CRATERS ON THE MOON FROM GALILEO TO WEGENER: A SHORT HISTORY OF THE IMPACT HYPOTHESIS, AND IMPLICATIONS FOR THE STUDY OF TERRESTRIAL IMPACT CRATERS

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Abstract. The origin of lunar craters has been discussed for centuries, since they were discovered by Galilei in 1609. The majority of researchers were of the opinion that they are volcanic structures, but a variety of "exotic" explanations that included tidal forces, circular glaciers, and coral atolls was also considered. The meteorite impact hypothesis had been discussed a few times, starting with Hooke in 1665, and formulated in more detail by Proctor in 1873 and Gilbert in 1893. However, this theory only gained momentum early in the 20th century, after the identification of Meteor Crater in Arizona as an impact structure, and after specific and plausible physical models for impact craters formation were devised by Öpik in 1916, Ives in 1919, and Gifford in 1924. Nevertheless, despite growing evidence for the interpretation that most craters formed by impact, proponents of the volcanic theory impact were still vociferous as late as 1965, just four years before the first samples were brought back from the moon. Important lessons could have been learned for the study of impact craters on the Earth, especially in view of evidence that large impact events had some influence on the geologic and biologic evolution of the Earth.

Keywords: History, impact craters, lunar craters, lunar maps

1. Introduction

Impact cratering is now recognized to be a very important (if not the most important) surface-modifying process in the planetary system. It is now fairly widely accepted that our moon, Mercury, Venus, Mars, the asteroids, and the moons of the outer gas planets are all peppered with meteorite impact craters. However, this "knowledge" is fairly recent. Well into the 20th century, it was "known" that all the lunar craters are of volcanic origin (and of course the presence of craters on planetary bodies other than the moon had not been established until spacecraft visited these planets from the late 1960s onwards). The origin of lunar craters had been discussed for centuries, and while the impact hypothesis had been considered a few times, it gained momentum only as late as the early 20th century. However, the results of these studies just meant that the impact hypothesis was discussed as a possible alternative to the still-dominating volcanic theory. As late as 1965, just four years before the first samples were brought back from the moon, astronomers

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and geologists from "vulcanist" and "impact theorist" camps held major debates and heated discussions at a meeting of the New York Academy of Sciences.

The history of study and acceptance of impact cratering over this century is somewhat similar to the record of the acceptance of plate tectonics. One of the reasons that continental drift (now more commonly called plate tectonics) found little acceptance early on was the absence of any known mechanism for moving continents. Only later, after irrefutable geophysical evidence had been found that the continents have indeed moved, were geologists forced to find a mechanism to explain these observations. Impact cratering had a similar fate: no mechanism was known to produce large circular craters by impact. Here, the situation is even more complicated, because even after some craters on Earth had clearly been shown to be the result of impact events, and after a physically plausible mechanism for their formation had been found, the process of impact cratering was still not widely accepted among geologists. Part of the reason was that a theory of impact mechanics had been worked out by astronomers and physicists, whose goal it was to explain the formation of lunar craters. In contrast, the existence of internal mechanisms on Earth that result in craters of various forms and sizes made it unnecessary for geologists to resort to extraterrestrial explanations. Only in the early 20th century was the analogy between explosion craters, lunar craters, and formation by impact of some terrestrial craters made.

Despite the fact that most astronomers and geologists during the second half of the 20th century agreed that craters on the moon most likely formed by impact, the same conviction did not reach mainstream geology regarding craters on the Earth. Small, unimportant craters, such as Meteor Crater in Arizona or Henbury in Australia, might have formed by meteorite impact, but geologists found it largely inconceivable (maybe even offensive) that an extraterrestrial object would have influenced the geological and biological evolution on the Earth. This might explain the mixture of disbelief, rejection, and ridicule with which the suggestion was greeted that an asteroid or comet impact wiped out the dinosaurs and other species at the end of the Cretaceous (Alvarez et al., 1980). It was the debate that followed this suggestion, which, over the past 20 years, finally led to a more general realization that impact cratering is an important process on the Earth as well, and not only on the other planetary bodies of the solar system. In this short contribution, I would like to comment on the evolution of the understanding of lunar craters, and the analogy to the understanding of terrestrial impact craters. For this discussion I have drawn on original sources (cited below) and on several excellent reviews (mainly Hoyt, 1987; Schultz, 1998) that cover various aspects of this topic and provide detailed and extensive background information and references.

Figure 1a. Enlargements of the Copernicus area from the lunar maps by Hevelius (a) and Riccioli (b), from the impression by Johann Doppelmayr (1730). Riccioli shows Copernicus as a proper crater, whereas Hevelius draws it is a mountain.

