that Gilbert was satisfied with the "meteoric" origin of most lunar craters, he turned to the Earth in search of a convincing analogue. Ironically, he did not have as much success applying to terrestrial cases what he had learned from the Moon. In a study of Meteor Crater in northern Arizona (then called Coon Butte or Coon Crater, later also called Barringer Crater), he concluded that it resulted from a steam explosion (Gilbert, 1896).

This crater is more than 1 km in diameter and nearly 200 m deep (Fig. 5). It is located in a region of flat-lying Permian and Triassic sedimentary rocks. Although the structure stands out as a striking anomaly on a flat plateau, had it occurred 30 km to the northwest, it would have been nestled inconspicuously among Quaternary volcanic craters (Mutch, 1972, p. 84).

Gilbert correctly noted that
If the crater was produced by the collision and penetration of a stellar body that body now lay beneath the bowl, but not so if the crater resulted from explosion. Any observation which would determine the presence or absence of a buried star might therefore serve as a crucial test. [Gilbert, 1896, p. 5]

To search for the "stellar" material by means of a shaft or drill hole was not considered feasible because of the expense involved. Therefore, Gilbert had to consider indirect methods. He proposed to solve the problem by topographic means:

If the crater were produced by explosion the material contained in the rim, being identical with that removed from the hollow, is of equal amount; but if a star entered the hole the hole was partly filled thereby, and the remaining hollow must be less in volume than the rim. The presence or absence of the star might therefore be tested by measuring the cubic contents of the hollow and of the rim and comparing the two. [Gilbert, 1896, p. 5]

Naturally, he could find no evidence of the presence of the impacting projectile, which he expected to be lodged below the crater floor. His basic error was in the overestimation of the size of the projectile and in his neglect of the possibility of its fusion, evaporation, and ejection. He expected to find local magnetic variations and a discrepancy between the volume of ejecta and volume of the cavity due to the presence of the projectile.

Thus, Gilbert felt forced to rule out an impact origin for the crater. Today all workers are convinced that it was formed by a meteor impact because of abundant evidence of disturbance and shock metamorphism: fracturing, brecciation, presence of glass formed by the shock melting, and occurrences of very high-pressure forms of silica: coesite (Chao and others, 1960) and stishovite (Chao and others, 1962). Before their discovery at Meteor Crater, these two minerals were known only from laboratory synthesis (Mutch, 1972, p. 86).

Today's estimate of the size of the impacting body is much smaller than what was assumed by Gilbert. The original body is now assumed to have been about 25 m in diameter and to have had a mass of about 65,000 metric tons. The impact is estimated to have released energy equivalent to three 2 X 10^6 metric tons of TNT (French, 1977, p. 151).

Although Gilbert felt compelled to reject the impact origin for this crater, his ever-present objectivity led him in the end to the correct conclusion that all the evidence was not in yet. He was familiar with the ideas, put forth by Edwin E. Howell, that the projectile may have consisted of small iron chunks embedded in a nonmagnetic material or that the target area may have been compressed by the impact. These theories caused Gilbert to doubt his own conclusions:

These considerations are eminently pertinent to the study of the crater... but the data which is particularly worthy of note at the present time is the ability to unsettle a conclusion that was beginning to feel itself secure. This illustrates the tentative nature, not only of the theories of Science, but of what Science calls its results. However grand, however widely accepted, however useful its conclusions, none is so sure that it cannot be called into question by a newly discovered fact. In the domain of the world's knowledge there is no infallibility. [Gilbert, 1896, p. 12]

OTHER LUNAR FEATURES

Gilbert also made detailed observations of features other than craters. Particularly noteworthy is his description of the sinuous
rises on the lunar surface known as mare ridges. He noted that they have antilatinal and monoclinal forms, but are so gentle of slope that they are seen only near the terminator. Today, some of our best photographs of these ridges were indeed taken near the terminator (Fig. 7). Some ridges mark the boundaries of raised shelves in the maria, and it was probably these features he described as monoclinal. This interpretation was not confirmed until in 1972 the Apollo Lunar Sounder provided us with profiles across lunar basins with circular ridge systems such as those in Mare Serenitatis (Maxwell and others, 1975).

He also described rilles, rille pits, and large furrows that he observed telescopically. However, none of the features that he described had as much significance to lunar geology as the crater rays and the "sculpture" that surrounds the Imbrium impact basin.