2. Early Hypotheses of Lunar Crater Formation

Galileo Galilei was probably the first scientist to recognize that the circular features on the moon are depressions (i.e., “craters”), not mountains, when he directed his telescope at the moon in 1609. He noted that the floors of some of these depressions were covered by dark material and that central peaks occur as well in the craters (Galilei, 1610). He did not seem to have a strong opinion one way or another regarding the nature of these craters. The first lunar map, in which formations were named, was published by Michel Florent van Langren in 1645, followed by the famous “Selenographia” by Hevelius (1647), who introduced the first systematic lunar nomenclature. However, the Riccioli moon map of 1651 is historically of greater importance, since it provided the basis for the system of lunar nomenclature still in use. Another interesting difference between the two maps is shown, for example, by the crater Copernicus: Hevelius draws it as a mountain, named Mt. Aetna (Figure 1a), whereas Riccioli draws it as a crater (Figure 1b).

Around the same time (1665), Robert Hooke speculated about the origin of lunar craters, and, from experiments with “boiled alabaster”, concluded that they formed by some gas explosion. Hooke also dropped solid objects into a mixture of clay and water and found that these experiments resulted in crater-like features. However, he rejected the possibility that the lunar craters could have formed in an analogous way, because it was not clear from “whence those bodies should come”

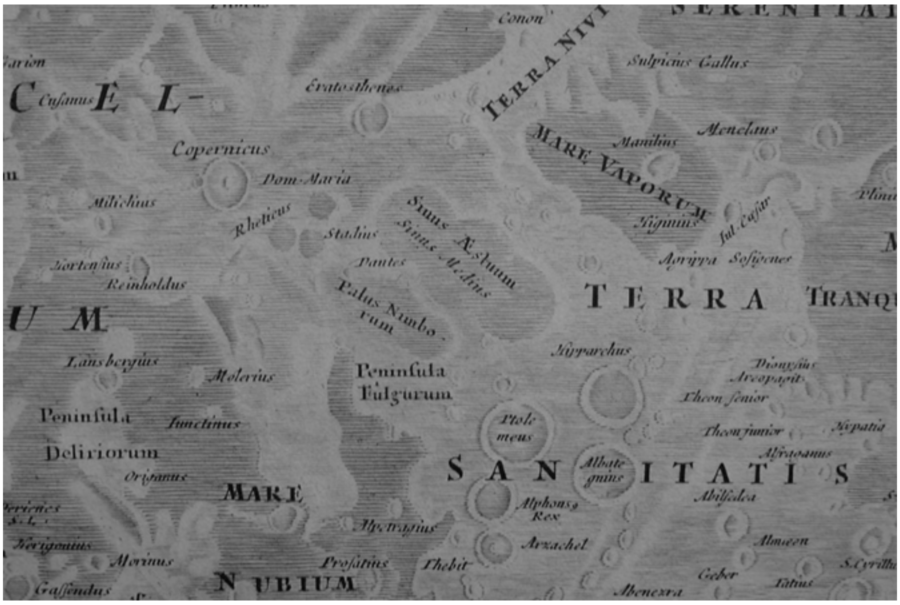

Figure 1b.

– the interplanetary space was, at that time, 135 years before the discovery of the first minor planet, considered to be empty.

The next century was dominated by the volcanic theory, as expressed by, e.g., Herschel, Schröter, and Beer and Mädler. The astronomer William Herschel (1738–1822), the discoverer of Uranus, allegedly saw in 1787 a volcanic eruption on the Moon: *"(April 19, 1787, 10h. 36′ sidereal time) I perceive three volcanos in different places of the dark part of the new moon. Two of them are either already nearly extinct, or otherwise in a state of going to break out; which perhaps may be decided next lunation. The third shows an actual eruption of fire, or luminous matter" … "(April 20, 1787, 10h. 2′ sidereal time) The volcano burns with greater violence than last night …. All the adjacent parts of the volcanic mountain seemed to be faintly illuminated by the eruption, and were gradually more obscure as they lay at a greater distance from the crater"* (Herschel, 1787). Herschel also thought it almost certain the moon is inhabited. As Harley (1886) notes, *"no doubt the great astronomer was mistaken"*.

Johann Hieronymous Schröter (1745–1816) published his seminal work "Selenotopographische Fragmente" in 1791. He measured the elevations of numerous lunar features and formulated an important observation, later known as Schröter's rule, which says that the amount of material around a crater (obviously thrown out of that crater) is exactly equal to the amount that it would take to fill the crater up again. However, he also drew crater rims to look like walls of trees and reported having seen green fields on the moon. Most experts had accepted the volcanic hypothesis, although a few voices remained in favor of an impact origin, such as, in

1829, the German astronomer Franz von Paula Gruithuisen (1774–1852). However, it did not help the impact hypothesis that Gruithuisen had announced a few years earlier that he had seen inhabited cities on the Moon, with cows grazing on lunar meadows, and a star-shaped temple. The banker Wilhelm Beer (1797–1859), the brother of the composer Giacomo Meyerbeer (Jacob Meyer Beer), together with the astronomer Johann Heinrich Mädler (1794–1874), who worked at Beer's private observatory, published maps and an atlas in 1834 and 1837. They provided accurate data for hundreds of lunar surface features, but adhered to the volcanic theory. In the mid 1840s, the eminent American geologist James Dwight Dana (1813–1895) published on boiling lakes of lava as analogies for the (relatively flat) lunar craters (Dana, 1846). In a 1849 textbook, John Frederick Herschel (1792–1871), William Herschel's son, declared that the lunar craters are perfect examples of volcanic craters, similar to Vesuvius on the earth.

3. Nasmyth and Carptenter vs. Proctor

In the 1870s, two important books on the moon were published. James Nasmyth (1808–1890), a retired engineer who had invented the steam hammer, had teamed up with the younger astronomer James Carpenter (1840–1899). In 1874, they published their *magnum opus* "The Moon" (Nasmyth and Carpenter, 1874). The book contains a number of amazing plates that were reproduced as "heliotypes", a now lost photograph-like process. Because of the low quality and resolution of earth-bound lunar photography, Nasmyth and Carpenter recreated lunar features in plaster after visual observations and photographed these models under low-angle illumination. This created spectacular impressions (an example is shown in Figure 2) of lunar craters and mountain ranges and helped to create the mindset for vertically exaggerated lunar landscapes that were perpetrated in astronomical illustrations and science fiction movies for the better part of the 20th century (cf. Jalufka and Koeberl, 2001).

Nasmyth and Carpenter were firm believers in the volcanic theory for the formation of lunar craters, which they describe in detail and illustrate in a series of diagrams (see Figures 3a, b). They cleverly explain even the formation of central peaks "as the eruption died away, it would add little by little to the heap, each expiring effort leaving the out-given matter nearer the orifice, and thus building up the central cone that is so conspicuous a feature in terrestrial volcanoes, and which is also a marked one in a very large proportion of the craters of the moon" (Nasmyth and Carpenter, 1874: 102); this is illustrated in Figures 3a,b. Multiple central peaks were explained as side-cones of volcanoes. Craters without central peaks were filled in by lava.

In contrast, Richard Anthony Proctor (1837–1888), the author of the second important book of the 1870s on "The Moon" (Proctor, 1873), was an astronomer and a science popularizer. His was a popular-level book on various aspects of the