Gilbert called the rays "white streaks," which he described as bands of color, sometimes faint, sometimes brilliant, but always indefinitely outlined, like the tail of a comet. . . . Some of them stretch for long distances across the moon's surface. . . . They pass up and down the slopes of craters without either modifying their forms or being interrupted by them. The more prominent of them, and probably all, occur in systems, and those of each system radiate from some crater. [Gilbert, 1893, p. 284]

Gilbert was aware of the unpublished suggestion of a Mr. William Würdemann of Washington that a meteorite striking the Moon's surface with great force would spatter the "whitish matter" in various directions. The explanation appealed to Gilbert because it accounted for

the straightness of the rays, for their vanishing edges and ends, for their independence of topography, for their relation to craters, for the whiteness of the associated craters, and for the nimbus in which the rays sometimes unite close to the crater. [Gilbert, 1893, p. 285]

The idea was appealing, and a reasonable theory was established. However, because of his meticulous observations and keen mind, Gilbert went on to pose several questions that until recently continued to puzzle lunar workers:

What is the white substance? Why do its traces become faint in passing from the bright uplands to the dark plains? Why do wavy lines replace straight ones in the radiation from Copernicus? Why do certain great rays of Tycho's system trend toward a point of the rim and not toward the center of the crater? Why are several craters, especially Tycho, surrounded by a relatively dark band inside the bright nimbus? [Gilbert, 1893, p. 285-286]
It was only after detailed lunar photographs were obtained and samples were returned that adequate answers to some of these questions were found (El-Baz, 1975; Masursky and others, 1978).

Gilbert did even better observing, describing, and interpreting the features which he termed "sculpture." He observed that the rims of certain craters are traversed by grooves or furrows, which arrest attention as exceptions to the general configuration. In the same neighborhood such furrows exhibit parallelism of direction. Similar furrows appear as tracts between craters . . . . Tracing out these sculptured areas and plotting trend lines on a chart of the moon, I was soon able to recognize a system in their arrangement, and this led to the detection of fainter evidence of sculpture in yet other tracts. The trend lines converge toward a point near the middle of the plain called Mare Imbrium [Gilbert, 1893, p. 275].

Thus, he was the first to recognize the extensive system of lineations and grooves known as Imbrium sculpture (Fig. 8). He
attributed this pattern to "a collision of exceptional importance" whose result was "the violent dispersion in all directions of a deluge of material—solid, pasty, and liquid." He was able to discriminate between "anachronism" and "postacronym" features and went on to state that "by the outrush from the Mare Imbrium were introduced the elements necessary to a broad classification of the lunar surface" (Gilbert, 1893, p. 279).

LUNAR STRATIGRAPHY

In his address as Retiring President of the Philosophical Society of Washington, delivered December 10, 1892, Gilbert's first remarks were "the face which the moon turns ever toward us is a territory as large as North America, and, on the whole, it is probably better mapped" (Gilbert, 1893, p. 241). To this day, the
statement holds true, for the Moon has been mapped by more sophisticated systems than much of North America, not to mention the rest of the world (El-Baz and Ondrejka, 1978, p. 704). Lunar mapping, however, is the domain of selenographers, and interpretation is the realm of selenologists.

Gilbert tackled the questions concerning the origin of the Moon's features in much the same way that he approached any terrestrial geomorphologic problem. He recognized that the basic geologic principles would be the same, and he painstakingly examined the available hypotheses. He was modest enough to state that his comments were not based on "protracted observation nor on protracted study." If his observations were indeed less than thorough, it is not obvious from his presentation. In fact, he anticipated the lunar stratigraphic system in use today.

Figure 7. Lunar mare (wrinkle) ridge in the eastern part of Mare Serenitatis showing the effect of low Sun illumination angles in emphasizing the form of the 1-km-wide ridge (Apollo 17 panoramic camera photo 2313).
Figure 8. The Imbrium sculpture is seen here as grooves in the cratered highland material in the central part of the near side of the Moon (Apollo 15 metric camera photo 1411).

The basic elements of lunar stratigraphy can all be found in Gilbert’s observations, including the recognition that (1) the Moon’s surface is a continuous panorama of impact physiography; (2) the abundance of craters on the Moon’s surface varies from place to place with fewer large craters in the maria; (3) the increase in crater size is accompanied by atrophy or degradation of crater form; (4) because craters overlap and the overlapping is never reciprocal, clear-cut age interpretations are possible; (5) the “white streaks” are crater rays; and, most significantly, (6) the “sculpture” on the near side of the Moon is due to the formation by impact of the Imbrium crater.