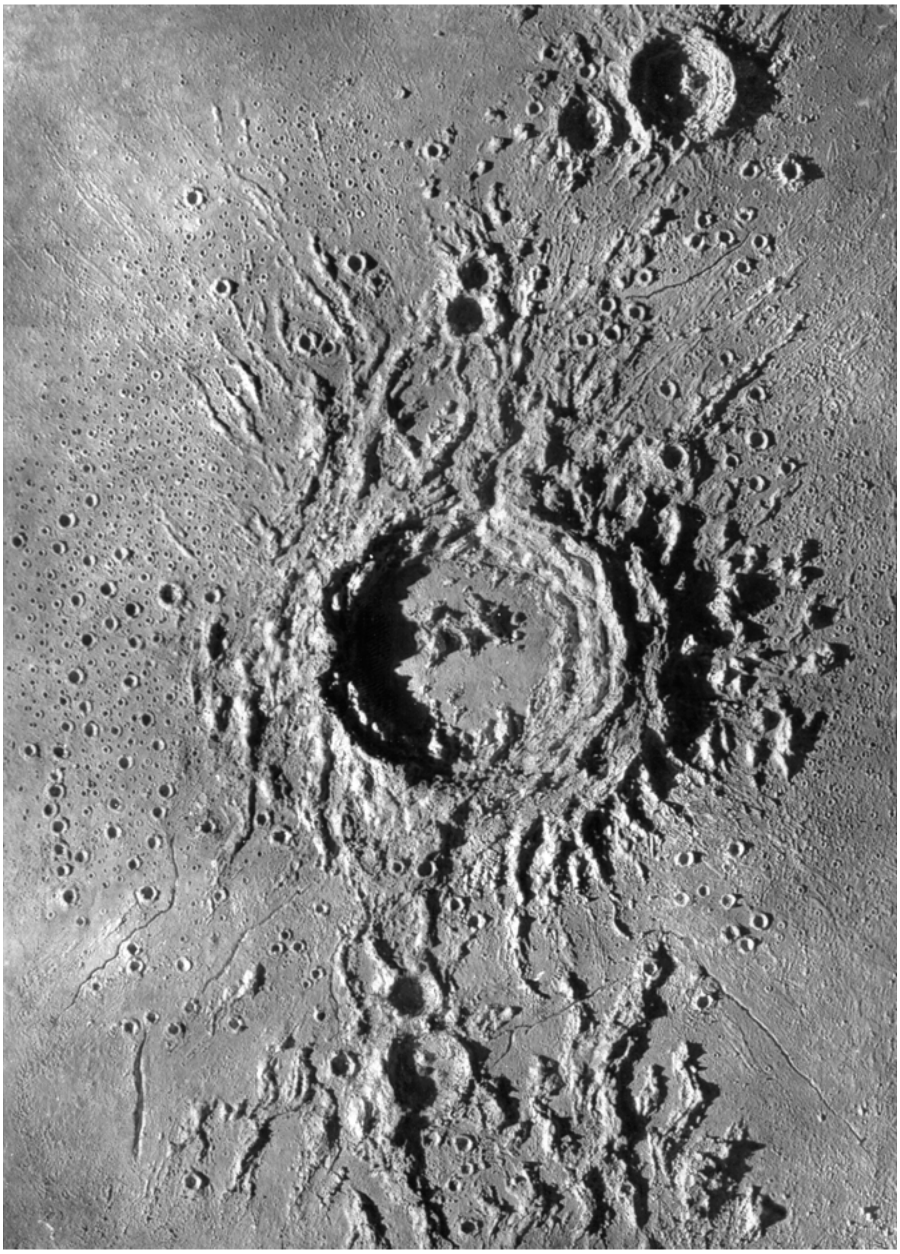

Figure 2. A heliotype from the book by Nasmyth and Carpenter (1874), showing the crater Copernicus and surroundings.

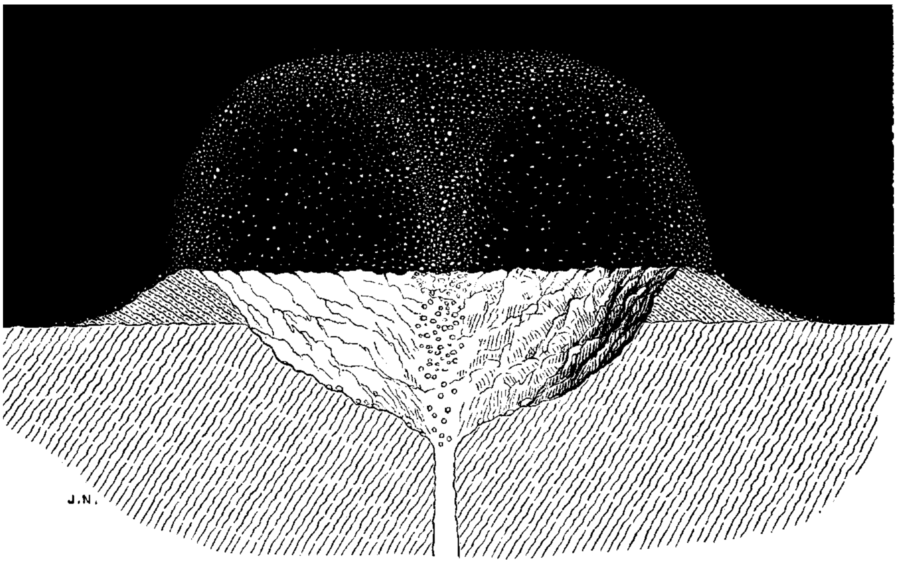

Figure 3a. (a) Early stages in the formation of a lunar crater by volcanism, and (b) late stages of crater formation, leading to the creation of a central peak. Both images from Nasmyth and Carpenter (1874).

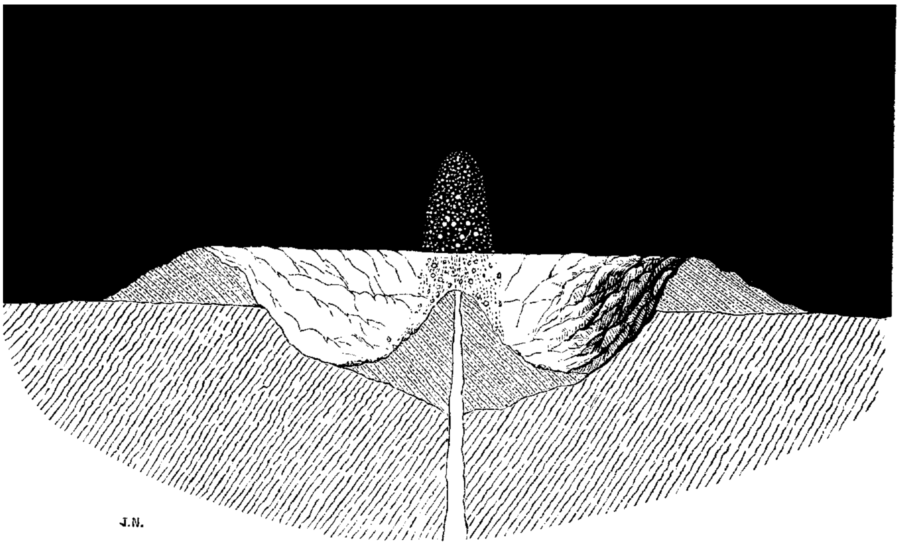

Figure 3b.

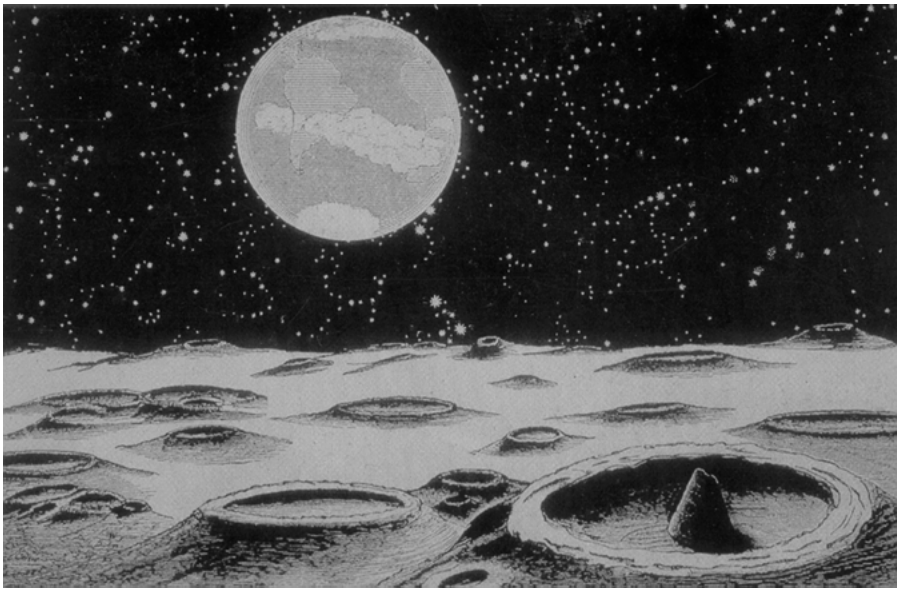

Figure 4. Exaggerated view of lunar craters with splash-shaped central uplift, from Proctor (1873).

moon. He rejected any resemblance of lunar features with terrestrial analogs. He is commonly credited as the first person to seriously advocate the impact theory for the formation of lunar craters. He had, however, an agenda. He rejected the then prevailing Laplace–Kant hypothesis that the planets had formed from a gaseous nebula, as was of the opinion that the planetary bodies in the solar system were the result of accretion of "meteoric" bodies. Thus, he explained the formation of lunar craters from bodies that hit the moon in its very early history, when he imagined the surface to still be plastic. This is also the reason why his crater pictures give the impression of frozen splashes as central peaks (Figure 4). Interestingly, his ideas were largely ignored (maybe because Nasmyth and Carptenter's more "serious" and monumental work appeared just a year later), and the impact hypothesis is missing from the next editions of Proctor's book.

4. Geologists and Astronomers at the Turn of the 19th to the 20th Century

During these times, the study of lunar craters was an affair mainly for astronomers (for a review, see Schultz, 1998). The few geologists that were concerned about lunar craters supported the volcanic hypothesis. Some unusual hypotheses were also discussed at the time as alternatives to the volcanic and impact theories. For example, Peale (1886) suggested that lunar craters were actually annular glaciers, and Hannay (1892), among others, suggested that tidal forces, at a time when the lunar crust was still thin, led to periodical extrusions of molten material. The first serious study of the impact hypothesis of lunar craters dates back to Grove Karl

Gilbert (1843–1918), whose positions included Chief Geologist of the US Geological Survey and President of the Philosophical Society of Washington. In 1892, after detailed studies of lunar craters and after performing impact experiments in his hotel room during a lecture tour, he concluded that only the impact hypothesis was able to explain the formation of the lunar craters. Unfortunately, he published his main work in a journal that was not read by many astronomers or geologists (Gilbert, 1893). He also recognized that the circularity of basically all lunar craters represents one of the major problems of the impact hypothesis (as formulated at that time): due to the variation in impact angle relative to the surface (from vertical, or 90°, to near 0°) the resulting craters should mostly be elliptical in shape and not circular. Only decades later was the solution to this problem found. In contrast, however, he rejected the hypothesis that Meteor Crater in Arizona was formed by impact, and concluded that this structure was the result of a steam explosion.

Steam explosions were also popular with the director of Harvard College observatory, William Henry Pickering (1858–1938). In his book (Pickering, 1903), he described his observations of ice, snowstorms, and (seasonally changing!) vegetation on the moon, and explained lunar craters as the results of steam explosions within the kilometer-thick snow cover of the moon, and crater rays as being analogous to cirrus clouds. His image of the full moon covered by ice is shown in Figure 5. However, as an eminent astronomer, Pickering was taken serious, whereas Gilbert was seen as a geologist who dabbled in amateur astronomy. This is illustrated by the well-known story of a local politician who criticized that the U.S. Geological Survey had so little work that one of its most prominent members had nothing better to do than observe the moon all night long – which led Gilbert to remark that clouds and politicians are equal hindrances to serious work. Nothing has changed since then.