With the establishment of these basic ideas, Gilbert correctly recognized that “the Moon is dead” and that impact is the main surface-sculpting mechanism, which is also responsible for lateral
movement of lunar surface materials. Study of the superposition of impact and other materials can, therefore, help in understanding the history of the lunar surface.

When the United States started preparing for the Apollo program, a major effort of geologic mapping of the Moon was initiated by the U.S. Geological Survey. Setting the stage were the papers by Shoemaker in 1960 and 1962 dealing with Meteor Crater and lunar craters, respectively. At the same time, Shoemaker and Hackett published the first stratigraphic discussion of the Moon; they were fully aware of the basic parameters that Gilbert established 80 yr earlier. Starting in the area of the crater Copernicus, they recognized that (1) it is younger than the neighboring Eratosthenes because its form is sharper and its rays are obvious and (2) Eratosthenes is younger than Imbrium because its ejecta overlap the Imbrium basin material.

In all, Shoemaker and Hackman (1962) recognized five overlapping sets of deposits that, except for the first, they called systems: (from oldest to youngest) pre-Imbrian, Imbrian, Procellarum, Eratosthenian, and Copernican. This stratigraphy was applied to nearly the whole Earth-facing lunar hemisphere, based mainly on telescopic observations (Wilhelms, 1970; Wilhelms and McCauley, 1971).

After the acquisition of photographs of the far side of the Moon, it was recognized that an extension of the nearside stratigraphy could be employed on the far side as well (El-Baz, 1974, 1975; Wilhelms and El-Baz, 1977). At the present time, a Moon-wide time-stratigraphic sequence exists, as described below in order of decreasing relative age:

**Pre-Nectarian.** All materials formed before the Nectaris basin (a large impact basin on the Moon's near side that is older than Imbrium) and as far back as the formation of the Moon are classed as pre-Nectarian. The majority of pre-Nectarian units are distinguished on the lunar far side, including mostly materials of very old and subdued basins.

**Nectarian System.** This system includes all materials stratigraphically above and including Nectaris basin materials, up to and not including Imbrium basin strata (Stuart-Alexander and Wilhelms, 1974). Ejecta of the Nectaris basin that can be traced near the east-limb region allow recognition of these materials as a stratigraphic datum for the farside highlands.

**Imbrian System.** A large part of the lunar surface is occupied by ejecta surrounding both the Imbrium and Orientale basins. These form the lower and middle parts of the Imbrian System, respectively. Two-thirds of the mare materials belong to this system, particularly in the eastern maria of Crisium, Fecunditatis, Tranquillitatis, Nectaris, the dark annulus of Serenitatis, as well as most mare occurrences on the lunar far side.

**Eratosthenian System.** This system includes materials of rayless craters such as Eratosthenes. Most of these are believed to have had displayed rays that are no longer visible because of mixing due to prolonged micrometeorite bombardment as well as solar radiation. The system also includes about one-third of the mare surface materials on the lunar near side, particularly in Oceanus Procellarum.

**Copernican System.** This is stratigraphically the highest and, hence, the youngest lunar time-scale unit. It includes materials of fresh-appearing, intermediate- to high-albedo, bright-rayed craters. The system also includes exposures of very high albedo material on inner walls of Copernican and older craters, as well as other scarps. Brightness in these cases is interpreted as the result of fresh exposure by mass wasting and downslope movement along relatively steep slopes.

From this, it is clear that Gilbert's ideas on the Moon greatly affected the evolution of a lunar stratigraphic column. It was thus a well-deserved honor that the International Astronomical Union (IAU) decided in 1964 to name a lunar crater after him (Fig. 9). The crater is 63 km in diameter and is centered at lat.: 3.5°S, long. 76.5°E. However, it is ironic that his contributions to knowledge of the Moon were not specifically mentioned in the IAU official transaction, which read (Menzel and others, 1971, p. 183):

Gilbert, G. K. (1843-1918). USA geologist; research en intrusive igneous features; introduced ideas of erosion, glaciation and river development to geomorphology; concept of glaciation in formation of Great Lakes.

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