Nathaniel Southgate Shaler (1841–1906), professor of paleontology and geology at Harvard University and Dean of the Lawrence Scientific School at the same university, had an almost visionary idea: “the fall of a bolide of even ten miles in diameter . . . would have been sufficient to destroy organic life of the earth” (Shaler, 1903). Unfortunately this was (as also noted by Schultz, 1998) no prescient vision of the impact-induced Cretaceous-Tertiary extinction theory (Alvarez et al., 1980), but an argument against the lunar impact hypothesis, because Shaler continues “. . . yet life has evidently been continued without interruption since before the Cambrian time”. Shaler was of the opinion that most craters were of volcanic origin.

Another scientist, who was ahead of his times in other topics as well, studied lunar craters shortly after Gilbert and concluded that the craters on the moon were of meteorite impact origin: Alfred Wegener (1880–1930), famous for his work on continental drift, published a little-known booklet (Wegener, 1921), in which he discussed his impact experiments and conclusions regarding lunar and some terrestrial craters (for details, see the review by Greene, 1998). Wegener worked out the formation of central peaks (Figure 6) and crater rays from his experiments

Figure 5. The full moon supposedly shows the extent of ice on the moon, and most craters formed by steam explosions. From Pickering (1903).

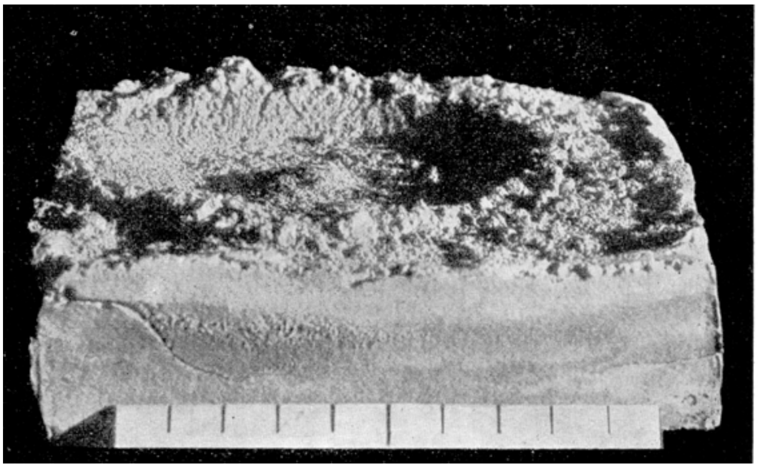

Figure 6. The result of one of Alfred Wegener's impact experiments into gypsum powder, sprayed with water; the hardened plaster model was then photographed under low-angle light. A central peak is obvious. From Wegener (1921).

of impacts into gypsum powder. Similar to his ideas on continental drift (which were only accepted many decades later), his views on lunar craters were largely ignored.

Around this time, some alternative and rather exotic hypotheses were also proposed for the formation of lunar craters. For example, Donald P. Beard stated in a short note: *"The five ramparts of Copernicus could not have been formed by any other process than the secular growth of corals and their successive sinkings beneath the ancient Imbrian sea"* (Beard, 1925).

5. Terrestrial Impact Craters and Formation Models

It is somewhat difficult to fault early researchers for not embracing the impact hypothesis, because no physically plausible mechanism to create large, always circular, craters existed. Rather, they were sticking with a process that was well-known and understood, namely volcanism. Only in the second and third decade of the 20th century, the picture changed. One of the first studies that demonstrated that, due to very high velocities with which a body hits the Moon or the Earth, impacts are similar to explosions, and, therefore, resulting craters are always circular, was formulated by the Estonian astronomer Ernest Öpik (1893–1985) in 1916. Unfortunately, he published his findings in Russian, with a French abstract, in a little-known Estonian journal, which made sure that hardly anybody read it. Independently, the American physicist Herbert E. Ives (who in the 1920s worked for Bell Laboratories and became one of the pioneers of television) worked out, from observations he made in the First World War, that explosion craters are good analogs for lunar craters (Ives, 1919). This opinion went against the then prevailing opinion, and shortly thereafter, three prominent astronomers and observatory directors published papers that strongly defended the volcanic theory (Campbell, 1920; Hale, 1920; Pickering, 1920). Later work by the New Zealand astronomer Algernon Charles Gifford (1861–1948), which was published in 1924 and 1930 in English in a more widely read journal, finally caused at least astronomers and physicists to take notice.

These developments happened around the time that the mining engineer Daniel Moreau Barringer (1860–1929) was actively involved in studying the "Coon Butte" or "Crater Mountain" structure in central Arizona. Iron meteorite fragments had been found around this 1.2 km diameter crater. Despite the opinion of several leading geologists (including Gilbert) that this structure was of volcanic origin and the presence of the meteorite fragments was only a coincidence, Barringer was convinced that this was an impact crater. His subsequent exploration of the crater (described in great detail by Hoyt, 1987), from about 1903 until his death in 1929, was mainly driven by the desire to find large metallic (meteoritic) deposits underneath the crater floor, which could be exploited for rare metals. No such large iron meteorite mass was ever found, leading many geologists to be more convinced than ever that impact had nothing to do with the formation of this structure. Nevertheless, physicists and astronomers, by now familiar with Öpik's and Gifford's arguments, had no problem in explaining both the impact origin of the structure (now called "Meteor Crater") and the absence of large amounts of

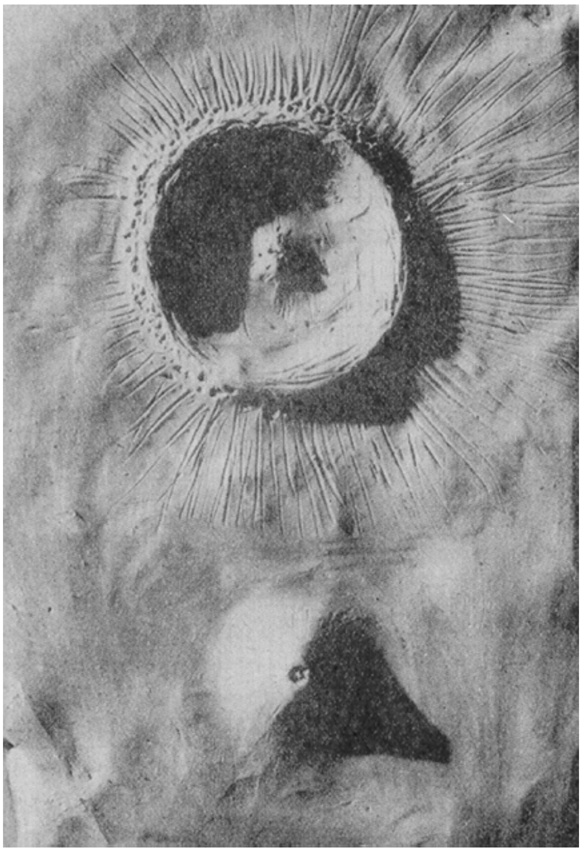

Figure 7. Photograph of a scale model of a typical lunar crater and a typical terrestrial volcanic cone, from Baldwin (1949). The distinct difference between the two is obvious.

meteoritic material: a body of only 30 to 50 m in diameter is required to cause a crater with a diameter of more than 1 km.

The early work by Barringer and others on Meteor Crater laid the foundations for a detailed understanding of impact cratering. Nevertheless, the impact hypothesis was still in its infancy, both for the explanation of terrestrial craters as well as for lunar craters. In a seminal book, Ralph Baldwin (1949) took the evidence from the studies of Meteor Crater and merged them with lunar observations and the theoretical work published two decades earlier, and presented a consistent theory of the formation of lunar craters by impact, and not by volcanism (see Figure 7 for an illustration).

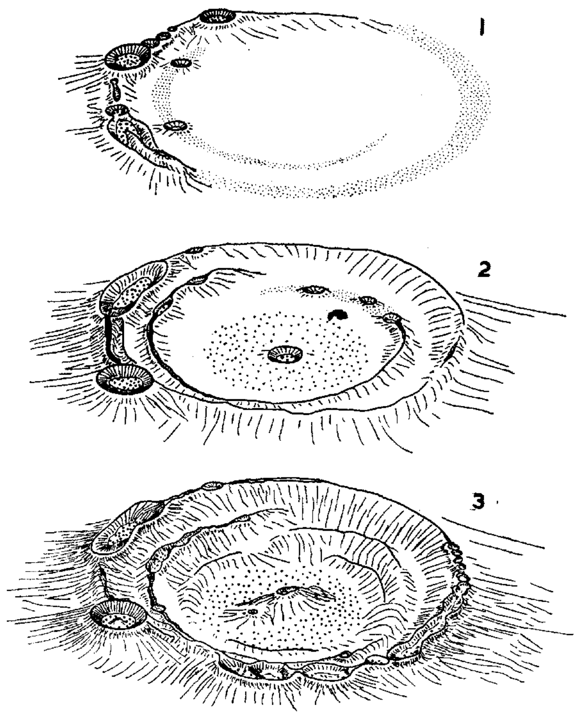

Figure 8. Even shortly before the first manned landing on the moon, some astronomers preferred to explain the formation of lunar craters by (fairly complicated) volcanic processes, as shown in this sequence, from Fielder (1965).

6. Lessons for the Recognition of Impact Craters on the Earth

In the second half of our century it was mainly planetary exploration and extensive lunar research that finally led to the conclusion that essentially all craters visible on the moon are of impact origin. However, opposition to the impact theory for lunar craters continued right up to the time of the first manned landing on the moon. For example, the British astronomer Gilbert Fielder stated in 1965: "Because of the popular support for the impact hypothesis, on the one hand, and the strong evidence that the lunar rings attained their present shapes by volcanism, on the other hand ..." (Fielder, 1965: 154–155). His complicated model for the formation of lunar craters by subsidence, development of ring faults, and melting of the crater floor is shown in Figure 8. In an earlier book, Fielder (1961) lists a useful bibliography of papers dealing with the volcanic and impact hypotheses. It seems that only the study of actual lunar samples after 1969 finally closed the book on this debate.

Meanwhile, since the early 1930s, a number of terrestrial structures had been proposed as having formed by impact. The history of this development, and the numerous counter-arguments of researchers who preferred these structures to have formed in some unknown "cryptoexplosion" process, is beyond the scope of this short article; see, e.g., Hoyt (1987) for a detailed history and references. In 1980, when the hypothesis was published (Alvarez et al., 1980) that the extinction of the dinosaurs, 65 million years ago at the Cretaceous-Tertiary boundary, was caused by the impact of a large asteroid or comet, the geological community was far from ready to accept such an outlandish proposition. By that time at least astronomers had accepted that the craters on the moon provided evidence that the Earth had also been subjected, over its history, to a significant number of impact events, but this conclusion was not widely accepted (or even known) among geologists. One reason was the obvious lack of large numbers of craters on the Earth's surface. The reason is of course that terrestrial processes (weathering, plate tectonics, etc.) effectively work to obliterate the surface expression of these structures on Earth.

It was noted that "resistance to the [impact] hypothesis seemed inverse to familiarity with impacting studies" (Glen 1994: 52). Planetary scientists, astronomers, and meteoriticists, who deal on a daily basis with topics including asteroids and meteorites (products of collisions between asteroids), were used to view "large-body impact as a normal geological phenomenon – something to be expected throughout Earth history – but another group, the paleontologists, is confounded by what appears to be an ad hoc theory about a nonexistent phenomenon" (D. Raup in Glen, 1994: 147). In this context, one should take into account the time scales that are involved in this discussion. What geologists have called "uniformitarianism" is the result of a large number of individual catastrophes of various magnitudes over a sufficiently long time span. Earthquakes, volcanic eruptions, landslides, etc., are locally devastating during periods on the order of about 20 to 100 years, but if the whole world and longer time spans are taken into account, these (local) "catastrophes" become part of the (global) "uniformitarian" process of explosive volcanism, earthquake history, or erosion. The bias in what is considered uniformitarian is related to the life span of humans and the human civilization. Large meteorite impacts have not been observed during the last few millennia, and, thus, such events tend to be neglected when constructing the "uniformitarian" history of the Earth. In contrast, small meteorites have been observed to fall from the sky quite frequently, but scientists have failed to make the connection to impact events by applying the same principle that is being used for extrapolating the frequency of volcanic eruptions and earthquakes: large and devastating ones occur less often than small events. There is no real conflict between uniformitarianism and meteorite impact. Over long periods of time, impact is a common and normal process on the Earth.

7. Conclusions

There are some interesting lessons to be learned from the history of the hypotheses that were postulated to explain the origin of craters on the moon. Hooke was already on the right track in 1665, but he had to reject the impact hypothesis because, at that time, he knew of no source for the projectiles. Proctor had the right idea for the wrong reason, just as Barringer came to the right conclusion (that Meteor Crater is an impact crater), but based on incomplete knowledge and misunderstandings. Gilbert and Wegener came to the right conclusions, but, just like with continental drift when first formulated, could not present a physically plausible mechanism to explain their convictions. After such a mechanism was found in the 1920s, however, resistance continued among astronomers, and it took decades during which a gradual shift towards the impact hypothesis for lunar craters occurred, which was more or less complete in 1969, when Apollo 11 landed on the moon. In contrast, geologists had no knowledge of impact processes and cratering phenomena, and, thus, initially did not take kindly to the proposal that impacts were an important factor in the geological and biological evolution of the Earth. In this case, though, the "paradigm shift", to once more (ab)use Thomas Kuhn's much quoted term, took only about one decade, until the discovery of the 200-km-diameter Chicxulub impact structure in Mexico, which was convincingly shown to be "the" Cretaceous-Tertiary impact structure. However, following the "mass extinction debates" (Glen, 1994, 1998) it becomes clear that history repeated itself and not much was learned from the debates about the history of lunar craters.

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